

Lecture Notes in Civil Engineering

Umberto Berardi
Julieta António
Nuno Simões *Editors*

Construction, Energy, Environment and Sustainability

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Energy)

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Preface

The third International Conference on Construction, Energy, Environment, and Sustainability (CEES 2025) was held in Bari (Italy) during June 11–13, 2025. The event was organized by Itecons/University of Coimbra in collaboration with the Polytechnic University of Bari. The conference welcomed 225 participants from over 25 different countries.

Prof. Jeffrey D. Sachs (Columbia University, USA), Prof. Patrícia Pereira da Silva (University of Coimbra, Portugal), Prof. Romeu Vicente (University of Aveiro, Portugal), and Prof. Aminhossein Jahanbin (Polytechnic University of Bari, Italy) gave invited keynote lectures. The presentation of a total of 209 papers was organized into several parallel sessions on the general themes of “Construction materials and technologies”, “Building physics”, “Energy”, “Water and sanitation”, “Environment”, “Construction and industry 4.0” and “Community challenges and policies”, as well as in 10 special thematic sessions organized by members of the Scientific Committee.

This volume entitled “Energy” contains 58 selected papers presented at the conference. Each paper was evaluated by at least two independent reviewers.

Each paper was evaluated by at least two independent reviewers. The conference organizers thank the members of the Scientific Committee for their invaluable contribution in reviewing and recommending the papers selected for publication and the conference sponsors and institutional supporters for their precious assistance. The conference organizers are also thankful to Springer, particularly the Editors-in-Chief, for agreeing to publish these papers.

The success of the conference is well reported in this video: <https://www.youtube.com/watch?v=kpzar9OKrq8&t=15s>

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An Inclusive Tool to Support the Implementation of Urban Living Labs in Positive Energy Districts



Martina Dell'Unto , Bahanur Nasya , Louise-Nour Sassenou ,
Claudia E. Collar , and Francesca Olivieri 

Abstract Positive Energy Districts (PEDs) are strategic models, recognized by the European Commission, that promote the energy transition of a neighborhood by transforming it into an area with a positive energy balance and zero net emissions. Indeed, neighborhood constitutes an adequate scale to drive a deep urban transformation that the local communities and organizations can understand and participate in. Despite this potential, the inclusion of the social context through engagement, participation, and co-creation methods is unfortunately considered secondary in many PED processes. The definition of the functions of the different stakeholders in this transition is a complex task that can become a major pitfall if not correctly addressed. This contribution aims to introduce the governance framework developed and validated within the POSEIDON project to manage this issue effectively. The governance plan designed for each of the project's urban laboratories—in Alcorcón (Spain), Antalya (Turkey), Cascais (Portugal), Cesena (Italy), Marseille (France), and Rome (Italy)—consists of seven stages and is based on the quadruple helix approach. In that sense, it aims to ensure participation from academia, business, public administration, and civil society. Its goal is to enable an inclusive energy transition in the district, that involves key actors with a dual perspective: one “designed with the users”, where the public administration will play the role of mediator and facilitator of the transition actions, and another “designed by the users”, where the direct users will assume the role of main actors of the transition.

Keywords Positive energy districts · Governance plan · Inclusive energy transition · Stakeholders' activation · Quadruple helix

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1 Introduction

Cities account for more than 50% of the world's population, 80% of global GDP, two-thirds of global energy consumption, and more than 70% of annual global carbon emissions. According to the latest IPCC report, these factors are expected to increase significantly unless mitigation action is taken soon, making it impossible to reverse climate change and its impacts [1]. Therefore, climate action in cities is an ambitious and essential goal to mitigate climate change and improve the livability of increasingly inhospitable cities (extreme heat, floods, droughts, etc.). In this context, Positive Energy Districts (PED) are presented as a promising model to accelerate the energy and sustainable transition of cities [2–4].

PEDs are energy-efficient and flexible urban areas that generate zero greenhouse gas emissions and proactively manage an annual surplus of renewable energy production. These districts demand the integration of diverse systems and infrastructures, fostering interaction between buildings, users, and regional energy, mobility, and ICT systems [5]. This integration optimizes the livability of the urban environment in accordance with social, economic, and environmental sustainability. Stakeholders see great potential in PEDs to alleviate energy vulnerability. However, to fully realize this potential, PEDs must be designed with a strong emphasis on social inclusivity [6]. These stakeholders, with their deep understanding of the urban context in which the intervention takes place, are well-positioned to play pivotal roles in advancing the transition. Beyond ensuring the continuity of this process, they can actively monitor and sustain the transformative changes over time, thereby securing the long-term success and durability of the transformation.

The primary stakeholders in this transition can be categorized into four sectors according to the quadruple helix approach: public administration, businesses, academia, and citizens [7]. This framework is intended to address the transformation from all relevant perspectives, ensuring a comprehensive approach that aligns with the complexity of the urban environment. In the implementation, a significant challenge relies in achieving consensus among the stakeholders. One model that has the potential to facilitate this intricate process is the Urban Living Labs (ULL) [8]. An ULL is an instrument that aims to foster the social acceptance and adoption of innovations and sustainable solutions in the urban system. These urban laboratories aspire to engage a diverse range of stakeholders, thereby striving to actualize their objective of facilitating the sustainable transition of cities. The activities that the ULLs propose involve participants in a democratic and active way, engaging them in the processes of design, development, testing, implementation, and evaluation of the proposed or co-created solution. This approach is designed to ensure that all participants have a comprehensive understanding of the significance of the transition actions to be implemented in the urban environment. The effective functioning of ULLs is contingent upon the establishment of a clearly defined governance and management structure [8].

This study aims to present a ULL governance framework developed for six cities in the context of the POSEIDON project. The governance plan, currently on adaptation

phase to the six-city-contexts, consists of seven stages. The POSEIDON project was funded under the European Driving Urban Transition partnership.

2 Methodology

The proposed methodology aims to address the challenges associated with the involvement of diverse stakeholders in the PED transition by reducing barriers to participation. The quadruple helix approach in this study adopts a dual perspective, encompassing both “designed with users” and “designed by users”.

The first approach is to be addressed in the initial phase of the process, in which the foundations of ULL are established with the public administration acting as a mediator and facilitator of all stakeholders. In the development of a secondary approach, direct users of the district are invited to actively participate through activities addressed to them. The primary objective is to create a process tailored for each ULL city, enabling participants to take on active roles (with varying responsibilities and capabilities) in driving the local transition. The methodology delineates seven sequential stages for formulating the city-specific ULL and its corresponding governance plan. The governance plan guides and supports all seven stages, requiring a degree of flexibility throughout the process. The methodology begins with the definition of the current situation (Stage 1), and then the needs will be observed (Stage 2). The ULL transition point will be defined (Stage 3), and the type of activities—face-to-face and digital—must be devised (Stage 4). The ULL activities will then be prototyped (Stage 5) and tested (Stage 6). Finally, the ULL will be implemented (Stage 7) (Fig. 1).

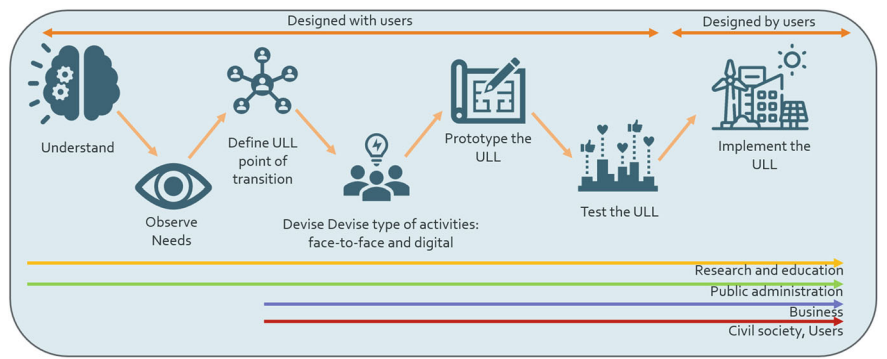


Fig. 1 Workflow of methodology

2.1 *Methodology Development Phases*

Stage 1: Understand The aim is to set the initial framework of the city and/or district. To that end, the involvement and collaboration of public administration and academic stakeholders is essential. In this first stage, the public administration provides a comprehensive framework on the initial situation of the municipality, and the research/education groups offer support in collecting the most relevant information (through a project-specific survey) to build a ULL framework for the energy transition towards PED models. Information is collected through two main instruments: surveys and face-to-face workshops. The information gathered during this phase serves as a foundation for Stage 2.

Stage 2: Observe needs The data obtained in the “Understand” stage is analyzed to create an initial overview of the city’s current situation. This overview serves as the foundation for developing the ULL concept. Additionally, the “transition point” is defined as the overarching goal guiding all ULL activities. The concept and the drafted goal for the ULL are shared and discussed with the public administration’s teams.

Stage 3: Define the ULL point of transition All relevant stakeholders are engaged following the quadruple helix approach, which includes public administration, businesses, academic institutions, and citizen participation. This phase is crucial for achieving stakeholder consensus on the ULL, ensuring that essential elements for the city’s energy transition are either confirmed or integrated into the plan. These collaborative efforts aim to align the transition point with the shared vision of all stakeholders. The tool for this phase is a survey aimed at assessing the city’s initial state and identifying its needs. Based on those insights, a preliminary version of the governance document is developed, incorporating the “transition point”. Then municipalities review their draft governance plans and elaborate collaboratively on the specific details. As a final step, the teams of city representatives assess the governance plan within their municipality and approve the approach as to its feasibility, as well as identify the roles to be played by the different actors.

Stage 4: Devise type of activities: face-to-face and digital After forming the governance consent, the partners determine the objectives to which the ULL will respond. ULL designers integrate the interest and the typology of activities to be carried out, both face-to-face and digital, to be defined in social programming. This stage also entails incorporating the survey results, completed by all relevant parties, subsequently grounding these efforts in the municipality’s capabilities to execute the chosen activities. In this phase, it is recommended to have bilateral meetings between the ULL designers and the public administration. After achieving a consensus on the typology of activities, these are incorporated into a subsequent iteration of the governance plan.

Stage 5: Prototype the ULL Following the establishment of the overarching framework of activities, the subsequent phase involves the initiation of prototyping and

design processes. These measures are intended to ensure the attainment of the objectives delineated in Stage 3. In this phase, information about the different ULL activities is first gathered through a “portfolio of activities” already developed by the ULL designers. These activities are selected by the survey results and the feasibility of municipal implementation. The assessment of potential municipal needs and the proposal of suitable solutions are a key aspect of this phase. These solutions are developed to facilitate the implementation of activities identified in the survey. The governance plan delineates the roles and tasks associated with each activity and establishes consensus among stakeholders.

Stage 6: Test the ULL Following the development of a prototype and a general portfolio of activities, this phase involves testing activities to identify final modifications to the approach, as well as potential needs that may be required for activities to be effectively implemented.

Stage 7: Implement ULL. This phase is dedicated to planning the implementation of the ULL and its impact. In particular, the calendar of activities, the physical locations and online platforms to be used for the ULL, and finally the quantification of the Key Performance Indicators (KPI) to be achieved in each city are planned. The governance plan also collects this information. In this particular phase of the ULL, all stakeholders are actively involved, so it is crucial to create realistic planning of the activities.

3 Results

As a result of this study, the methodology is validated in six case studies located in different Mediterranean cities: Alcorcón (Spain), Antalya (Turkey), Cascais (Portugal), Cesena (Italy), Marseille (France), and Rome (Italy). These cities are participating in the European POSEIDON Project awarded in the framework of the Driving Urban Transition call. These cities have different PED transition objectives, and the governance plan developed has aimed to unify the transition strategy at the social level and at the same time design a ULL in harmony with the real needs of each city and district. The results obtained for each phase of this methodology are presented below.

3.1 Methodology Validation in the POSEIDON Project

Stage 1: Understand In this phase, the ULL designers conducted a survey that could be sent to municipalities. The survey collected information to understand the municipality’s current state in the energy transition, as well as their needs and expectations regarding ULLs. The survey was disseminated to municipal technicians in each city

to complete. Following the collection of this information, it was summarized and shared during a face-to-face activity. Representatives from each municipality participated in this preliminary session. In this activity, the results were shared, and a new debate and discussion were initiated among the case studies. This activity was instrumental in deepening the perspective of each municipality on ULLs and in identifying the differences between the different cities.

Stage 2: Observe needs In this phase, the data obtained in the two activities of the “Understand” phase were analyzed and summarized in a common view (Table 1).

Table 1 Case studies overview

City	Country	City commitments	Energy transition goal in POSEIDON
Alcorcón 170.817 inhab.	Spain	Neutral target in 2040	Energy efficiency, renewable energy generation, and the promotion of energy communities
Antalya 1.203.994 inhab.	Türkiye	Neutral target in 2050 according to SECAP	Social and technical urban energy transition
Cascais 214.158 inhab.	Portugal	Carbon neutrality roadmap 2050 was designed in 2020 associated with: mission innovation's urban transition	Innovative solutions that promote climate change adaptation and mitigation, such as energy efficiency solutions, soft mobility, NBS, spatial planning, and urban design
Cesena 97.137 inhab.	Italy	Mayors adapt, covenant of mayors, sustainable energy and climate action plan (SECAP), climate emergency declaration, green city accord (GCA)	Integrated and sustainable urban practices are pursued through different planning tools and the construction of networks at international, European, regional, and local level
Marseille 930.393 inhab.	France	Net zero city Marseille climate city contract (CCC), commitment to reach –50% of GHG emission by 2030, priority 3 of CCC—Scale up sobriety, efficiency, and renewable energies	Accelerate the deployment of projects with a strong climate impact on Marseille's territory, through the mobilization of local, national, and European financial tools
Rome 2.857.321 inhab.	Italy	100 climate-neutral and smart cities by 2030, covenant of mayor, global covenant of mayor for climate and energy, C40 deadline 2020, C40 green and healthy streets declaration, C40 urban nature declaration signatory cities	Defining specific urban landscapes and different possible scales of intervention that can condition the organization of a decentralized energy production system

Stage 3: Define the ULL point of transition This stage involved all relevant stakeholders from each city according to the quadruple helix concept: public administration, businesses, academia, and citizens. To this end, a survey was developed by the ULL designers to address the necessary aspects for its conceptualization. Once the survey was prepared, it was disseminated by the municipalities to key stakeholders in their respective cities, at least four people (quadruple helix). The survey has thus far garnered the participation of 26 individuals. The industry sector accounts for 31% of the total, with Public Administration, Academia, and Civic Society accounting for 23%. As a result of the survey, a transition point and type of challenge (Table 2) for each municipality were devised (based on the vulnerabilities and expectations).

Stage 4: Devise the type of activities: face-to-face and digital Following the identification of the transition point and the challenges inherent to it, the initial version of the governance plan was disseminated to the municipalities, and bilateral meetings were convened with the municipalities. The objective of the meeting was twofold: firstly, to ascertain the feasibility of the governance plan, and secondly, to delineate the potential requirements for implementing the ULL. Additionally, the typology of activities to be carried out was agreed upon. Through these bilateral meetings, it was possible to define six new versions of the governance plan.

Stage 5: Prototype the ULL Following the delineation of the typologies of activities required by the case studies, the ULL partners and designers initiated the collection of potential activities to be executed both in person and digitally. These activities were conceived by the partners or identified as exemplary practices for replication within the context of the PED transition by the case studies. This process resulted in a portfolio of ten types of activities, which could be selected according to the specific municipality's implementation capabilities.

Stage 6: Test the ULL The testing of these activities will be carried out in a face-to-face meeting in the Municipality of Marseille (April 2025). This meeting will

Table 2 Transition points and associated challenges identified in the case studies, classified as Social (S), Technical (T), Logistical (L) or Economic (E)

City	Point of transition	Challenges
Alcorcón	Affordable and accessible energy for all	S, T, L, and E
Antalya	Inform citizens about the potentialities of energy transition and what they can do	S, and E
Cascais	Win local actors for the climate neutrality transition	S, L, and E
Cesena	We are building resilience to climate change and advancing municipal climate neutrality	S, L, and E
Marseille	Creating a neighborhood dynamic for a just and inclusive transition	S
Rome	Getting the community involved and providing technical expertise on PED	S, L, and E

Table 3 Selected KPIs to measure the social impact of the ULL

KPI	Measure
Stakeholders’ engagements	Types of stakeholders involved (name and number) People empowered (number)
Driving entity PED	Creation of figures to drive the transition (name and number) Creation of guides and instruments to continue the transition (guide)
Improving quality of life	Perception of well-being (environmental, social, and spatial) (survey) Quantification of environmental and spatial improvements (m ² and survey)
Affordability of transition	Total cost savings in housing are due to empowerment through energy literacy activities. (survey, €)

entirely be dedicated to the testing of the ULL activities and the definition of the possible needs of the different municipalities. Once the most feasible activities will define for each municipality, they will be added to the governance plan of each city.

Stage 7: Implement ULL After defining the activities to be carried out and confirming their feasibility with the municipalities, the implementation of the ULLs will be planned in different aspects: timetable, locations, roles, and KPIs (Table 3). After this phase, the governance plan of the ULLs will finally be finalized, and the implementation of the ULL in each city will start.

4 Conclusions

This research presents a methodology for formulating a governance plan for the design and activation of a ULL with a focus on the PED energy transition. ULLs have been identified as a promising tool to actively and participatively engage and empower stakeholders who have the potential to be key actors in the city’s transition. However, it is crucial to acknowledge that implementing a ULL necessitates a meticulous process of agreement and consent among stakeholders. To this end, the necessity arises for the formulation of a substantial framework to accord the different parts.

The present study proposes a seven-stage methodology to facilitate the conception of a ULL and embed it in a governance plan that can drive the PED transition. The validity of this methodology has been substantiated through its implementation in six case study cities. The result of this activity has been to first define the context of the cities through the Understand and Observe needs stages. Following the establishment of the fundamental framework, a survey was conducted to solicit the input of various stakeholders, including public administration, businesses, academia, and citizens. This survey aimed to gather their perspectives on the case study cities and to ascertain their needs and expectations for the ULLs to be developed at the local level. Through

the analysis of the collected data and the facilitation of bilateral meetings with the municipalities, the transition point for each case study was determined, and the types of activities to be carried out were defined. Following the establishment of the general framework, specific activities were proposed for implementation in the ULLs, and potential needs and barriers to their execution were identified through testing. Finally, the implementation framework of the ULLs was defined, delineating roles, timetables, locations for activity implementation, and KPIs to measure the impact of the ULLs. As a result of these phases, six governance plans were defined, one for each case study.

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References

1. IEA empowering cities for a net zero future. Available online <https://www.iea.org/reports/empowering-cities-for-a-net-zero-future>. Accessed on 12 Mar 2025
2. Civiero P, Pascual J, Abella JA, Figuero AB, Salom JP (2021) Positive energy district renovation model for large scale actions. *Energies* (Basel) 14. <https://doi.org/10.3390/en14102833>
3. Villa-Arrieta M, Sumper A (2019) Economic evaluation of nearly zero energy cities. *Appl Energy* 237:404–416. <https://doi.org/10.1016/j.apenergy.2018.12.082>
4. Bossi S, Gollner C, Theierling S (2020) Towards 100 positive energy districts in Europe: preliminary data analysis of 61 European cases. *Energies* (Basel) 13. <https://doi.org/10.3390/en13226083>
5. JPI Urban Europe. Available online <https://jpi-urbaneurope.eu/>. Accessed on 15 June 2023
6. Hearn AX (2022) Positive Energy District stakeholder perceptions and measures for energy vulnerability mitigation. *Appl Energy* 322. <https://doi.org/10.1016/j.apenergy.2022.119477>
7. Padial M, Pinzón S, Navarro B, San Juan P, Ruiz J, Espinosa JM (2019) Effective implementation of the quadruple helix-based innovation model for active ageing. *Gac Sanit* 33:491–494. <https://doi.org/10.1016/j.gaceta.2018.08.003>
8. Chronéer D, Ståhlbröst A, Habibipour A (2019) Urban living labs: towards an integrated understanding of their key components

Expansion of the Market for Passive Daytime Radiative Cooling and Future Perspectives



Masahiro Suemitsu, Ryosuke Osugi, and Alexander Schmoldt

Abstract Passive daytime radiative cooling (PDRC) is an innovative technology born from academic research with the potential to revolutionize cooling solutions. By reflecting sunlight and emitting thermal radiation directly into outer space, PDRC materials enable daytime cooling without energy consumption. This provides a swift and straightforward solution to both mitigating and adapting to global warming, contributing to the realization of a sustainable society. SPACECOOL has been at the forefront of this technological innovation, driving the development and commercialization of PDRC materials. This presentation will explore the journey of PDRC from research and development to real-world applications, showcasing SPACECOOL's innovative approach to market implementation. Our proprietary PDRC film achieves cooling effects of 2–5 °C below ambient temperature under direct sunlight, even during humid Japanese summers. Unlike traditional cooling methods, it requires no external energy or refrigerants, significantly reducing greenhouse gas emissions and energy consumption. The transition from laboratory-scale research to scalable production posed challenges, such as material durability, manufacturability, and market acceptance. SPACECOOL overcame these hurdles through robust design, feedback from extensive field testing, and strategic partnerships with industry stakeholders. Today, SPACECOOL's PDRC film is applied in diverse sectors, including building materials, transportation, and industrial processes. Pilot projects in arid regions have also demonstrated reduced energy demand incase combined with active cooling. Furthermore, SPACECOOL is exploring new strategic partnerships and business models to accelerate the global adoption of PDRC. By sharing our journey, we aim to inspire further advancements and collaborations in sustainable cooling technologies, contributing to a more sustainable future.

Keywords Technology to market · Passive cooling · Adaptation · Mitigation · Global warming

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1 Introduction

Global warming is advancing at an unprecedented rate, with significant impacts on not only the natural environment but also society, the economy, and everyday life. The challenges associated with global warming are diverse, including extreme weather events, rising sea levels, and increased energy demand due to rising temperatures. Addressing these challenges necessitates the adoption of renewable energy sources alongside new energy-saving technologies. Among such emerging technologies, passive daytime radiative cooling (PDRC) materials have recently gained attention for their ability to lower temperatures passively without consuming energy, even under direct sunlight. These materials leverage the radiative cooling phenomenon, where heat is converted into thermal radiation within the wavelength range of 8–13 μm (known as the “atmospheric window”) and thus emitted into outer space. This effect has been widely reported in the literature [1–6].

PDRC materials have the potential to be applied in various fields, including cooling of buildings cooling and outdoor electrical equipment. This paper discusses the fundamental principles and potential applications of PDRC materials while also outlining recent research findings and the progress in their societal implementation.

2 Cooling Principles of PDRC Materials

This section explains the mechanism by which PDRC materials achieve temperatures lower than the ambient air under direct sunlight. The radiative cooling effect, commonly mentioned in weather forecasts, occurs when an object radiates heat in the form of infrared radiation into outer space, which has an extremely low temperature of $-270\text{ }^{\circ}\text{C}$. This phenomenon is well known as the cause of frost forming on car surfaces during the night. However, for conventional materials, the heat gain from solar radiation and atmospheric infrared radiation exceeds the cooling effect of radiative heat loss, making daytime cooling challenging. The PDRC material developed by SPACECOOL Inc. achieves daytime cooling by ensuring that radiative heat loss to outer space exceeds the heat gain from solar and atmospheric infrared radiation. This section explains the spectral emissivity characteristics required for such a material. Figure 1 illustrates the solar spectrum (AM1.5G), the atmospheric transmittance spectrum (limited to wavelengths longer than 4 μm for clarity), and the ideal emissivity spectrum of a PDRC material.

The wavelength range of 8–13 μm , where the atmosphere has high transmittance, is referred to as the “atmospheric window.” Thermal radiation emitted in this range escapes directly to outer space without being absorbed by the atmosphere. To achieve effective radiative cooling, it is desirable to maximize emissivity in this wavelength range. Conversely, to achieve daytime cooling, it is essential to minimize solar heat absorption by reflecting as much solar radiation as possible in the

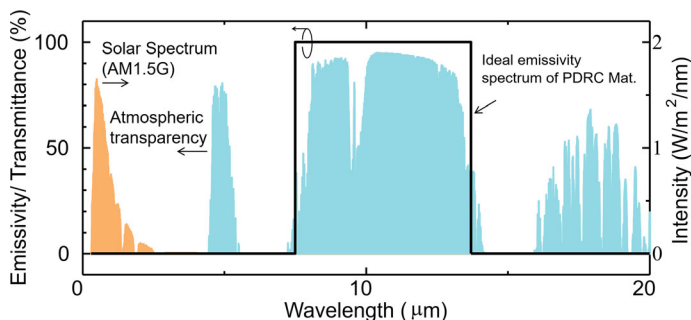


Fig. 1 The ideal emissivity spectrum of the radiative cooling material (solid line), the solar spectrum (AM1.5G, orange), and a portion of the atmospheric transmittance spectrum (only wavelengths longer than 4 μm are shown, light blue). The atmospheric transmittance spectrum represents values under clear sky conditions at an altitude of 4000 m. It should be noted that the atmospheric transmittance at sea level (0 m altitude) is lower than the values shown in the figure

0.3–4 μm wavelength range. Based on Kirchhoff's law of thermal radiation, the emissivity and absorptivity of a material are equal at thermal equilibrium. Therefore, an optimal PDRC material should have near-zero emissivity (high reflectivity) in the solar spectrum range and near-unity emissivity in the atmospheric window range.

3 Performance of PDRC Materials

This section describes the performance of radiative cooling materials under summer conditions in Japan. The experiment was conducted on the rooftop of a two-story building located along the coast in Osaka City, as shown in Fig. 2a. The measurement system, depicted in Fig. 2b, was designed to minimize thermal interference from solar radiation by using high-transparency white glass. The sample was supported by glass pillars and placed inside a lidless glass container with high transparency to solar radiation. To eliminate convective heat transfer effects caused by wind, the top surface of the container was covered with polyethylene film. The polyethylene film allows infrared radiation to pass through the atmospheric window and does not obstruct the radiative cooling effect. Temperature measurements were taken using a thin-film resistance temperature detector (RTD) attached to the ground-facing side of the sample, ensuring minimal thermal mass interference. The white thermometer shown in Fig. 2a is used to measure the outdoor air temperature and is different from the thermometer used to measure the ambient temperature shown in Fig. 2c. The thermometer used for measuring the ambient temperature in Fig. 2c was placed close to the sample and properly shielded from direct sunlight by positioning it in the shade. Furthermore, by using a thin-film resistance temperature detector (RTD) with low thermal mass, the influence of solar heating is minimized, while convective heat exchange with the surrounding air becomes dominant, enabling accurate

and responsive measurement of ambient temperature. The experiment was conducted over three days, from September 1, 2017, and the results are presented in Fig. 2c. The study compared the temperature performance of radiative cooling materials, stainless steel (SUS) plates, and SUS plates coated with a solar reflective coating (commonly used to reduce building exterior surface temperatures). The radiative cooling material used in this experiment consisted of an inorganic radiative layer composed of SiO_2 and B_2O_3 , combined with a reflective layer made of Ag and Al. This design achieved a solar reflectance of over 95% and an emissivity of over 95% in the atmospheric window. As shown in Fig. 2c, the solar intensity during the three-day period (represented by the orange line) was approximately 1000 W/m^2 at solar noon, with consistently clear weather conditions. It is known that radiative cooling is more effective in dry climates, while high humidity levels reduce the cooling effect. Japan's humid climate poses challenges for radiative cooling performance. The measured backside temperatures of the samples are shown in Fig. 2c. The ambient air temperature (blue line) ranged from 32 to 35 °C during the daytime. In contrast, the SUS sample (gray line) reached a maximum temperature of nearly 80 °C, and the solar reflective coating (blue line) peaked at approximately 45 °C. However, the radiative cooling material (red line) consistently maintained a temperature 2–6 °C below the ambient temperature throughout the three-day period. Additionally, at noon, the radiative cooling material was 10–15 °C cooler than the solar reflective paint. During the experiment, the water vapor content in the air was measured at approximately 13 g/m^3 during the day and 15 g/m^3 at night, indicating high humidity levels. For reference, absolute humidity in previous studies such as Raman et al. [1] and Zhai et al. [2] is not reported, but estimated values from U.S. National Weather Service data suggest typical levels of 2–5 g/m^3 in those test locations. This indicates that our results demonstrate the viability of sub-ambient daytime radiative cooling even under more humid atmospheric conditions than those considered in prior studies. In drier regions or higher-altitude locations, the cooling effect is expected to be greater than that observed in Fig. 2c; [7]. For example, in February 2023, an experiment conducted in Riyadh, Saudi Arabia, demonstrated that the daytime temperature of the radiative cooling material was 10 °C lower than the ambient air temperature, highlighting the significant enhancement of cooling performance in arid environments. To ensure transparency and reproducibility, we provide detailed ambient humidity measurements and sensor configurations in this study. Sub-ambient cooling using Ag/glass-based emitters has been reported in previous work, such as Zhao et al. [8]. However, the specific conditions for ambient temperature measurement—such as whether the sensor was placed inside or outside the convection shield—are not described, and while the study evaluates the influence of humidity on radiative cooling performance through numerical simulations using precipitable water vapor (PWV), no measured values of relative humidity or absolute humidity (e.g., in g/m^3) are provided for the experimental days. Therefore, a direct comparison of cooling performance is not possible and is not attempted in this paper.

In addition to rigid inorganic radiative cooling materials, recent developments have introduced flexible, sheet-type films for passive daytime radiative cooling

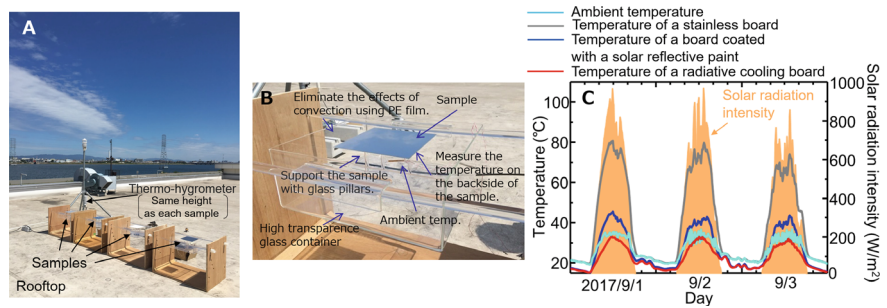


Fig. 2 Evaluation of the radiative cooling material. **a** Measurement setup appearance. **b** Details of the measurement system. **c** Demonstration results

(PDRC). Figure 3 presents one such example, a flexible film incorporating a polymer-based optical multilayer structure. Although traditional inorganic materials (such as those tested in Fig. 2c) often have rigid form factors, certain sheet-type films can achieve solar reflectance exceeding 95% and thermal emissivity exceeding 95% within the atmospheric window, thereby demonstrating cooling performance comparable to their inorganic counterparts. These sheet-type materials are typically engineered through multilayer polymer architectures that optimize reflectance and emissivity. Commercially available forms include adhesive-type films (Fig. 3a) and membrane fabric (Fig. 3b).

They can be attached, sewn, or heat-laminated onto various surfaces, thus offering a versatile means of integrating radiative cooling functionality into diverse applications. As an example, SPACECOOL[®] offers such a flexible sheet-type product, although other manufacturers also provide similar solutions in the field of PDRC.

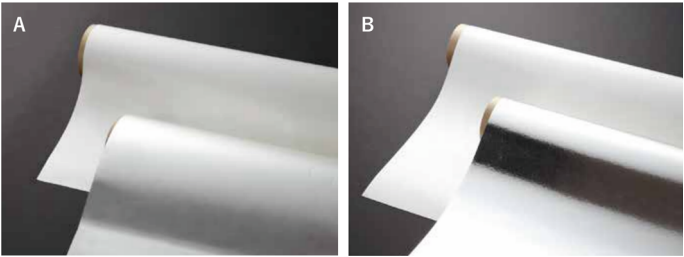


Fig. 3 Appearance of a Sheet-Type PDRC Film (SPACECOOL[®] as one example). **a** Adhesive PDRC film: available in two matte finishes—silver and white. **b** PDRC membrane fabric: available in two colors—silver and white



Fig. 4 Examples of radiative cooling material applications in buildings. **a** Roof shade method. **b** Waterproof sheet method (roofing method): a case where 600 m² was installed for the Tokyo Metropolitan Bureau of Transportation. **c** Concept image of the gas pavilion made with radiative cooling material

4 Applications in Building Cooling

PDRC materials have been incorporated into building materials, with applications expanding steadily. The “Roof Shade Method” by NIHON WIDECLOTH Co., Ltd. allows for easy implementation on metal roofing commonly used in factories and warehouses (Fig. 4a).

Similarly, the waterproofing sheets developed by Lonseal Corp. enable simple installation on flat-roof structures such as residential and office buildings (Fig. 4b). Additionally, tent fabrics incorporating PDRC materials have been developed by KANBO PRAS CORP., making them applicable for various purposes, including temporary warehouses and event venues. One notable application is the “Gas Pavilion,” the world’s first building made entirely of PDRC materials, which has been constructed for the Osaka-Kansai Expo 2025.

5 Life Cycle Assessment

To evaluate the energy-saving potential of PDRC materials, a life cycle assessment (LCA) was conducted on a 10 m² gathering tent using SPACECOOL[®] membrane fabric (Fig. 5a) [9]. This LCA was based on a cradle-to-gate system boundary, covering processes from raw material extraction to factory shipment. Use-phase impacts and end-of-life considerations were not included in this study.

The evaluation was conducted through year-round field testing, with cooling season defined as April to September and heating season as October to March. Both cooling and heating effects were assessed based on actual measurements, not simulations. The results indicate that, in the absence of air conditioning, the zenith temperature of the PDRC membrane was the lowest among the tent types evaluated (Fig. 5b). However, the recorded temperatures were still higher than the ambient air temperature, likely due to heat gain from the tent’s vertical sidewalls. Radiative cooling materials achieve the most significant temperature reduction at the zenith, where exposure to the sky is greatest. In contrast, vertical surfaces are more affected

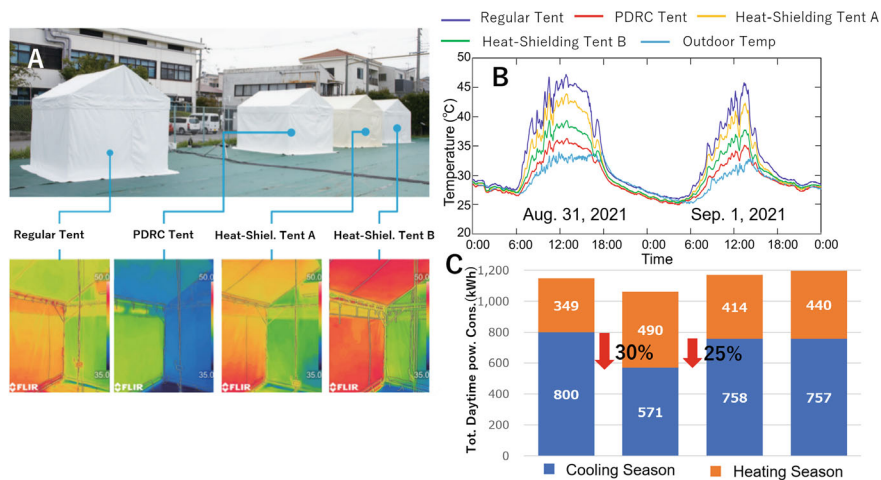


Fig. 5 Tent testing **a** exterior view taken from the south. From left to right: regular tent, PDRC tent, heat-shielding tent A, and heat-shielding tent B. **b** Tent ceiling temperature from August 31 to September 1, 2021. **c** Perceived temperature inside the tents (globe temperature) during the same period

by ground radiation and are prone to higher temperatures. Compared to conventional and heat-shielding tents, the PDRC tent reduced air conditioning energy consumption by 25–30% during the cooling season, resulting in an estimated 86 kg-CO₂ reduction in greenhouse gas emissions and a 33 kg-CO₂ annual reduction (Fig. 5c). Although the use of the PDRC membrane fabric incurred approximately 11 kg of CO₂ emissions per tent during production, the overall energy savings more than offset this additional carbon footprint. During the heating season, a slight increase in indoor perceived temperature was observed in the PDRC tent compared to conventional tents, due to reduced solar heat gain. This energy penalty was also based on measured data, further highlighting the importance of considering seasonal trade-offs in practical applications. Future work will extend similar LCA assessments to other membrane fabrics and consider full cradle-to-grave evaluations, including transportation, use, and end-of-life disposal.

6 Conclusion

This paper discussed the fundamental principles, applications, and recent advancements in PDRC materials. As an energy-saving technology complementing renewable energy, PDRC materials should play a crucial role in global warming countermeasures by reducing energy consumption and greenhouse gas emissions. The results indicate that these materials provide a cost-effective and sustainable cooling solution, particularly in building and industrial applications. LCA evaluations further

confirm that the CO₂ emissions generated during manufacturing are quickly offset by the energy savings achieved.

With their wide applicability in construction materials, tent structures, and industrial applications, PDRC materials are expected to see further adoption, contributing not only to climate change mitigation but also to a reduction of the growing global energy demand.

References

1. Raman AP et al (2014) Nature 515:540
2. Zhai Y et al (2017) Science 355:1062
3. Yuan H et al (2018) Opt Express 26:28885
4. Suemitsu M et al (2018) Radiative cooling device and radiative cooling method. Japan Patent JP6861614
5. Suemitsu M, et al. (2019) In: The 80th JSAP autumn meeting 2019, 21a-E208-11
6. Osugi R, et. al. (2023) The 84th JSAP autumn meeting 2023, 23p-A309-2
7. Huang J et al (2022) Int J Heat Mass Trans 186:122438
8. Zhao B et al (2019) Appl Therm Eng 155:660–666
9. Osugi R, et al. (2024) The 51th textile research symposium, C1-01

Passive Daytime Radiative Cooling for Energy Savings: A Multi-country Study Across European Climates



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Abstract Climate change intensified the need for sustainable solutions to mitigate urban heat and reduce buildings' energy consumption. Among the most promising strategies, there are cool roofing materials, particularly those utilizing passive daytime radiative cooling (PDRC) technologies, which enhance building thermal performance and minimize the reliance on energy-intensive cooling systems. PDRC materials reflect solar radiation and emit heat as infrared radiation through the atmospheric window. This mechanism enables them to achieve surface temperatures below ambient temperature. In this study, developed within the project 21GRD03 PaRa-MetriC founded by the European Union, the performance of PDRC materials with a solar reflectance of 0.93 and thermal emissivity of 0.877 (5–50 μm) and 0.889 (7–13 μm) is analyzed. Four building types are simulated in the EnergyPlus engine, including a six-story multifamily building and three single-family houses. These buildings are located in southern European cities with varying climates: Milan (Italy), Athens (Greece), Marseille (France), and Varaždin (Croatia). Two scenarios are evaluated: a baseline scenario using conventional roofing materials and two alternative scenarios employing PDRC materials, considering a constant or spectral emissivity-dependent model. Results demonstrate that the constant emissivity model overestimates PDRC performance. Considering the spectral emissivity-dependent model, in the coldest climate (Varaždin), the heating demand increase outweighs cooling savings, leading to a net rise in primary energy consumption with respect to the baseline scenario, equal to + 7.3%. Conversely, in Athens, the warmer climate enhances the effectiveness of PDRC, and total energy consumption decreases by – 5.4%.

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Keywords Passive daytime radiative cooling · Cool roof · European climates

1 Introduction

Cool roofs are designed to reflect more sunlight and absorb less heat than traditional roofs, using materials with high solar reflectance and infrared emittance [1]. Cool roofs help reduce indoor temperatures, decreasing the need for air conditioning and achieving energy savings, especially in hot climates. On an urban scale, they mitigate overheating caused by climate change. Some studies suggest that cool roofs are even more effective than green roofs in reducing cooling demand [2]. Passive daytime radiative cooling (PDRC) uses materials capable of emitting infrared radiation within the 7–13 μm atmospheric transparency window, allowing heat dissipation to outer space without external energy [3]. This enables materials to achieve sub-ambient temperatures, even in daylight [4], by minimizing solar absorption while maintaining high emissivity in the long-wave infrared (LWIR) range. PDRC materials have high solar reflectance, low reflectance within the atmospheric window, and high emissivity in the 7–13 μm range. These materials often feature multilayer or hybrid structures [5], e.g., multilayer coatings, porous polymers, and meta-surfaces. These structures may incorporate metals, as silver (superior optical performance in the solar spectrum) and aluminum (high solar reflectance), or dielectrics as silicon and titanium. Silicon, not widely used in daytime radiative cooling for its solar absorption, may appear in layered photonic structures or in night-time cooling applications. In recent years, PDRC have been studied with increasing interest; i.e., in 2017 they accounted for 14% of the cool roofs research, while in 2022 they are a notable percentage (60%) [6]. However, studies focus more on their chemical properties than on their interaction with the building [3, 5, 7]. None of the widespread current dynamic energy analysis software is able to integrate a thermal emissivity that varies with the wavelength; thus, PDRC materials are difficult to evaluate for a building level [8]. To overcome these knowledge gaps, this study aims to evaluate the effect of PDRC application on different residential buildings (single or multi-story) using EnergyPlus. The innovation lies precisely in the implementation of these materials in EnergyPlus and in the comparison with the behavior of “traditional” cool roof materials (constant emissivity model). The study is part of the 21GRD03 PaRaMetriC project, which facilitates passive radiative cooling materials performance in real-world conditions and assesses potential energy savings through their adoption.

2 Methodological Approach

This section describes the methodological process to evaluate PDRC's effectiveness in improving buildings' energy performance in different southern European cities. DesignBuilder [9] and EnergyPlus [10] are used for building energy modeling and simulation.

The existing constant emissivity model in EnergyPlus can't evaluate a variable cool roof thermal emissivity (ε). Then, a numerical model is developed in MATLAB [11] to investigate the real spectral emissivity-dependent behavior of a PDRC on the roof, as suggested by Yang et al. [12]. The heat flows that affect the external surface of the roof are represented schematically in Fig. 1 (left) and in Eq. (1). P_{ATM} [W/m²] is the atmospheric radiation absorbed by the roof's external surface under clear sky conditions, while P_R [W/m²] represents the radiation released by the roof's external surface. P_{SUN} [W/m²] is the absorbed solar radiation by the roof's external surface, and P_{CONV} [W/m²] is the convective heat exchange between the roof's external surface and the environment's air.

$$P_{ROOF} = P_{ATM} - P_R + P_{SUN} + P_{CONV} \quad (1)$$

$$P_{ATM} = 2\pi \int_0^{\frac{\pi}{2}} \sin \theta \cos \theta d\theta \int_{7 \mu m}^{20 \mu m} I_{BB}(T_{AMB}, \lambda) \varepsilon_R(\lambda) \varepsilon_A(\theta, \lambda) d\lambda \quad (2)$$

$$P_R = 2\pi \int_0^{\frac{\pi}{2}} \sin \theta \cos \theta d\theta \int_{7 \mu m}^{20 \mu m} I_{BB}(T_A, \lambda) \varepsilon_R(\lambda) d\lambda \quad (3)$$

$$P_{SUN} = \int_0^{4 \mu m} \varepsilon_R(\lambda, \theta_{SUN}) I_{SUN}(\lambda) d\theta \quad (4)$$

$$P_{CONV} = h_c(T_A - T_S) \quad (5)$$

$$\varepsilon_A = 1 - [t(\lambda)]^{\frac{1}{\cos \theta}} \quad (6)$$

$$I_{BB}(T, \lambda) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{\frac{hc}{\lambda k_B T}} - 1} \quad (7)$$

θ [rad] is the solar azimuthal angle, λ is the wavelength [m], T_A [K] and T_S [K] are outdoor environmental temperature and roof surface temperature respectively, ε_R is the PDRC material emissivity, which is equal to 0.889 in 7–13 μm and 0.3 outside this range (as observed in [13, 14]), ε_A is the atmospheric emissivity evaluated as in Eq. 6, I_{BB} [W/(m²·sr·m)] is the wavelength-dependent radiance of a blackbody with a temperature T [K] as in Eq. 7, I_{SUN} [W/(m²·m)] is the solar spectrum, h_c is the convective heat transfer coefficient on roof external surface, $t(\lambda)$ is the atmosphere

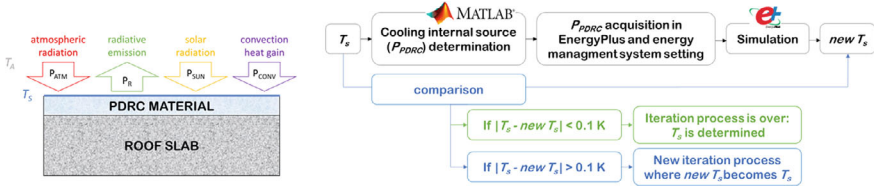


Fig. 1 Energy flows into/trough PDRC layer (left). Spectral emissivity-dependent model in MATLAB-EnergyPlus flowchart (right)

transmittance, h is $6.62 \cdot 10^{-34}$ J·s (Planck's constant), k_B is $1.38 \cdot 10^{-23}$ J/K (Boltzmann constant) and c is $3.0 \cdot 10^8$ m/s (light speed in vacuum). Cloud cover is not considered.

P_{SUN} and P_{CONV} (convective and radiative heat exchange) are already evaluated in EnergyPlus. Thus, in MATLAB P_{ROOF} is evaluated considering only P_{ATM} and P_R . In EnergyPlus, a cooling source is introduced, inserted as an internal negative heat source in the software. The external material has been set with the thermal emissivity (ε) equal to zero, in this way, the radiation model with constant emissivity is deselected. Furthermore, since roof outdoor surface temperature (T_s) is correlated to P_{ROOF} , an iterative procedure is necessary between the determination at each step of the new cooling internal source in MATLAB and its acquisition in EnergyPlus, as suggested in [8]. A schematic flowchart of the proposed approach is reported in Fig. 1 on the right.

Simulations are carried out for a baseline scenario with a bituminous sheath ($\varepsilon = 0.900$ and $SR = 0.06$); a constant emissivity model scenario, representing a traditional cool roof, with characteristics similar to the PDRC, thus $\varepsilon = 0.877$ and $SR = 0.93$; a spectral dependent emissivity model simulating the PDRC material with $SR = 0.93$ and $\varepsilon = 0.889$ in $7-13 \mu m$ and 0.3 outside this range. Results are analyzed in terms of (i) roof surface temperature (T_s); (ii) cooling/heating energy need, considering the top floor or the whole building; and (iii) annual primary energy consumption (PEC) for the whole building. Four cities located in Southern Europe are chosen for energy simulations, as required by the 21GRD03 PaRaMetriC project. Surely the study would benefit more from larger variation locations (e.g. desert climates, higher elevated locations and so on), but also within the group of the examined cities, there are climatic differences so that different benefits for PDRC materials applications emerge. The outdoor average annual air temperature in Marseille is $14.8^\circ C$, in Varaždin is $11.1^\circ C$, and in Milan is $12.4^\circ C$. Athens is characterized by the greater value, equal to $17.9^\circ C$.

3 Case Studies

The considered buildings all have flat roofs, suitable for cool materials application. They are all selected by the 21GRD03 PaRaMetriC project purposes. Every building is divided into night-day zones. The values for HVAC systems definition, thermal loads, and operating schedules are taken from the ASHRAE [15] standard. In this research, four case studies have been investigated:

1. a six-story multifamily building (MFB) in Marseille (France) in Fig. 2a;
2. a single-family house (SFH) in Varaždin (Croatia) in Fig. 2b;
3. a detached house (DH) in Milan (Italy) in Fig. 2c;
4. a detached house (DH) in Athens (Greece) in Fig. 2d.

Table 1 reports the main information. H_t is the global coefficient of heat exchange and S/V is the building dispersing surface/conditioned volume. Exposures are thus indicated: North (N), South (S), East (E), West (W). The MFB has the greatest thermal insulation levels and the lowest S/V value, i.e., significant volumes and limited dispersing surfaces, typical of large buildings. The two single-floor structures (in Varaždin and Athens) show major dispersing surfaces exposition and an S/V ratio typical of compact single houses. The DH in Athens is the most sensible to outdoor temperature variation, with the greatest U -value.

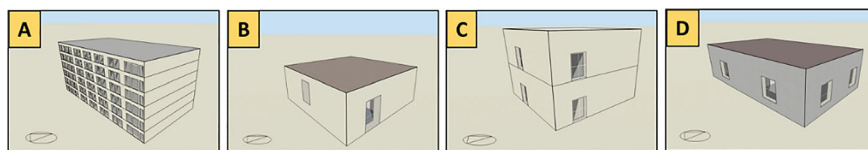


Fig. 2 DesignBuilder 3D rendering for MFB-Marseille, (a) SFH-Varaždin, (b) DH-Milan (c), DH-Athens (d)

Table 1 Geometrical/thermal features: MFB (a), SFH (b), DH (c), DH (d)

Building-location	MFB-Marseille	SFH-Varaždin	DH-Milan	DH-Athens
Floors-apartments	6–86	1–1	2–1	1–1
H_t [W/m ² K]	0.86	3.18	5.22	9.16
S/V [m ⁻¹]	0.29	1.57	0.84	1.11
Conditioned building area [m ²]	5586.7	73.1	173.1	107.2
Roof U -value [W/m ² K]	0.28	0.29	2.19	3.11

4 Results and Discussion

Figure 3 presents annual roof surface temperatures (T_s) for the baseline, spectral emissivity-dependent, and constant emissivity models. PDRC consistently lowers T_s , especially in summer. The constant emissivity model overestimates this effect, aligning with Yu et al. [8]. Using the spectral emissivity-dependent model, annual average T_s drops by 6.8 °C in Milan, 5.7 °C in Athens, 6.2 °C in Varaždin (SFH), and 2.3 °C for the MFB. Peak T_s reductions range from 11.4 °C in Marseille to 33.7 °C in Milan. Table 2 shows annual heating/cooling needs per conditioned area in the baseline. Figure 4 displays heating/cooling changes across models and scenarios. MFB, with low S/V and H_t , has limited heat loss, so PDRC has a minor effect. SFH in Varaždin sees moderate cooling benefits (− 23.8%) versus Milan/Athens due to its colder climate. DH in Milan/Athens shows the greatest cooling reduction (− 75%), confirming PDRC's effectiveness in hot climates. However, heating needs also rise, especially in Athens. Milan, with a 12.4 °C average temperature, shows high heating demand due to cold winters and moderate S/V and H_t , increasing vulnerability to heat loss. PDRC reduces summer cooling, notably on top floors exposed to solar radiation. DH in Athens, with high S/V (1.11 m^{−1}) and H_t (9.16 W/m²K), is more sensitive to outdoor conditions. Between the two models, energy needs with PDRC differ slightly: cooling savings are smaller with variable emissivity, while heating increases are lower than expected with constant emissivity. Several experimental and numerical studies confirm our results: cool coatings reduced cooling by 9–11% but increased heating (+ 1.7–2.6%) [16]; office building cool roof wintertime penalty (+ 14%) in Athens [17]; PDRC raised heating demand up to 2% in China [12]. Table 3 shows annual primary energy consumption (PEC). MFB has a negative (− 0.2%) energy variation (Δ PEC): PDRC leads to an improvement because of Marseille's relatively mild climate and good envelope thermophysical properties. Varaždin SFH has a Δ PEC equal to + 7.3% because of the cold climate, i.e., greatest heating needs: cool roof application is not advantageous. For DH in Milan, PDRC leads to an almost negligible total PEC decrease, i.e., PEC for heating and for cooling balance each other. For DH in Athens, PDRC brings greater benefits: warmer climate and high S/V building indicate a sensitivity to external climatic conditions.

5 Conclusions

This study assesses passive daytime radiative cooling (PDRC) effectiveness in building energy performance improvement in southern European cities through dynamic simulations. Roof temperatures decrease by 2.3 °C (Marseille) to 6.8 °C (Milan) using a spectral emissivity-dependent model, with the constant emissivity model overestimating performance (1–2 °C reduction). PDRC effectiveness varies by climate, building geometry, and thermal performance. It reduces cooling needs in hot climates (Athens, Milan) but may increase heating demands, particularly for

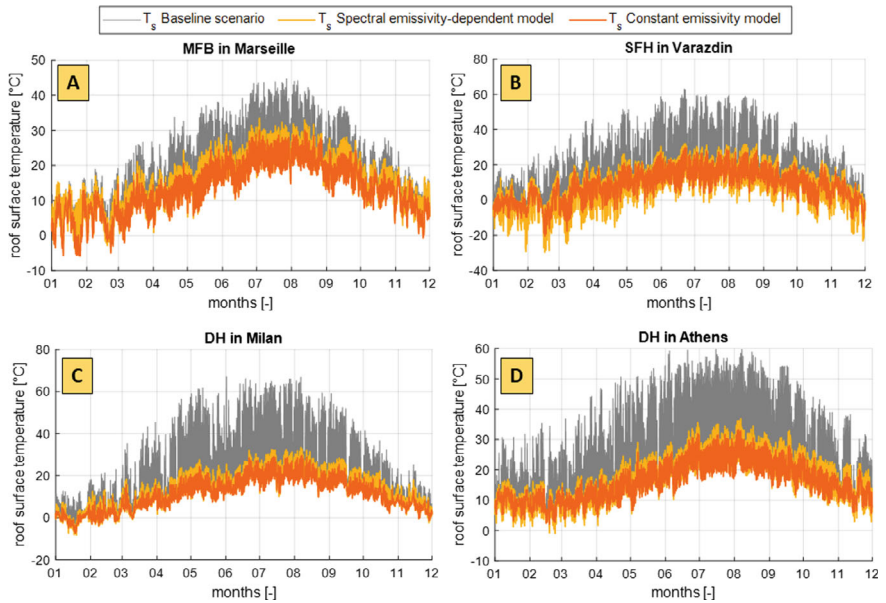


Fig. 3 Roof outside temperature with/without PDRC: MFB (a), SFH (b), DH (c), DH (d)

Table 2 Annual heating/cooling needs per conditioned floor area in the baseline scenario

Building-location	Top floor		Whole building	
	Cooling needs [kWh _t /m ² a]	Heating needs [kWh _t /m ² a]	Cooling needs [kWh _t /m ² a]	Heating needs [kWh _t /m ² a]
MFB-Marseille	107.7	154.7	26.1	33.2
SFH-Varazdin	4.2	31.3	4.2	31.3
DH-Milan	30.5	160.3	20.7	131.5
DH-Athens	40.8	58.8	40.8	58.8

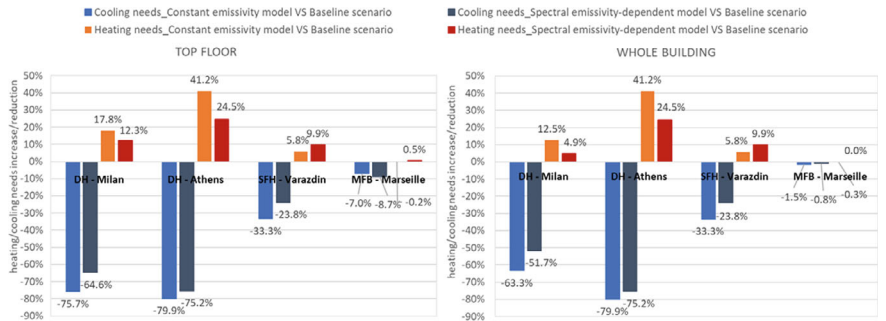


Fig. 4 Heating/cooling needs increase/reduction: spectral emissivity-dependent model versus baseline scenario, constant emissivity model versus baseline scenario

Table 3 Annual primary energy consumption (*PEC*) in the baseline scenario and the spectral emissivity-dependent model. *PEC* variation (Δ) with PDRC compared to the baseline

Building-location	<i>PEC</i> [kWhp/m ² a]		Δ <i>PEC</i>
	Baseline scenario	Spectral emissivity-dependent model	Spectral emissivity-dependent model
MFB-Marseille	64.0	63.9	– 0.2%
SFH-Varaždin	44.0	47.3	+ 7.3%
DH-Milan	187.5	187.2	– 0.1%
DH-Athens	109.1	103.2	– 5.4%

buildings with high heat loss. In Varaždin, heating needs outweigh cooling benefits (+ 7.3% for the primary energy consumption—*PEC*) while in Athens, *PEC* decreases by – 5.4%. Future researches could examine PDRC in combination with traditional retrofitting measures to assess seasonal trade-offs, taking into account also cloud cover and its effect on radiative cooling effect too. The developed numerical models could be used to analyze indoor microclimate conditions, thermal comfort, and condensation risks.

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References

1. Rawat M, Singh RN (2022) A study on the comparative review of cool roof thermal performance in various regions. <https://doi.org/10.1016/j.enbenv.2021.03.001>

2. He Y, Yu H, Ozaki A, Dong N (2020) Thermal and energy performance of green roof and cool roof: a comparison study in Shanghai area. J Clean Prod 267. <https://doi.org/10.1016/j.jclepro.2020.122205>

3. Bao H, Yan C, Wang B, Fang X, Zhao CY, Ruan X (2017) Double-layer nanoparticle-based coatings for efficient terrestrial radiative cooling. Sol Energy Mater Sol Cells 168:78–84. <https://doi.org/10.1016/J.SOLMAT.2017.04.020>

4. Carlosena L et al (2021) Experimental development and testing of low-cost scalable radiative cooling materials for building applications. Sol Energy Mater Sol Cells 230:111209. <https://doi.org/10.1016/J.SOLMAT.2021.111209>

5. Zhang S et al (2022) Full daytime sub-ambient radiative cooling film with high efficiency and low cost. Renew Energy 194:850–857. <https://doi.org/10.1016/J.RENENE.2022.05.151>

6. Morales-Inzunza S et al (2023) On the potential of cool materials in the urban heat Island context: scalability challenges and technological setbacks towards building decarbonization. Energ Build 296:113330. <https://doi.org/10.1016/J.ENBUILD.2023.113330>

7. Jeong SY et al (2020) Field investigation of a photonic multi-layered TiO₂ passive radiative cooler in sub-tropical climate. *Renew Energy* 146. <https://doi.org/10.1016/j.renene.2019.06.119>
8. Yu X, Chen C (2021) Coupling spectral-dependent radiative cooling with building energy simulation. *Build Environ* 197:107841. <https://doi.org/10.1016/J.BUILDENV.2021.107841>
9. DesignBuilder [Online]. Available <https://designbuilder.co.uk/>. Accessed 22 May 2024
10. US Department of Energy. Energy efficiency and renewable energy office, building technology program, EnergyPlus (version 8.4). [Online]. Available <https://energyplus.net/>. Accessed 22 May 2024
11. MathWorks. MATLAB—MATrixLABoratory (version 2022). [Online]. Available <https://it.mathworks.com/products/matlab.html>. Accessed 22 May 2022
12. Yang Y, Zhang G, Rong L (2024) Assessing energy saving potential of wavelength-dependent passive daytime radiative cooler implemented with EnergyPlus by a roof model. *Heliyon* 10(5). <https://doi.org/10.1016/j.heliyon.2024.e26428>
13. Gao W, Chen Y (2023) Emerging materials and strategies for passive daytime radiative cooling. *Small* 19(18):2206145
14. Chae D, Son S, Lim H, Jung PH, Ha J, Lee H (2021) Scalable and paint-format microparticle–polymer composite enabling high-performance daytime radiative cooling. *Mater Today Phys* 18:100389
15. ASHRAE. [Online]. Available <https://www.ashrae.org/>. Accessed on 02 Dec 2024
16. Berardi U, Garai M, Morselli T (2020) Preparation and assessment of the potential energy savings of thermochromic and cool coatings considering inter-building effects. *Sol Energy* 209:493–504
17. Ascione F, De Masi RF, Santamouris M, Ruggiero S, Vanoli GP (2018) Experimental and numerical evaluations on the energy penalty of reflective roofs during the heating season for Mediterranean climate. *Energy* 144:178–199

6th Generation District Heating and Cooling Networks: Design, Experimental Results and Future Challenges



Ricardo Lima 

Abstract This paper describes the design and testing of an innovative lab-sized 6th generation district heating and cooling network (6GDHCN) using CO₂ as heat transfer fluid to evaluate its simultaneous heating and cooling capabilities and highlight current design challenges and future pathways to enhance the system. The 6GDHCN distinguish from its predecessor by the use of phase change phenomena to transfer heat. The innovative use of phase change significantly enhances energy density, thus enabling smaller infrastructure requirements and simpler deployment in dense urban environments. The experimental setup, developed to emulate real-world conditions on a reduced scale, includes a central plant circulating CO₂ through network connecting cooling and heating users. Experiments focused on validating the concept and the correct operation of each subsystem as well that of the overall facility. Similarities with a larger facility provided a solid basis of demonstration of the emulation capabilities. In particular, the experiments allowed to identify the major design challenges and identify pathways for enhancing system resilience, scalability, and energy efficiency in sustainable thermal networks.

Keywords Energy · District · Heating · Cooling · Network · CO₂ · Phase-change · Construction · Environment · Sustainability

1 Introduction

Thermal energy distribution networks are key components of territorial energy systems. These have evolved through different generations to meet technical and energy needs characterising their time period. Despite five successive generations of technological advancements, the fundamental principle—circulating a single-phase fluid with sensible heat exchange—has remained unchanged.

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The main characteristic of the first heat distribution network, dating back to the fourteenth century [9], remained unchanged for four technological generations (i.e. from 1GDHN to 4GDHN): energy-heat production distributed by a single-phase fluid with a significant temperature difference from the environment. This system is characterized by a single service (heating or cooling), fixed producer and consumer roles (no interaction), high temperature differences between the fluid and the environment (losses), and medium energy density (large piping). The evolution between different generations of networks is characterised by a decrease of their operating temperature, decreasing the heat losses and therefore, increasing the efficiency and the potential for integrating renewables. Alternatively, the 5GDHCN (or “aenergie network”) circulates a low temperature fluid, typically water, that serves as cold source for heat pumps and chillers. Lowering the network temperature reduces thermal losses but decreases energy density, which is offset by increasing the mass flow and consequently, increasing the pipe diameter (to reduce the friction losses). This makes the network less suitable for urban areas where underground space is constrained and large construction works significantly impact local citizens (e.g. noise, dust, traffic management) and economy.

To address these, a 6GDHCN has been developed. This network uses a fluid in liquid and vapor phases (i.e., a two-phase system) that leverages the enthalpy of vaporization and condensation for heat exchange. This system combines the advantages of all previous generations with phase-change, exploiting a higher energy density and therefore using smaller diameter pipes, making it simpler to deploy. However, it also introduces challenges, particularly in managing phase-change, operating mode transitions and operating pressure. Furthermore, notable research gap remains in demonstrating the operational viability and control strategies required for phase-change networks under realistic multi-user conditions.

The potential of 6GDHCN using CO₂ concept was firstly studied by Weber and Favrat [8], where they demonstrated that it is both energetically and financially more advantageous than an equivalent water-based network. Other fluids have been considered by Henchoz [3], but CO₂ was shown to be best option. The concept was theoretically analysed in different studies ([2, 4, 7]).

The feasibility of this technology was partially demonstrated with a scaled-down CO₂ network [3] consisting of a central plant connected to a single user, a cooling user (i.e. user to be cooled, thus, evaporating CO₂ liquid). However, in a practical scenario, such a network would consist of various users, each interacting with the network differently. In this context, two projects 6GDHCN were studied: one in Sion at the Energypolis site, where a network supplies three buildings, and the other in Geneva at the Fusterie site (city center), designed to interact with the GENILAC network (a 5GDHCN). Despite these studies, this remains a recent technology, for which there is no numerical model or physical facility capable of replicating the operation of a real-world case. It is in this scope that ROADMAP [5] research project has been developed: develop a physical test section and a numerical model allowing to emulate and simulate, respectively, the 6GDHCN. This paper focus on the design and testing of an innovative lab-sized 6GDHCN, that includes both heating and cooling users,

to evaluate its simultaneous heating and cooling capabilities and highlight current design challenges and future pathways to enhance the system.

2 6GDHCN Principle

The 6GDHCN—or CO₂ network—is a recent technology that differs from 5GDHCN, by the use of liquid and vapor phases to convey heat, taking advantage of phase-change (evaporation and condensation) for transferring heat. The operating principle of the CO₂ network is schematically illustrated in Fig. 1. It consists of two pipelines at very close temperatures and pressures: one transporting vapor and the other one transporting liquid. Heat transfer between the network and each user is achieved almost exclusively by leveraging the latent heat associated with the phase change of the working fluid. A cooling user transfers heat to the network by evaporating CO₂ drawn from the liquid pipeline and introducing the resulting vapor into the vapor pipeline. A heating user operates inversely. The balance between consumers may or may not be zero; therefore, a central station is required. In Fig. 1, the central plant is equipped with a cold source and a compressor, but other configurations are possible. In this setup, the compressor is used solely to slightly superheat the vapor. The figure illustrates two users: the first consumes cold energy through “free cooling,” while the second consumes hot energy using a decentralized heat pump. When the network is overall in surplus of hot energy (i.e. deficit of cold), excess thermal energy is released into a cold source, such as a lake, through the condensation of vapor, which is then injected into the liquid pipeline (Fig. 1a). Conversely, when the network is in deficit of heat, the reverse process is performed (Fig. 1b).

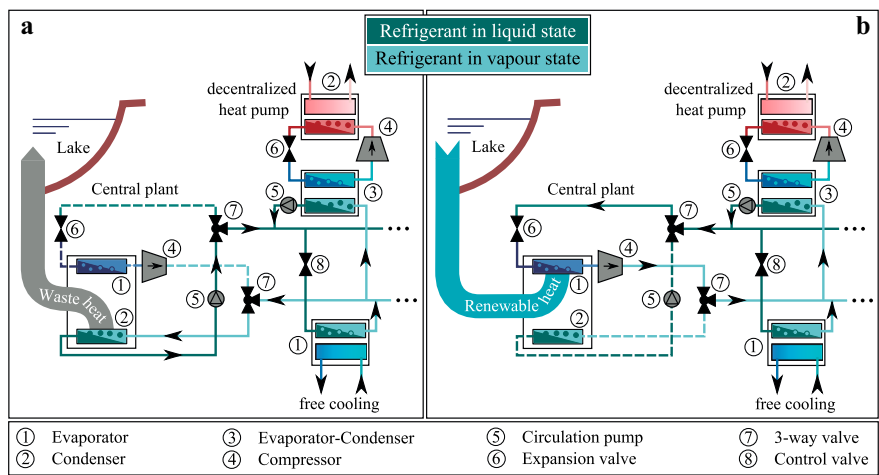


Fig. 1 Schematic representation of a refrigerant based district energy network for two cases, **a** net cooling operation and **b** net heating operation [3]

3 6GDHCN Facility Design

Based on the objectives and on a previous design [3], the system was upgraded with many improvements, in particular, a heating user as shown on the schematic in Fig. 2 and accordingly to the characteristics listed in Table 1. The operating parameters regarding the new heating user were selected based on optimal balance between thermodynamic efficiency, material constraints, and system safety margins, informed by preliminary calculations.

The central plant regulates the CO₂ operational conditions in function of the network status (i.e. users demand). The plant is equipped with a variable-flow pump and a heat exchanger that can be used as evaporator or condenser. In particular, it can automatically shift between heating or cooling modes, depending on the overall network demand. The vapor and liquid lines—7/8" and 3/4" heavily insulated copper tubes, respectively—operate in superheated (15 °C and 50 bar) and subcooled (13 °C and 52 bar) conditions, respectively. The cooling user consists of a CO₂ evaporator where the mass flow is controlled via a superheat of 3 K. The heating user consists of a CO₂ condenser, liquid reservoir and variable-flow pump, where the mass flow is controlled via a subcooling of 3 K.

The experimental facility, originally developed by Henchoz [2], underwent significant modifications in order to meet the new design specifications. Besides upgrading the central plant and adding the cooling user (condenser, reservoir and pump, control valves, security components, instrumentation and control), the modifications included enhanced and additional instrumentation, additional safety mechanisms, new heat and cold sources and respective hydraulics, a massive update of the CO₂ ducts and regulation and control software. The resulting experimental facility is depicted in Fig. 3.

4 Experimental Results

An extensive experimental campaign has been undertaken to validate the correct operation of each subsystem (central plant, cooling user, heating users, security, measurement, data acquisition and control), as well of the correct operation of the overall facility. The results validated each one of the items and furthermore, have proven that the concept is fully functional. The data is open source and freely available [1].

The results [5] have clearly shown trends similar to those observed within the larger facility of Energypolis [6]. The observed similarities provide a solid basis of demonstration of the emulation capabilities of this experimental facility.

Among the different tests, the one covering the automatic shift between heating and cooling modes of the central plant was selected. Figure 4 depicts the CO₂ pressures (numeric code indicates the measurement instruments in Fig. 2) at different locations of the facility: the CO₂ mass flow rates in the liquid and vapor lines and in the heating user, the hot and cold water volumetric flows at the central plant and

Table 1 ROADMAP project 6GDHCN experimental facility characteristics

Section	Parameter	Value	Unit/Notes
Generalities	Network pipe length	2×100	m
	Total fluid volume	175	Lt
	Max. CO ₂ pressure	64	bar
	Dimensions	$2.5 \times 2.5 \times 5.5$	m (H $\times$ W $\times$ D)
Nominal operating conditions	CO ₂ mass	90.3	kg
	CO ₂ saturation pressure	50	bar
	CO ₂ saturation temperature	14.2	°C
	Hot water source temp	40	°C
	Cold water source temp	8	°C
Liquid line	Temperature	13	°C
	Pressure	52	bar
	Diameter	3/4"	(19 mm)
	Volume	34.6 (17.7)	Lt
	Mass	29.2 (14.6)	kg
Vapor line	Temperature	15	°C
	Pressure	50	bar
	Diameter	7/8"	(19 mm)
	Volume	35.4 (31.4)	Lt
	Mass	5.3 (4.9)	kg
Main plant	Power	26	kW
	CO ₂ flow rate	134	g/s
	Hot water flow rate	260	g/s (0.94 m ³ /h)
	Cold water flow rate	2074	g/s (7.47 m ³ /h)
	Control	ΔP between liquid and vapor line: 2 bar	
Cooling user	Power	13	kW
	CO ₂ flow rate	67	g/s
	Hot water flow rate	130	g/s (0.47 m ³ /h)
	Control	Superheat at evaporator outlet: 3 K	
Heating user	Power	13	kW
	Hot water flow rate	67	g/s
	Cold water flow rate	1037	g/s (3.73 m ³ /h)
	Control	Subcooling at condenser outlet: 3 K	

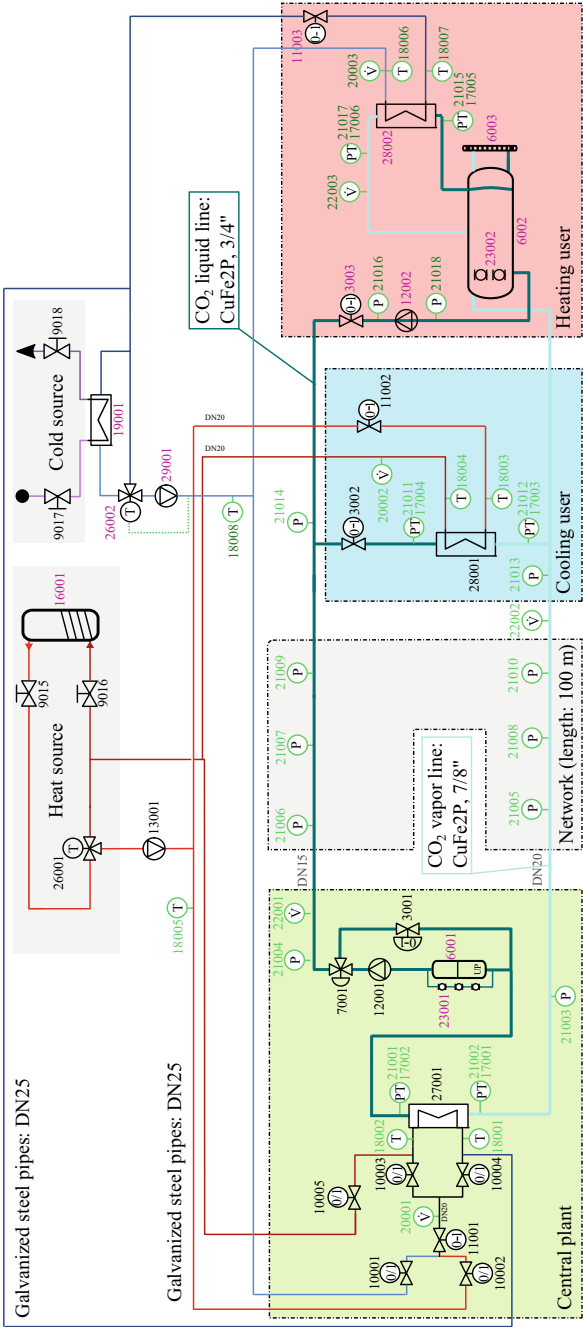


Fig. 2 ROADMAP project 6GDHCN experimental facility schematic. Certain details are intentionally omitted for IP protection purposes



Fig. 3 ROADMAP project 6GDHCN experimental facility

users and finally, the enthalpy variation of water—or the thermal power exchanged—at the central plant and by users, all in function of time (in minutes). At the beginning of the test, only the cooling user is active. At about 5 min, its demand is gradually reduced by reducing its hot water mass flow, until full stop. During that process, the CO_2 mass flows in the liquid and vapor lines clearly follow the same trend. At about 6 min, the heating user is engaged and its demand gradually increased (see its water flow increase). The network overall heat demand is shifted from heating to cooling, forcing the central plant to shift from heating to cooling mode with the liquid and vapor mass flows direction shifting in their respective lines. This heating mode transition noticeable impacts the CO_2 pressure in the network. Indeed, during the transition the central plant is stopped and not equilibrating the network. After about 5 min, the system reaches steady state again.

Thanks to the experimental campaign, it was possible to identify the major design challenge: dynamic flow control. At start-up or at user load variations, the system has shown to undergo transients that have to be correctly addressed. Within this project, the dynamic control parameters were empirically set for each experimental condition, and therefore not optimised. Oscillatory trends were observed, sometimes leading to undesirable effects such as central plant's pump dryout. The challenges related to the dynamic flow control concern both central plant and users, for which subcooling and superheat have to be precisely controlled to avoid instabilities.

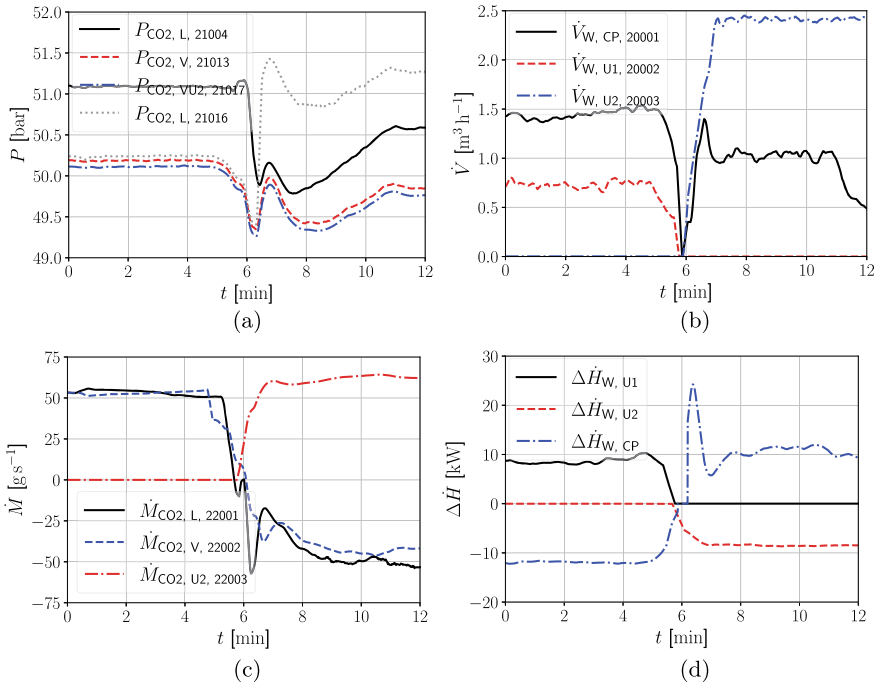


Fig. 4 Experimental results of **a** pressures, **b** water mass flows, **c** CO₂ mass flows rate and **d** enthalpy variation of water (thermal power), during central plant shift between cooling and heating modes

5 Conclusions

This study successfully demonstrated the feasibility and operational viability of a lab-scale CO₂ based 6GDHCN, highlighting its potential for real-world urban deployment. Critical insights were gained into dynamic control challenges, providing a clear pathway for future system enhancements.

The present study allowed to design, build and test an innovative lab sized CO₂ based 6GDHCN. The experimental facility incorporates a cooling and a heating users of 13 kW each, within a network of 100m long, allowing to emulate real-world cases in particular, study and characterize the behavior of a study case network under specific operating conditions. The main features of this experimental facility are its modularity and flexibility. In terms of modularity, it can be easily modified to add/modify users or any other component/hardware. In terms of flexibility, its operating conditions can be quickly set/modified to emulate a real/study-case network under different experimental conditions (e.g. extreme stochastic loads). Furthermore, the experimental facility also allows to quickly deploy and test regulation/control strategies.

Experiments focused on the validation of the design and operation of the different subsystems (central plant, cooling and heating users, security, measurement instrumentation, data acquisition and control). The experiments validated the design and operation of the system. Most of all, they have shown that the concept is fully functional, i.e. it is possible to successfully operate a phase-change latent heat based DHCN. Results have also shown trends similar to those observed with a larger facility, therefore providing a solid basis of demonstration of the emulation capabilities.

Future research should prioritize addressing specific technological hurdles such as dynamic control under transient conditions and integrating advanced predictive algorithms for enhanced operational stability. To mitigate instabilities during central's plant mode shifting, heating and cooling systems should be separated. This would also contribute for effective scalability and resilience, ensuring robust performance and efficiency at larger scales.

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References

1. ENERGETIQUES LLDS (2024) CO₂ dhcn roadmap. <https://doi.org/10.5281/zenodo.10938844>
2. Henchoz S (2011) On a multi-service, co₂ based, district energy system for a better energy efficiency of urban areas. In: Proceedings of the world engineers' convention 2011, Geneva, Switzerland. <https://infoscience.epfl.ch/record/169243>
3. Henchoz S (2016) Potential of refrigerant based district heating and cooling networks. Ph.D. thesis, École Polytechnique Fédérale de Lausanne, Lausanne, Switzerland, https://infoscience.epfl.ch/record/217013/files/EPFL_TH6935.pdf
4. Henchoz S, Favrat D, Weber C (2015) Performance and profitability perspectives of a co₂ based district energy network in Geneva's City Centre. *Energy* 85:221–223
5. Page J, Rey T, Ramirez K, Lima R, Winzer B (2022) Roadmap: Réseau de distribution de chaleur et de froid de 6ème génération—simulation et essai expérimental. Tech Rep Haute école spécialisée de Suisse occidentale (HES-SO), Sion, Suisse, <https://www.hes-so.ch>
6. Page J, Dorsaz C, Rey T, Mian A, Henchoz S, Chatelan P, Girardin L, Duc PJ (2023) Réseau de distribution de chaleur et de froid utilisant le co₂ comme fluide caloporteur (réseau-co₂). Tech. Rep. SI/502049-01, Département fédéral de l'environnement, des transports, de l'énergie et de la communication (DETEC), Office fédéral de l'énergie (OFEN), Berne, Suisse, <https://www.hevs.ch>
7. Suci R, Stadler P, Ashouri A, Maréchal F (2016) Towards energy-autonomous cities using CO₂ networks and power to gas storage. In: Proceedings of the 29th international conference on efficiency, cost, optimization, simulation and environmental impact of energy systems (ECOS), Portorož, Slovenia, https://infoscience.epfl.ch/record/226186/files/ECOS2016_RalucaSuci.pdf
8. Weber C, Favrat D (2010) Conventional and advanced CO₂ based district energy systems. *Energy* 35(12):5070–5081. <https://doi.org/10.1016/j.energy.2010.08.008>, <https://www.sciencedirect.com/science/article/pii/S0360544210004354>, the 3rd International Conference on Sustainable Energy and Environmental Protection

9. Wiltshire R (2015) Advanced district heating and cooling (DHC) systems, 1st edn. Woodhead Publishing Series in Energy, Woodhead Publishing Ltd, Cambridge. <https://doi.org/10.1016/B978-1-78242-374-4.00001-X>

Positive Energy Districts in Switzerland: Analysis from a Technical, Social and Business Point of View



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Abstract The PEDSET project explores the role of Positive Energy Districts (PEDs) in Switzerland's energy transition by creating urban areas that generate more energy than they consume. As Switzerland moves towards its 2030 CO₂ law targets, PEDs integrate renewable energy, enhance efficiency, and promote social and economic sustainability. The project assesses PED concepts and existing technologies while considering Switzerland's specific context, including innovations and societal energy goals. Through literature review and analysis of PED-like initiatives, this article identifies key energy technologies and evaluates their feasibility in Swiss cities. Beyond technology, this paper highlights social acceptance and citizen participation. The analysis emphasizes the critical role of active citizen and stakeholder engagement in enhancing social acceptance and driving the success of PED initiatives in Switzerland. This study explores Swiss business models in energy, mobility, and building renovation, emphasizing innovation, cooperation, and emerging financing solutions. The objective of this article is to present the PEDSET project, together with its three perspectives on existing practices (technological solutions, societal acceptance, and business models) surrounding the implementation of PEDs in Switzerland. The aim is to identify critical synergies, barriers, and opportunities to guide future sustainable urban developments.

Keywords Positive energy districts · Transition · Environment · Sustainability

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1 Introduction

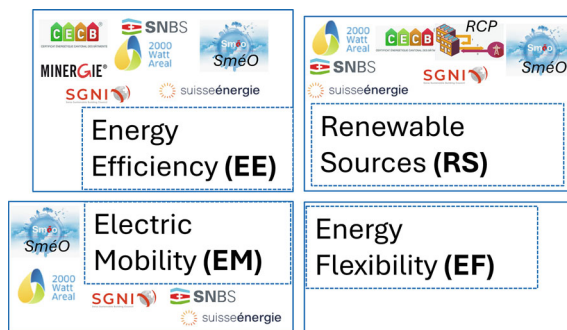
Positive energy districts (PEDs) concepts have emerged as a new paradigm of sustainable cities and urban areas [4]. PED could be defined as connected buildings or areas that benefit from bigger annual renewable energy production than consumption at an annual scale [8] which further combines the notion of efficiency and renewable energy production [15]. It also entails matters such as energy justice, affordability, or resilience to achieve climate neutrality addressing sustainability in a more holistic view rather than a pure positive balance of energy [8]. JPI Urban Europe, 2020 [8] the first European programme contributing to the ambitious goals of the Strategic Energy Technology Plan (SET-Plan Action 3.2) has established the *Positive Energy Districts for Sustainable Urban Development (PED/PEN3) programme*, which supports the planning, deployment and replication of 100 PEDs by 2025. This program defined a framework for PED's as "Positive Energy Districts are energy-efficient and energy-flexible urban areas which produce net zero greenhouse gas emissions and actively manage an annual local or regional surplus production of renewable energy. They require integration of different systems and infrastructures and interaction between buildings, the users and the regional energy, mobility and ICT systems, while optimizing the liveability of the urban environment in line with social, economic and environmental sustainability" [8].

Among the PEDSET project phases, a comprehensive literature review and analysis of existing PED-like projects in Switzerland was conducted to ascertain the state of the art of PED-like concepts from multiple perspectives. This study begins with a technical approach, proposing a set of the most used technologies in existent PEDs and Swiss energy concepts. Secondly, the transition of a region towards PEDs necessitates societal changes that redefine the geography and governance of energy. This process renders citizen and other stakeholders involvement a key point of interest [9]. Finally, innovative business models have significant impact on the adoption and scalability of new technologies and labels, and practices [1]. Therefore, there is a need for supporting business models that address the different dimensions of PEDs. Providing literature review from three points of view, the objective is to take stock of experiences with PEDs and related concepts in Switzerland, and to define the scope of the analysis of potential impacts of PED diffusion in Switzerland.

2 Existing Swiss Energy Concepts

The integration of insights from the JPI Urban Europe, 2020 [8] and the booklet of PED Solution [6] with existing strategies of Switzerland (EnergyPerspective2050+ from Swiss Federal Statistical Office of Energy (SFOE)) was undertaken to firstly highlight the main functions/guidelines that define PEDs, and secondly to demonstrate how Switzerland addresses them in its energy policy. Four PEDs technological components, defined in [6], are shown in Fig. 1 with the directly or indirectly related Switzerland energy concepts, indicating which specific functions of PED

Fig. 1 PEDs components with related Swiss energy concepts (CECB, Minergie, RCP, SGNI, SméO, SNSB, Swiss Energy Programme, 2000-Watt Society. Modified from [6])



are addressed within these concepts. Figure 1 demonstrates clearly the absence in literature of a Swiss energy concept incorporating the four functions.

3 Analysis of Most Used Technological Solutions for PEDs and Swiss Energy Concepts

Figure 2 illustrates the most common energy technological solutions (Europe and Switzerland) divided from the targeted function to the final solution, including the necessary primary source[11, 15]. Both in Europe and in Switzerland, solar energy technologies (Photovoltaic (PV), Solar Thermal (ST)) have been identified as the main energy solutions in almost all cases reviewed. In terms of the supply of heat, District Heating (DH) is the most prevalent solution across the majority of the European projects that have been analysed. It is also a solution that is frequently referenced in Swiss energy strategies. According to SFOE, the installation of heat pumps (geothermal, air-water and water-water) is also on the increase, with growth of 60% between 1990 and today.

4 Analysis of Social Acceptance, Citizen, and Stakeholder Engagement of PEDs in Switzerland

4.1 Citizen's Roles and Social Acceptance

Roles of Citizens: In Switzerland, there is little evidence and discussion on whether and/or what roles that the Swiss citizens are willing to take as such prosumers, energy traders, investors (e.g. cooperative members) and are not explicitly discussed. Schmid et al. [13] conducted a survey with 289 cooperatives in Switzerland and found that the members are mostly private individuals (almost in every cooperative), municipalities and energy utilities. Swiss cooperatives in majority focus on the

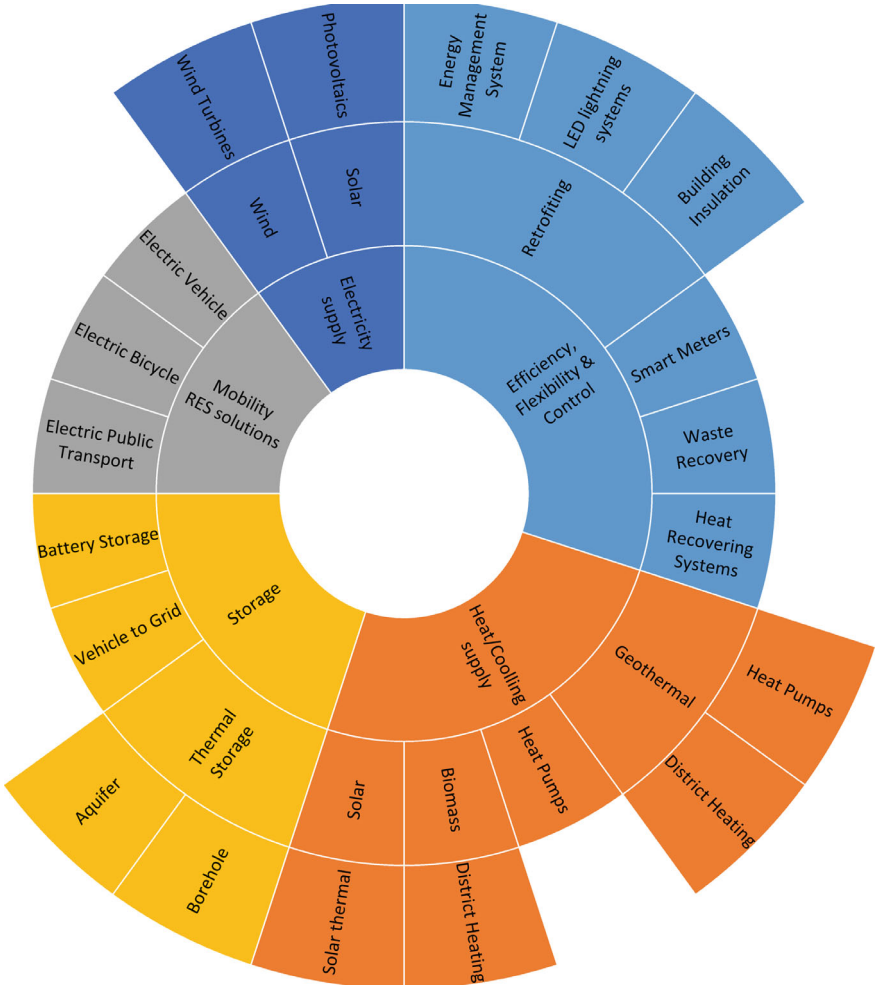


Fig. 2 Technological solutions offered for positive energy district [11].

expansion of renewable energy generation, especially PV. Nevertheless, the literature review shows that citizens taking diverse roles would be beneficial for the district and cities as it enhances public trust in government and democratic institutions, and improves the quality of policies, governance, and services. Citizens can, for instance, act as prosumers, cooperative investors, peer-to-peer energy traders, co-designers in planning processes, local ambassadors for energy awareness, or even take part in monitoring and maintaining community energy systems.

Social Acceptance: Far more acceptance, consent, engagement, and participation of people as citizens as well as energy users (i.e. consumers) will be needed than ever

before for adoption of technologies, flexibility programmes and so on. It is imperative to first understand whether citizens are willing to engage in PEDs, furthermore how citizens want the energy systems configured and to what extent they want to participate taking different roles in the decision-making.

A literature survey regarding the willingness to join PEDs/energy communities revealed *Knowledge on energy transition*, *Positive attitude towards energy communities* and *Trust in stakeholders* as major factors[7]. Other influencing factors like *Socio-economic data* (age, income, gender...), *Social norms* and *Experience with PEDs* should also be considered.

In Switzerland, PED development will require careful examination of potential residents based on their socio-demographic and psychographic characteristics [10]. There is a huge diversity in the preferences of citizens regarding the technologies and ownership and governance of these technologies. More engaging and participatory approaches are needed to build energy and environmental awareness in order to develop PEDs[10].

4.2 Involvement of Citizen and Stakeholders in PEDs

Citizen Involvement: Case studies (e.g. *Quartierstrom* and *Möriken-Wildegg*) demonstrate that the most active and engaged energy communities achieve greater success in adopting sustainable social practices, such as shifting energy use patterns. Conversely, communities with limited interaction with intermediaries or utility companies rarely experience significant changes.

These findings underscore the significance of collaborative innovation, wherein citizens, regime actors, research organisations collaborate to co-design solutions that support a sustainable energy transition. In Europe and slowly starting in Switzerland, participatory processes are gaining importance through projects such as SWEET LANTERN and SWEET SWICE [14], funded by the SFOE, to transform energy practices within communities.

Other Stakeholders' Involvement: Stakeholder engagement is identified as the most important success factor of PEDs [4]. In Switzerland, the different possible stakeholders are: Energy companies, Owners and renters, technical providers, Researchers and academics and Municipalities.

Energy companies, often owned by municipalities or cantons, play a key role in managing infrastructure, energy flexibility, and community tariffs. These companies may also be members of energy cooperatives and actively invest in self-consumption communities. Building owners and renters, particularly in self-consumption communities, are directly involved in these initiatives, alongside other private companies, start-ups, and technical providers that contribute to projects in Switzerland. These companies offer services such as PV deployment, automation optimization, and local market development. Researchers and academics design programs, conduct surveys with citizens, and assess project impacts, with the *Quartierstrom* project serving as a prime example of innovative energy management within a community. Finally,

municipalities, like the one in the *Luggaggia* community, play a crucial role by owning public infrastructure acting as prosumers, and ensuring fairness in energy community development. Furthermore, it is important for municipalities and other stakeholders to take up the efforts to motivate social actors and consumers to integrate in the decision-making process [15].

5 Analysis of Swiss Business Models in the Energy, Mobility and Building Renovation Sectors

5.1 Energy Sector

Switzerland has a strong tradition of energy cooperatives, primarily focused on electricity production and heating networks. While Peer-to-Peer (P2P) energy exchange (Community prosumerism) is not yet viable due to market regulations, collective self-consumption models known as ZEVs (*Zusammenschluss zum Eigenverbrauch*) are well established. A ZEV is a Switzerland legal framework allowing consumers and producers within the same building or site to share locally generated electricity. The *Quartierstromm* pilot project remains the main Swiss experience with local electricity markets, providing insights into decentralized trading mechanisms [12]. Most small producers in Switzerland sell surplus electricity to the grid at feed-in tariffs, while bundling production to access higher market prices remains marginally beneficial due to transaction costs [12]. Emerging business models include aggregators offering flexibility services, as tested in pilot projects like *BackupFlex* and *Equigy*. Third-Party Sponsored Communities, often led by utilities, serve as testbeds for new energy services. Additionally, Energy Service Companies (ESCOs) provide contracting solutions, particularly solar contracting, which is widely adopted in industrial and commercial areas with large rooftop surfaces [12].

5.2 Mobility Sector

Current mobility in Switzerland is in need of transformation, driven mainly by the growing need for sustainable transportation solutions. In this context, understanding and analysing the different business models is essential for companies, policy makers and researchers to navigate and capitalize on emerging opportunities. Among the various models, there are at least two different car-sharing business models [3, 5]: traditional car-sharing, in which an operator owns a fleet of vehicles and distributes their use among its customers, and P2P car-sharing, which is based on private car owners offering their vehicles on a platform and renting them out for up to a few hours or days. The most well-known traditional car-sharing operator in Switzerland is the cooperative Mobility®, which offers subscription and pay per use models to its customers. P2P platform also had a boom in early 2000 and some companies such as Sharoo® and 2EM® are active in the Swiss market [2]. Pay per use model is not only

an option for car sharing but also for sharing light weight vehicles such as scooters and cargo velos. In Switzerland several bundle service platforms, which allow trip planning using different transformation methods, are at the moment in testing phase.

5.3 *Building Renovation*

Business models for building renovation in Switzerland vary based on financing sources and partnerships. The traditional model typically involves direct funding from property owners and tenants. Governments and non-profit organizations often provide subsidies, rebates, tax credits, and low-interest loans to incentivize energy-efficient upgrades. Other models include green mortgages, cooperative refurbishment schemes, and energy performance contracting, where specialized companies fund renovations and share the energy savings. Alternative financing solutions like Property Assessed Clean Energy (PACE) and on-bill financing also exist, though their application remains limited. Innovative approaches such as crowdfunding are emerging, enabling multiple investors to contribute to the funding of energy-efficient building renovations.

6 Conclusion

The literature review presented in this article was conducted with the aim of assessing the synergies between Swiss energy policy in general and existing Swiss energy concepts with the main functions of PEDs namely energy production, mobility, energy efficiency and flexibility, and finally identifying the state of art of these functions from a technological, social, and business point of view. The review shows that indeed technologies that are discussed as part of the Swiss energy policy are very similar to those of PEDs in the Europe. From a technological point of view, there is a need of studies on the different configurations of these technologies for the existing buildings stocks diversely configured in districts in Switzerland in order to assess the positivity that can be achieved.

Regarding the analysis of social acceptance, the focus is very much on the functions of the PEDs but separately such as technology adoption (PV, EVs, HP), and/or flexibility options (e.g. direct load control, home energy management systems) without certain rationales like community autonomy, district and/or community self-sufficiency. Further engagement strategies for collective practices should be encouraged, going beyond the limited approaches for individual practices. Most importantly, how citizens can engage within the process of planning, developing and implementing the PEDs, for example taking part in the governance.

The business aspect provides a conclusion to the analysis of the implementation of PEDs in Switzerland. This aspect of PEDs was covered in three phases. In the first

phase, an analysis of the existence of economic models for the energy sector was performed. On the second phase, an overview of existing business models for the mobility sector was presented. A clear distinction was made between the traditional sharing model and the P2P model. Finally, the second largest energy-consuming sector in Switzerland was treated. Existent and emerging economic models for energy-efficient renovation of buildings were presented, to highlight the importance of economic support from the cantonal, municipal and federal authorities.

PEDSET approach emphasizes that advancing the PED framework in Switzerland will require harmonized efforts across technology deployment, inclusive social participation, and adaptive business strategies, ensuring a holistic and successful transition towards sustainable urban environments.

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References

1. Baden-Fuller C, Haefliger S (2013) Business models and technological innovation. *Long Range Plan* 46(6):419–426
2. Benz S (2022) Impacts of peer-to-peer carsharing. Bachelor Thesis, Institute for Transport Planning and Systems, ETH Zurich, Zurich. <https://ethz.ch/content/dam/ethz/special-interest/baug/ivt/ivt-dam/publications/students/701-800/sa761.pdf>
3. Boer M, Türeken O, Adali OE (2022) a review of business models for shared mobility and mobility-as-a-service (MaaS): a research report. Eindhoven University of Technology, Eindhoven
4. Bossi S, Gollner C, Theierling S (2020) Towards 100 positive energy districts in europe: preliminary data analysis of 61 European cases. *Energies* 13(22):608
5. Cohen B, Kietzmann J (2014) Ride on! mobility business models for the sharing economy. *Organization Environ* 27(3):279–296
6. European Commission SCM (2021) Solution booklet positive energy districts. <https://smart-cities-marketplace.ec.europa.eu/insights/solutions/solution-booklet-positive-energy-districts>
7. Fischer B, Gutsche G, Wetzell H (2020) Who wants to get involved? Determinants of citizens' willingness to participate in German renewable energy cooperatives. In: MAGKS-joint discussion paper series in economics. <http://www.uni-marburg.de/fb02/makro/forschung/magkspapersCoordination:Berd>
8. Gollner C (2020) White Paper—reference framework for positive energy districts and neighbourhoods. <https://coilink.org/20.500.12592/m6t8kj>, publisher: Joint Programming Initiative (JPI) Urban Europe. Austria
9. Kalkbrenner BJ, Roosen J (2016) Citizens' willingness to participate in local renewable energy projects: the role of community and trust in Germany. *Energy Res Soc Sci* 13:60–70
10. Mihailova D, Schubert I, Martinez-Cruz AL, Hearn AX, Sohre A (2022) Preferences for configurations of positive energy districts—insights from a discrete choice experiment on Swiss households. *Energy Policy* 163(112):824
11. Morais Pinheiro D (2023) Pedset—positive energy districts as an instrument to govern for the Swiss energy transition. Tech Rep, Haute École du Paysage, d'Ingénierie et d'Architecture (HEPIA). Accessed 20 Mar 2023

12. Ribi F, Perch-Nielsen S (2021) Vermarktungsmodelle für Solarstrom. Tech Rep <https://www.ebp.ch/de/projekte/vermarktungsmodelle-fuer-photovoltaik-anlagen>
13. Schmid B, Meister T, Klagge B, Seidl I (2020) Energy cooperatives and municipalities in local energy governance arrangements in Switzerland and Germany. *J Environ Develop* 29(1):123–114
14. Swiss Federal Office of Energy (SFOE) (2022) LANTERN and SWICE awarded SWEET funding. <https://www.bfe.admin.ch/bfe/en/home/news-and-media/press-releases/mm-test.msg-id-87862.html>
15. Zhang X, Penaka S, Giriraj S, Sánchez M, Civiero P, Vandevyvere H (2021) Characterizing positive energy district (PED) through a preliminary review of 60 existing projects in Europe. *Buildings* 11(8):318

Analysis of Thermal Conditions at a Bus Shelter in a Brazilian City with a Humid Subtropical Climate



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Abstract The intensification of urban heat islands, resulting from increased population densification in cities and the effects of climate change, makes bus shelters more vulnerable to extreme weather conditions, discouraging their use and negatively impacting the population's quality of life. This research aims to measure the air and surface temperatures in a bus shelter in a Brazilian city with a humid subtropical climate. For this purpose, a standard shelter model located in Foz do Iguaçu was identified and defined as a case study. Air temperature was measured using dataloggers, and surface temperatures were recorded using a thermographic camera. The results from the monitoring campaign revealed high values of ambient and surface temperatures, indicating long periods of thermal discomfort for users. Considering the preliminary results of this research, the inadequate use of materials in the structure of bus shelters and the lack of bioclimatic strategies aimed at mitigating heat exposure and improving outdoor thermal conditions, thus establishing a mismatch between sustainable development proposals and their actual implementation, resulting in uncomfortable environments for users and consequently slowing down the process of encouraging the use of public transportation.

Keywords Thermal conditions · Bus shelter · Thermal monitoring · Public transportation infrastructure · Bioclimatic strategies

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1 Introduction

Public transport plays a central role in Brazilian urban mobility, especially through bus services. According to the National Association of Urban Transport Companies [1], buses account for approximately 85% of all urban trips in the country. Although this transport mode represents one of the key agents of sustainable urban development, studies [2, 3] highlight the inadequate infrastructure at bus shelters.

Recent studies point out that, despite mitigation efforts, global warming has surpassed 1.2 °C compared to the pre-industrial period [4]. As a result of the progression of global warming, extreme events such as heatwaves, heavy rainfall, or droughts have become frequent worldwide [5]. Thus, tropical countries have become more susceptible to a decrease in the temperature range considered comfortable [6, 7].

Bus shelters are locations of human exposure to weather conditions. Therefore, it is evident that studies on thermal comfort at bus shelters are highly relevant. This work aims to analyze the thermal conditions at a bus shelter in a city with a humid subtropical climate for definition of possible mitigation measures.

1.1 *Climate Characterization of the Study Location*

Foz do Iguaçu is located in the far west of Paraná state, in southern Brazil, tri-border region with Argentina and Paraguay, at latitude 25° 32' 52"S, longitude 54° 35' 17"W, and an altitude of 164 m. With a humid subtropical climate, its average annual temperature ranges from 27 to 29 °C. It has hot summers (above 30 °C) and short winters with rare frost [8].

1.2 *General Overview of Bus Shelters in Foz do Iguaçu*

Located in southern Brazil, the city of Foz do Iguaçu, like most Brazilian cities, is characterized by a wide variety of bus shelter models, arbitrarily distributed across the urban territory. Below is presented a survey of the bus shelters models identified in the city (Fig. 1).



Fig. 1 Examples of bus shelters found in Foz do Iguaçu

2 Materials and Methods

2.1 Case Study Characterization

Despite the several models of bus shelter identified in Foz do Iguaçu, the most common geometry is that of group (A), with roof only and no side protections. Therefore, the bus shelter located in the northern part of the city was defined as the case study location for conducting the measurements, as shown in Fig. 2. In the immediate surroundings of the studied bus shelter, within a radius of approximately 20 m, asphalt pavement is present to the south, while the north and east sides feature vegetated soil with medium and large-sized trees. To the west, the ground cover is mixed (vegetation and concrete), also including large trees.

An initial pilot test was conducted from January 29 to February 4, 2025, with the equipment (HOBO U100-001 Temp. dataloggers) installed at a height of 2.3 m above the floor. Based on a preliminary analysis of the results, the need for repositioning

Foz do Iguaçu (Brazil)



Immediate surroundings



Bus shelter



- 01- Foz do Iguaçu (Brazil)
 02- Cidade de Leste (Paraguay)
 03- Porto Iguaçu (Argentina)

Fig. 2 Case study location

the sensors was identified to improve data representativeness. Based on the preliminary findings, a second phase of on-site temperature monitoring was carried out on February 5, 2025, with adjusted sensor positioning to improve data accuracy. To identify ambient and surface temperatures, HOBO U100-001 Temp. dataloggers and a FLIR TG165 portable thermographic camera were used, respectively. As shown in Fig. 3, the dataloggers were placed at three different heights: 0.5 m (A), 1.5 m (B), and 2.3 m (C) above the floor. Surface temperatures were measured using a FLIR TG165 thermographic camera, positioned 2 m from the shelter and aimed at structural components such as the roof and seating area. The emissivity (ϵ) was configured as 0.95, which is a standard value suitable for non-metallic, matte, or painted urban surface. Although different materials present variations in emissivity, for instance, painted concrete, wood, and fiber cement may range from 0.90 to 0.95. A constant value was adopted for all readings to ensure consistency and comparability. This simplification may introduce a margin of error in absolute temperature values but does not compromise the relative analysis across surface.

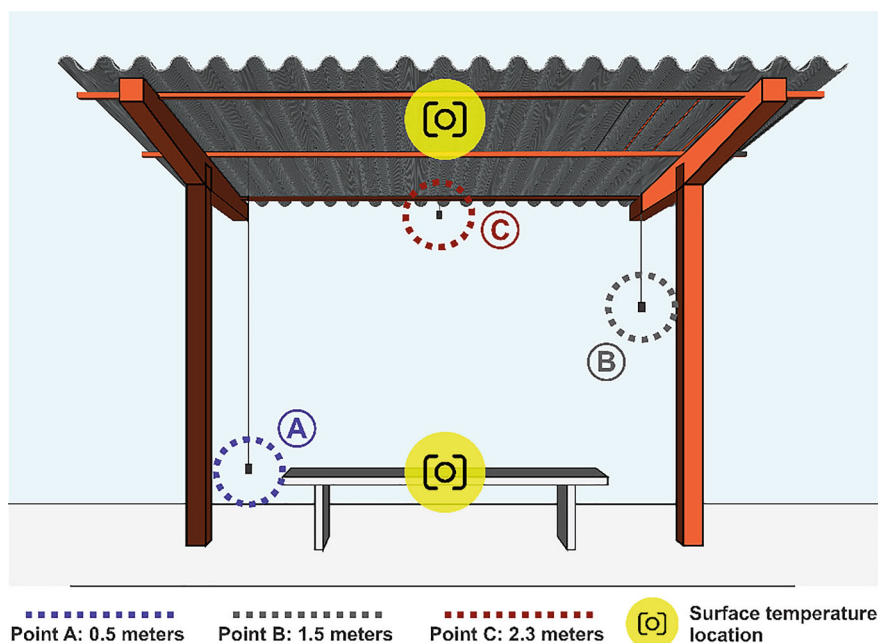


Fig. 3 Identification of measurement points

External air temperature data used for comparison were obtained from the automatic meteorological station operated by the National Institute of Meteorology (INMET) in the city of Foz do Iguaçu [9]. This station provides hourly records under standardized environmental exposure conditions, ensuring reliable reference values for regional atmospheric conditions during the monitoring period.

3 Results and Discussion

As part of the preliminary monitoring phase, conducted between January 29 and February 4, 2025, ambient and surface temperature data were collected at three points (A, B, and C), all positioned at a height of 2.3 m above ground level within the bus shelter. During this period, temperatures above 39 °C were recorded across all points. The lowest values occurred between 5:30 a.m. and 6:30 a.m. on January 31, with readings of 21.76 °C at points A and C, and 21.85 °C at point B. The average temperatures recorded over the seven days were 30.56 °C, 30.78 °C, and 30.28 °C at points A, B, and C, respectively. For comparison, external air temperature data obtained from the INMET station in Foz do Iguaçu showed a maximum of 34.3 °C and a minimum of 19.9 °C during the same period. These results are presented in Fig. 4.

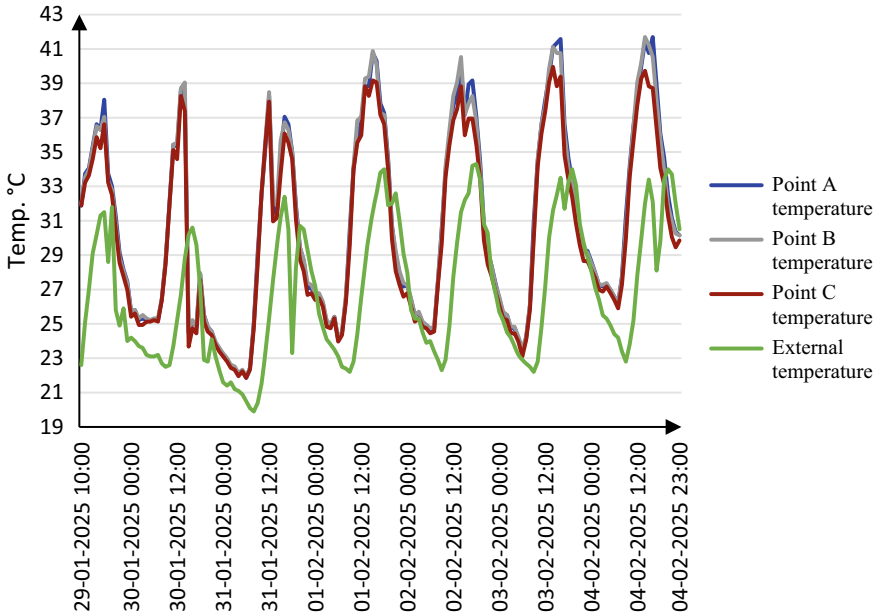


Fig. 4 Thermal behaviour in different positions: air temperature

As observed in Fig. 5, air temperature varied throughout the day, considering the three monitored heights (0.5 m (A), 1.5 m (B), and 2.3 m (C)). A gradual temperature increase is observed starting at 8:00 a.m., with a sharp rise after 11:00 a.m., and the highest values recorded between 2:00 p.m. and 3:00 p.m. Overall, the external temperature remained higher than the internal ones. The internal temperatures showed ranges exceeding 10 °C compared to the external temperature. Overall, the interior temperature remained higher than the exterior.

Figure 6 presents the variation in surface temperature recorded on the bus shelter's roof and seat throughout the day, compared to the external air temperature. Data show that the roof reached the highest surface temperatures, with values close to 72.4 °C around 2:00 p.m. The seat temperature also increased considerably during the day, reaching 48 °C in the afternoon. Meanwhile, the external air temperature remained significantly lower, between 23 and 32 °C.

The temperature measurements at the bus shelter reveal a concerning thermal discomfort. Regarding ambient temperature, the three measured points showed higher temperatures than the outdoors, with the internal average being 5.28 °C higher than the external temperature. It was noted that the closer to the ground, is presented the lower value for the recorded temperature, suggesting that the bus shelter's geometry favors thermal comfort for seated users. This analysis is better understood when considering surface temperature data, which shows that the roof surface temperature reached high thermal peaks, exceeding 70 °C. The bench reached temperatures between approximately 30 and 49 °C.

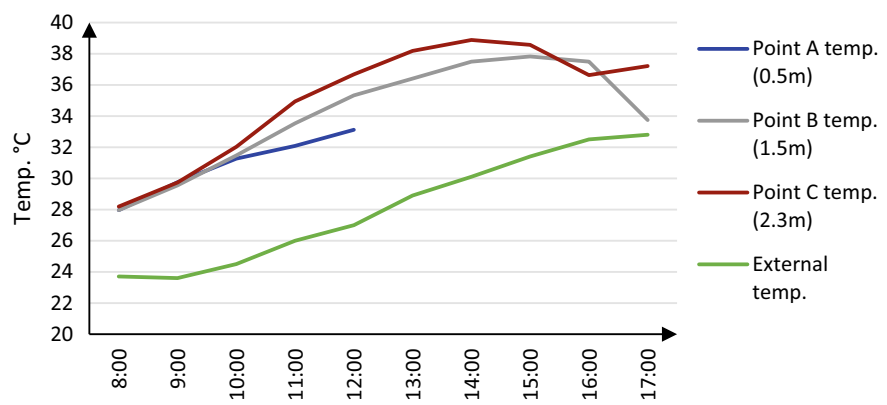


Fig. 5 Thermal behaviour in different positions: air temperature

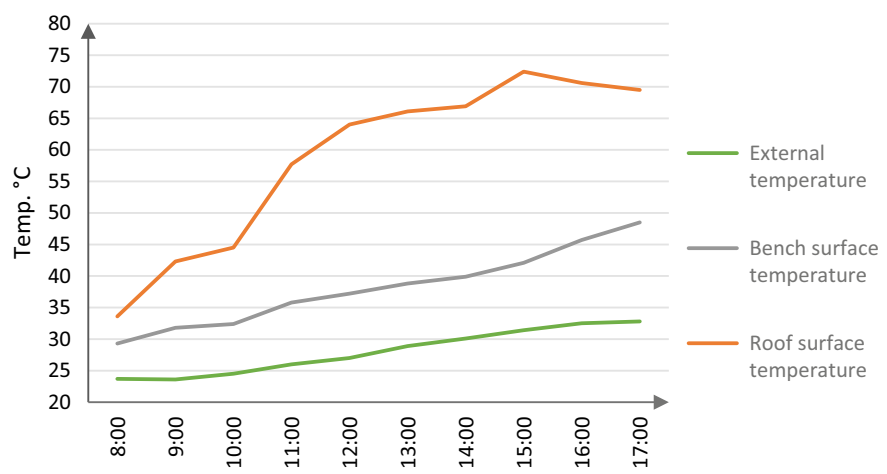


Fig. 6 Surface temperatures measured via thermographic imaging

The data also reveal a sharp increase in ambient and surface temperatures between 10:00 a.m. and 3:00 p.m. This period corresponds to the highest solar radiation incidence inside the bus shelter, as well as the reflectivity of surrounding materials. Thus, even with a roof as a solar shading, this feature proves ineffective at various times.

In light of this information, it is understood that the thermal performance of the studied bus shelter could be improved by applying passive thermal comfort strategies for outdoor environments, such as ventilation design, strategic positioning of roofs and benches according to solar orientation, green roofs, and high thermal insulating materials.

4 Conclusions

The evaluation of the studied bus shelter's temperature showed that basic infrastructure elements like a roof and bench are insufficient for ensuring acceptable thermal conditions in a hot-humid climate city. The data presented surface temperatures above 70 °C and internal ambient temperatures higher than 38 °C. In this context, the selection of appropriate roofing materials can substantially mitigate heat gain and contribute to improved thermal comfort.

In conclusion, the absence of bioclimatic strategies to optimize thermal comfort perceived by bus shelter users does not support the promotion of public transport use. In this scenario, further studies are necessary to investigate more deeply the relationship between temperature and user perception at bus shelters in hot climates, proposing bioclimatic design solutions to optimize the thermal experience of the population in these urban structures. It is worth noting that the bus shelter is located near a densely vegetated area, which directly influences the local microclimate, particularly by attenuating air temperatures during the early hours of the day. Although this effect was not quantified in the present study, it should be considered in future analyses.

References

1. Associação Nacional das Empresas de Transportes Urbanos (2024) Os grandes números da mobilidade urbana. <https://ntu.org.br/novo/AreasInternas.aspx?idArea=7>
2. Dzyuban Y, et al. (2021) Public transit infrastructure and heat perceptions in hot and dry climates. *Int J Biometeorol* 66:345–356. <https://doi.org/10.1007/s00484-021-02074-4>
3. Souza MM, et al. (2019) Sensação térmica no serviço de transporte circular da Universidade Federal do Pará. *Mix Sustentável* 5(3):103–114
4. Hansen JE, et al. (2023) Global warming in the pipeline. *Oxford Open Climate Change* 3(1):1–33. <https://doi.org/10.1093/oxfclm/kgad008>
5. IPCC—Intergovernmental Panel on Climate Change (2023) Climate change 2023: synthesis report. In: Contribution of working groups I, II and III to the sixth assessment report. IPCC, Geneva. <https://www.ipcc.ch/report/ar6/syr/>
6. Zhang J, et al. (2023) Inequality of global thermal comfort conditions changes in a warmer world. *Earth's Future* 11(2):e2022EF003109
7. Choi YW, Khalifa M, ElTahir EAB (2024) North–south disparity in impact of climate change on “outdoor days”. *J Clim* 37(12):3269–3282
8. Delgado JSC, Sacht HM, Vettorazzi E (2016) Estratégias bioclimáticas para projetos urbanos em Foz do Iguaçu: estudo de caso do Marco das Três Fronteiras. In: Anais do VII Congresso Luso-Brasileiro para o Planejamento Urbano, Regional e Sustentável. Maceió. <https://fau.ufal.br/evento/pluris2016/files/Tema%201%20-%20Ambiente%20e%20Energia/Paper751.pdf>
9. INMET, Instituto Nacional de Meteorologia (2024) Dados históricos. <https://portal.inmet.gov.br/dadoshistoricos>

Painting Roofs White: An Affordable Strategy to Improve Indoor Comfort in African Buildings



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Abstract Corrugated metal sheets are the most widely used roofing solution in Africa. This low cost solution prevents rain from pouring inside the building, but lacks any thermal insulation and reaches very high temperatures by absorption of solar radiation. A solution to prevent indoor overheating is to paint the outer covering of the roof with white coatings having a high solar reflectance to prevent heating, and a high emissivity to dissipate accumulated heat. The lower temperature of the roof further improves the indoor comfort through the reduction of the thermal radiation from the ceiling. The present study estimates the effectiveness of this solution, through the study case of a factory building located in Rwanda. A simulation model was generated including the geometrical, constructive and operational characteristics of the building. Different roof coatings in use for different periods were characterized in Rwanda, using portable equipment for measuring reflectance in the 380–1700 nm wavelength range and directional emittance in the 1.5–21 μm range. For conventional paints, the thermo-optical parameters range from those of a red roof with solar reflectance (SR) of 0.290 and hemispherical total emittance (HTE) of 0.740 and those of a grey one with SR of 0.045 and HTE of 0.877. Among the new white paints, including both local and European products, the highest SR is 0.887 for a coating with HTE of 0.872. The lowest reflectance (0.647) corresponds to the paint with the highest emittance (0.906) related to a content of siliceous aggregate to improve acoustic performance. The results of energy simulations considering the thermo-optical properties measured in situ show that white paints achieve significant energy savings with respect to conventional ones, allowing, in some cases, to avoid the use

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of air conditioning altogether to keep the temperature inside the factory below 25 °C in the hottest month.

Keywords Roof paints · Thermo-optical characterization · Roof rehabilitation · Rwanda buildings · Energy saving

1 Introduction

Thermal comfort is an essential property to achieve a sustainable architecture. A quality of space that influences the habitability and energy consumption of a building. Generating comfortable indoor temperatures depends largely on the thermo-optical properties of construction materials. In building rehabilitation, emphasis is often placed on the thermal insulation of the envelope; low thermal conductivity materials are incorporated to delay heat losses and gains [1]. However, improving thermal insulation can entail costs that are not always affordable.

There are rehabilitation strategies based on the thermo-optical properties of the roof surface. The reflectance, absorptance and emissivity of the roof-coatings manage part of the incident solar radiation and can reduce the accumulation and transmission of the heat to the interior [2], a favourable effect in regions with hot summers.

High reflective and emissive materials can be expensive [3]. However, under the same principle, similar low-cost alternatives can provide significant thermal benefits, especially for population facing difficult economic situations.

Africa is a continent facing significant social challenges within its territory. In countries like Rwanda, 39.1% of the population lived in poverty between 2013 and 2014 [4]. In this context, many so-called informal houses were built with affordable materials rather than suitable ones [5], compromising the thermal performance of the building.

Within this framework, the Cool White project aims to convince decision-makers in the partner African countries and in Europe of the positive effects of white roofs on the climate, people's well-being and the economy. Roofs in Rwanda, Tanzania, South Africa and Kenya have already been coated in white and the effect of this action is currently under analysis.

This study shows the results of the characterization of pre-existing and white coated roofs, obtained during a field visit to Rwanda. Reflectance and emissivity measurements were taken on three buildings, each located in a different region: Kigali, Mugasera Lake and Nyanza. An evaluation of the coatings impact on the thermal and energy performance of buildings is performed using a computational model.

2 Method

2.1 Monitoring

An in-situ thermo-optical characterization campaign was conducted involving eight roof finishes on three buildings located in different regions of Rwanda: Kigali, Nyanza and, Mugasera Lake (Fig. 1).

At Baraka Properties in Kigali, a recently applied white paint from a local company (BKW), an aged dark gray paint (BKG), and an aged blue paint (BKB) were measured. At a school in Nyanza, a white paint from a local company (NYWR) and a white paint from Germany (NYWG), both applied five months earlier, were measured, along with pre-existing red paint (NYR). At a pineapple and avocado processing plant in Mugasera Lake, a white paint with siliceous aggregates (MUW) applied several months earlier, and the pre-existing dark red paint (MUR) were measured.

Uncoated corrugated steel sheet used locally was measured as well. A separate sheet sample (MUM) was sent to Instituto de Ciencias de la Construcción Eduardo Torroja to be measured in its laboratory.

The thermo-optical characterization of the finishes include reflectance and emissivity measurements using portable equipment. A modular fibre-optic spectrophotometer from Stellarnet and an ET100 emissometer from Surface Optics Corporation were used to characterise at least three different points in each surface analysed. The solar absorptance coefficient was calculated from reflectance measurements performed in the range of 350–1700 nm and in accordance with the UNE EN



Fig. 1 Roof finishes measured in situ in Rwanda

410:2011 standard. The total hemispherical emissivity (HTE) was determined from directional reflectance measurements from 1500 to 21000 nm, in accordance with the ASTM E408 standard.

2.2 Simulation

To analyse the building’s performance with five of the roof finishes measured highlighted in Table 1, including the unpainted roof sheet, a computational model of the Mugasera Lake processing plant was made. DesignBuilder was the tool used to simulate the thermal performance of the building. Although the configuration of the interior thermal environment is influenced by elements such as doors, shading devices or exterior solar obstructions (trees, adjacent buildings), the created model focuses on the evaluation of the heat gains derived from the roof. Therefore a computational model was generated that simplifies the geometry, composition, and use of the building under study. The building has an interior area of 429.1 m² (29.55 × 14.52 m), and the maximum interior height of the gabled roof is 8.05 m. The walls are composed by 290 mm solid brick and an interior 10 mm mortar layer. The floor is a 100 mm concrete slab, and the roof is a 0.5 mm steel sheet. The glazing consists of a 6 mm clear glass sheet.

The building was modelled with two type of cooling methods. The first configuration includes only natural ventilation, the second includes an air-conditioning system, which is activated when temperatures exceed 25 °C. In both configurations, a template referring to an industrial process area was used to establish, for example, hours of use, occupancy, internal gains. The performance on February, the warmest month at the factory location, was simulated. The Nairobi Airport weather file was used, as it presents similar meteorological conditions to the study region.

Table 1 Thermo-optical properties of roof finishing materials. The five materials considered in the simulation are highlighted in bold

Ref	Location	Characteristics	ρ_v	ρ_s	HTE
BKB	Baraka properties	Blue (original)	0.087	0.163	0.828
BKG		Grey	0.075	0.045	0.877
BKW		White local new	0.889	0.822	0.886
NYR	Nyanza school	Red (original)	0.271	0.290	0.740
NYWG		White German aged	0.756	0.766	0.888
NYWR		White local aged	0.888	0.887	0.872
MUR	Mugasera factory	Dark red (original)	0.159	0.147	0.826
MUW		White siliceous aged	0.660	0.647	0.906
MUM	IETcc lab	Silvery	0.592	0.542	0.069

A simulation compared the building’s interior temperature and the exterior roof surface temperature with each of the roof finishes.

3 Results

3.1 Thermo-Optical Characterization

Figure 2 shows the mean reflectance spectra measured in situ for all the finishes in Fig. 1. As expected, white paints recorded the highest reflectance, especially the aged local paint. White paint with aggregates had the lowest values, even dropping below 50% in the long wavelength range. Red, dark red, grey, and blue paints used before painting white remained close or below 40%, with the grey paint curve having the lowest values.

The mean reflectance coefficients (solar and visible) and HTE values are shown in Table 2. White paints have ρ_s values between 0.647 and 0.887, and HTE between 0.872 and 0.906, while non-white paints have ρ_s between 0.045 and 0.290, and HTE between 0.740 and 0.877.

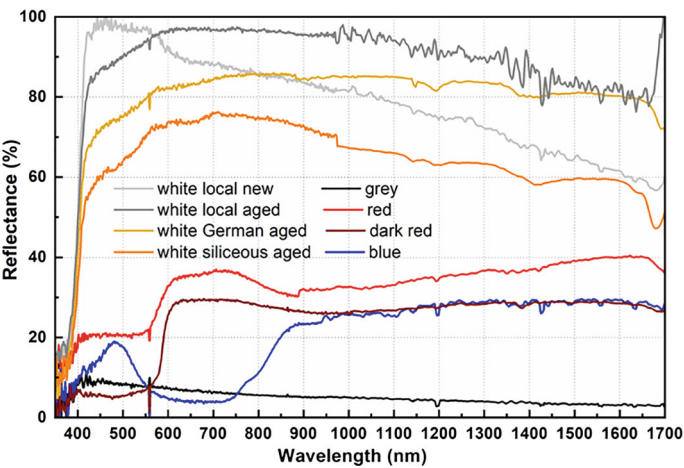


Fig. 2 Reflectance spectra of the paints measured in situ

Table 2 Building energy consumption

Energy consumption	Finishes				
	NYWG	NYWR	MUR	MUW	MUM
kWh/month	339.97	60.96	3844.00	835.77	3380.10
kWh/m ² ·month	0.792	0.141	8.958	1.948	7.877

3.2 Performance of the Finishes on the Building Roof

The results of the simulation in natural ventilation configuration show considerable differences between the roof finishes. The red paint, representing the pre-existing roof finish (MUR), reaches surface temperature up to 68 °C, a figure surpassed only by the uncoated steel sheet (MUM). The three white paints significantly reduce interior overheating. The aged white paint (NYWR) records lower temperatures, never exceeding 29 °C (Fig. 3).

The roof with the MUR paint provides the highest surface temperature among the paints; only the unpainted steel sheet (MUM) had higher figures. However, in the thermal environment inside the building, the MUR paint had the highest interior temperature, up to 38 °C, even higher than the MUM roof (up to 36 °C). Considering average figures, MUR and MUM had an average interior temperature of 25 °C, while NYWR paint, which kept the roof surface less warm, resulted in the lowest average interior temperature of 21 °C.

By including a mechanical HVAC system and eliminating natural ventilation, the energy consumption for refrigeration of the different finishes was determined (Table 2).

The building with the MUR paint in roof has the highest energy consumption (8.980 kWh/m²), even higher than that the non-painted steel roof, consistent with the fact that the red paint generates the warmest interior environment. As expected, the white local paint NYWR, due to its lower surface and interior temperatures, leads to the lowest energy consumption (0.141 kWh/m²), 8.817 kWh/m² lower than MUR. The simulation results indicate that applying that white paint to the steel roof instead of the pre-existing red one represents a reduction in energy consumption for refrigeration of 98.43%.

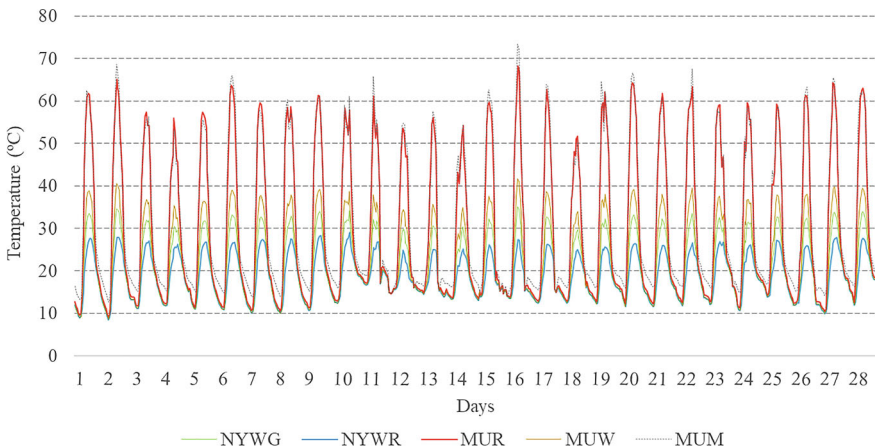


Fig. 3 Roof surface temperatures with the five finishes considered in the simulation

4 Conclusions

This paper presents the thermo-optical characterization of nine roof finishes. Eight of them correspond to paints measured in situ on buildings located in three regions of Rwanda (Kigali, Nyanza and Mugasera Lake). The other roof finish characterised is the uncoated corrugated steel sheet used locally, a sample of which was characterised in the laboratory. The coefficients obtained from the reflectance and emissivity measurements were compared, specifically looking for differences between the reflectance values of white and non-white paints. Furthermore, they were used to model one of the study buildings to compare its thermal and energy performances when applying five of the measured finishes.

The reflectance of the finishes varies significantly according to its colour. White paints show the highest reflectance values, ranging from 0.647 to 0.887 in the solar range, while non-white paints register values between 0.147 and 0.290. Regarding emissivity, all paints range from 0.740 to 0.906. The characterization highlights the low emissivity of the unpainted steel sheet (0.069) that can increase up to 0.887 by applying a white paint.

Using a computational model of the pineapple and avocado processing plant in Mugasera Lake, the thermal and energy performance of five of the measured finishes was estimated. The simulation results show that in the naturally ventilated configuration, the paint with the highest reflectance (NYWR) achieved the lowest temperatures values (surface and interior). The pre-existing dark red paint (MUR) presents the highest average interior temperature and an average surface temperature only lower than that of the uncoated steel sheet, which probably presented the highest figure due to its low emissivity. Adding a mechanical HVAC system shows the advantages of painting roofs white in terms of energy consumption. A 98% reduction of monthly energy consumption for refrigeration is estimated by changing the pre-existing conventional paint (MUR) by a local cool white paint (NYWR).

In this study, simulation demonstrates the benefits of using high-reflectance and high-emissivity coatings to reduce heat gains in steel-sheet buildings located in Africa. This low-cost strategy, adopted by the CoolWhite project is proven to improve habitability conditions and energy consumption in buildings. In addition to the thermo-optical measurements shown in this study, temperature data are available for the buildings under study, before and after applying a white paint to the roof. These data will be used to validate a more complex computational model that will provide more detailed simulation results.

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Disclosure of Interests The authors have no competing interests to declare that are relevant to the content of this article.

References

1. Ozel M (2011) Thermal performance and optimum insulation thickness of building walls with different structure materials. *Appl Therm Eng* 31(17–18):3854–3863. <https://doi.org/10.1016/j.applthermaleng.2011.07.033>
2. Tian W et al (2018) A review of uncertainty analysis in building energy assessment. *Renew Sust Energy Rev* 93:285–301. <https://doi.org/10.1016/j.rser.2018.05.029>
3. Xu F, Hang J, Wang H, Gao Z, Zhang JJ, Yang J (2024) An experimental study of the effects of using cool materials at different building heights on the indoor and outdoor environment. *Build Environ* 259:111664. <https://doi.org/10.1016/j.buildenv.2024.111664>
4. National Institute of Statistics of Rwanda (NISR) (2016) Statistical yearbook 2016 edition (SYB2016), Nov 2016
5. Mwizerwa F, Buddhi D (2019) Status of green buildings in Rwanda: need and scope. *Int J Eng Res Technol* 8(7):199–208

Acoustic Properties of a Biocomposite Insulation Material Obtained from End-of-Life Wind Turbine Blades



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Abstract The escalating global volume of waste from end-of-life wind turbine blades presents a significant environmental challenge, with projections indicating that approximately 2.9 million tons of this waste will require processing in Europe alone by 2050. The complex management of this waste, coupled with limited reuse options, predominantly leads to its utilization as fuel or disposal in landfills, which generates environmental concerns. This study explores the valorization of this waste through the development of a biocomposite for buildings acoustic insulation using a bio-binder. The acoustic properties of the material were evaluated by determining the sound absorption coefficient (α) and the Noise Reduction Coefficient (NRC) using the impedance tube method, and the Transmission Loss (TLn) to assess insulation performance. Samples with different bio-binder proportions (15, 20, and 25% relative to recycled fiberglass) were produced and tested. Sound absorption results were compared with commercially available materials, revealing promising and competitive performance (NRC). Transmission loss analysis demonstrated the potential of the biocomposite for acoustic insulation, with values frequently exceeding those of the reference mineral wool. The conclusions demonstrate the feasibility of producing a sustainable biocomposite for acoustic insulation in construction from wind turbine blades waste, offering an alternative solution for its management and reuse.

Keywords End-of-life wind turbine blades · Bio-binder · Sound absorption coefficient · Transmission loss · Noise reduction coefficient

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1 Introduction

The wind energy sector's rapid growth, reaching 906 GW globally in 2022 [1], presents a significant environmental challenge in managing end-of-life turbine blade waste, estimated to reach 2.9 million tons in Europe by 2050 [2, 3]. The complex, non-biodegradable composition of these blades hinders conventional recycling, leading to landfill disposal and negative environmental consequences [4]. Simultaneously, the building and construction sector is a major contributor to GHG emissions [5, 6], highlighting the urgent need for energy efficiency improvements through innovative insulation materials, aligning with directives like the EPBD [7].

Sustainable construction is increasingly exploring biocomposites utilizing bio-binders from renewable sources [8, 9]. Marine biomass, particularly sodium alginate derived from brown algae, offers a promising alternative due to its gelling, biodegradable, biocompatible, and cost-effective properties [10]. Research using various plant fibers like wood [11] and rice straw [12] has demonstrated the potential of biocomposites to create effective insulating materials, often matching or exceeding the performance of conventional options [13, 14].

This study addresses both the wind turbine blade waste management issue and the demand for sustainable construction materials by proposing an innovative circular economy approach. It investigates the transformation of mechanically processed end-of-life wind turbine blade waste into fibrous material, combined with bio-binders, for the production of acoustic insulation panels for the construction sector. This approach offers a viable and sustainable solution for managing difficult-to-treat waste while contributing to the reduction of the construction sector's environmental impact through material reuse and circularity.

2 Materials and Methods

2.1 Formulation and Manufacture of Biocomposites

The obtained material from end-of-life wind turbine blades, is primarily composed of fiberglass and epoxy resin, along with minor quantities of balsa wood and a polyurethane coating. The blades underwent a three-stage process of cleaning, mechanical reduction, and homogenization. Initially, the material was transformed in fragments of approximately 500×500 mm. In the laboratory, these pieces were cut into 50×50 mm segments using a miter saw equipped with a diamond blade, followed by shredding in a knife mill with a 10 mm sieve, resulting in a relatively homogeneous fibrous material (see Fig. 1a).

Three biocomposite formulations, labeled BioGF15, BioGF20, and BioGF25, were developed with varying bio-binder-to-fiberglass ratios of 15%, 20%, and 25%, respectively. The bio-binder consisted of sodium alginate, calcium sulfate (to enhance curing and water resistance), and sodium citrate (as a pH regulator). It was prepared

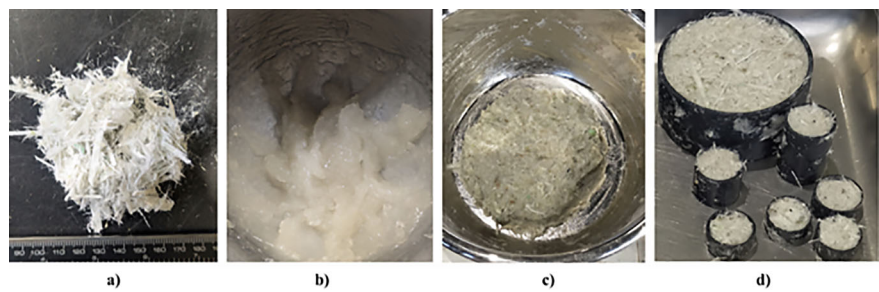


Fig. 1 Biocomposite processing: **a** Fibrous material, **b** bio-binder, **c** biocomposite, **d** biocomposite molding

by dry-mixing these components and then dissolving them in distilled water using a planetary mixer at 1000 rpm and 20 °C for 40 min, resulting in a pale-yellow viscous paste (Fig. 1b). This paste was then manually mixed with the processed fiberglass for 10 minutes to produce the final biocomposite materials (Fig. 1c). The binder quantities were selected based on mechanical strength optimization from prior research [15]. The detailed composition of these formulations is presented in Table 1.

The biocomposite was then molded into different shapes for acoustic testing specimens: three samples with a diameter of 100 mm and a thickness of 32 mm, and three samples with a diameter of 29 mm and a thickness of 32 mm, corresponding to the cross-sectional area of the impedance tube (see Fig. 1d). Apply a pressure of 5.5 kPa to the samples, which are kept in an oven at 40 °C for 48 h. Subsequently, the load was removed, and the samples remained in the oven for an additional 24 h period. Finally, they were stabilized in a climate chamber at 20 °C and 60% relative humidity for 72 h.

Acoustic measurements were conducted using a Holmarc ITA219 impedance tube under ambient environmental conditions and in the presence of ambient noise, in accordance with ISO 10534-2 standard [16]. The aim of the test was to determine the Sound Absorption Coefficients (SAC), which represent the fraction of sound

Table 1 BioGF composite formulations

Composition	BioGF15		BioGF20		BioGF25	
	W (g)	% (w/w)	W (g)	% (w/w)	W (g)	%(w/w)
Fiberglass	140.0	20.0	140.0	15.8	140.0	13.0
Sodium alginate	21.0	3.0	28.0	3.2	35.0	3.3
Calcium sulphate	3.5	0.5	4.6	0.5	5.8	0.5
Sodium citrate	0.5	0.1	0.7	0.1	0.8	0.1
Water	535.0	76.4	713.3	80.5	891.7	83.1
Total	700.0	100.0	886.6	100.0	1073.3	100.0
Bio-binder/GF weight ratio		15		20		25

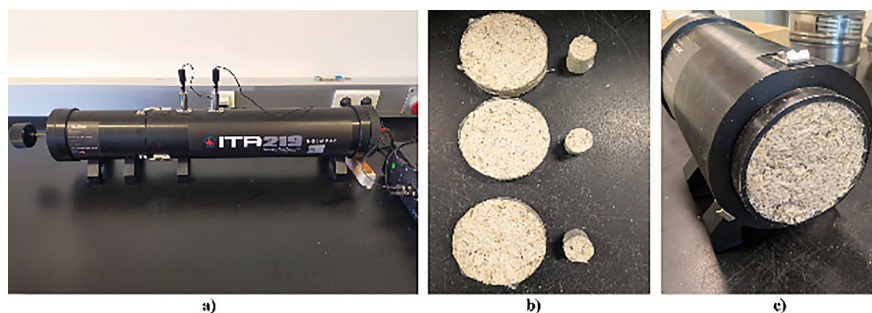


Fig. 2 Acoustic tests: **a** Impedance tube, **b** samples and **c** samples in the test tube

energy absorbed by the material, ranging between 0 and 1 [17]. For each sample, data points were obtained in the frequency range of 100–6300 Hz. Using the obtained SAC values, the Noise Reduction Coefficient (NRC) was determined. The NRC represents the arithmetic average of the amount of sound absorbed by an acoustic insulation material at the frequencies of 250, 500, 1000, and 2000 Hz. The NRC index ranges from 0 to 1, where 0 indicates that the material does not absorb sound and 1 signifies total sound absorption [17], offering a concise metric for comparing the average sound absorption effectiveness of the acoustic insulation, especially within the human speech frequency range.

For the evaluation of transmission loss, a second test was conducted following the specifications of ASTM E1050 standard [18], utilizing the same biocomposite samples. Data points were obtained in the frequency range of 100–6300 Hz. Sound Transmission Loss is a measure of a material's ability to reduce the intensity of sound passing through it, serving as a fundamental parameter in assessing acoustic insulation performance. Figure 2 illustrates the impedance tube, the samples used, and the testing procedure.

According to the standard, the acoustic properties of materials are related to their physical characteristics, such as density. However, the objective of this study is to evaluate the effect of varying bio-binder/GF ratios on the sound absorption and transmission loss of the biocomposite.

3 Results and Discussion

3.1 A Subsection Sample Analysis of the Sound Absorption Coefficient

The SAC values were evaluated for BioGF15, BioGF20, and BioGF25 across the 100–6300 Hz frequency range and compared with 40 mm thick mineral wool, a widely used reference material. Initially designed to exceed 40 mm, the BioGFs

shrank during curing, leading to the properties in Table 2. Figure 3 illustrates this comparison, enabling performance analysis, peak absorption identification, and material correlation.

Mineral wool exhibits increasing absorption with frequency, performing poorly in the bass range (100–250 Hz) but significantly improving above 1000 Hz, reaching coefficients near or above 0.80. This behavior is typical of porous materials, where sound energy dissipates via internal friction [19].

The biocomposites show varying absorption. In the mid-range (250–800 Hz), BioGF15 absorbs less than mineral wool despite peaks at 315 and 630 Hz. BioGF20 improves with frequency, approaching mineral wool’s performance, while BioGF25 shows the lowest absorption among the biocomposites.

At higher frequencies (1000–6300 Hz), BioGF15 surpasses mineral wool at 1250 Hz. BioGF20 exhibits the most consistent high performance, often exceeding mineral wool, with peaks at 1250 and 4000 Hz. BioGF25 also performs well, peaking at 4000 Hz and slightly outperforming mineral wool in some areas. Overall, BioGF20 and BioGF25 show promise for superior high-frequency absorption, while mineral wool remains more consistent across mid and high ranges.

Table 2 presents some physical properties of the BioGF materials, including the SAC values used in the NRC calculation, as well as the final NRC value for each biocomposite.

Table 2 Physical properties of BioGF and resulting SAC and NRC values

Material	Thickness (mm)	Bulk density (kg/m ³)	SAC values				NRC
			250 Hz	500 Hz	1000 Hz	2000 Hz	
Mineral wool	40	55.00	0.28	0.33	0.81	0.74	0.54
BioGF 01	32	292.78	0.05	0.15	0.85	0.71	0.44
BioGF 02	32	282.75	0.04	0.22	0.79	0.75	0.45
BioGF 03	32	229.41	0.03	0.12	0.60	0.76	0.38

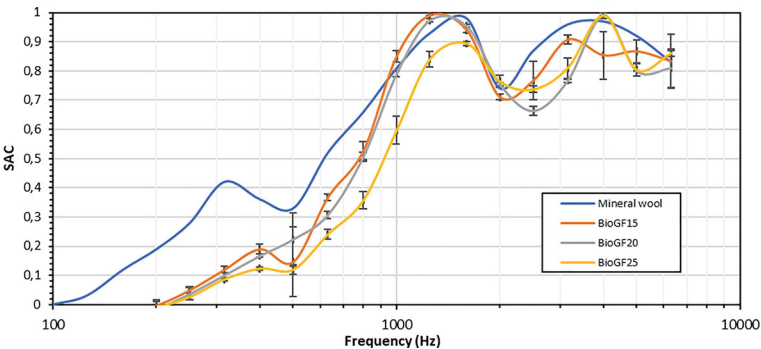


Fig. 3 The sound absorption coefficient dependence on frequency of the incident sound

The BioGF materials exhibit a significant variation in their bulk density, ranging from 229.41 to 292.78 kg/m³, a considerably higher value than that of mineral wool (55.00 kg/m³), while the thickness remains constant at 32 mm. Despite this substantial difference in density, the NRC values of the BioGF materials (0.44, 0.45, and 0.38, respectively) are lower than that of mineral wool (0.54), indicating that density alone does not translate to better average sound absorption performance.

The analysis of NRC values in relation to the composition (bio-binder/GF ratios of 15%, 20%, and 25%, respectively) suggests a slight influence of the component proportions on sound absorption capacity. BioGF20 (20% of binder) exhibits the highest NRC (0.45) among the BioGF materials, indicating a more effective balance between structural cohesion and the porosity required for sound energy dissipation. BioGF15 (15% binder) displays a slightly lower NRC (0.44), suggesting that a lower amount of binder may result in a structure with slightly different absorption properties. BioGF25 (25% of binder) presents the lowest NRC (0.38), which can be attributed to an excess of binder filling the porous spaces, making the material stiffer and less effective in sound absorption, especially at the lower frequencies considered in the NRC calculation.

In conclusion, the comparative analysis of BioGF materials demonstrates that the average sound absorption performance, evaluated by the NRC index, does not exhibit a positive linear correlation with its apparent density. Although BioGF01 has the highest density, it did not present the highest NRC value, suggesting that factors beyond density are more influential. Instead, the composition of the material, particularly the ratio between the bio-binder/GF, seems to play a decisive role in its acoustic properties. The existence of an optimal bio-binder proportion (apparently around 20% for these materials) which maximizes the NRC suggests that the balance between the structural cohesion provided by the binder and the porosity offered by the fibrous matrix is crucial for optimizing the biocomposites sound absorption.

3.2 Sound Transmission Loss Analysis

Figure 4 presents the Sound Transmission Loss (TL_n) values in decibels (dB) for mineral wool and the three biocomposites across the 100–6300 Hz frequency spectrum, which encompasses the human audible range.

The sound transmission loss (insulation) of BioGF biocomposites generally surpassed that of mineral wool across most of the analyzed frequency spectrum (100–4000 Hz). At lower frequencies (100–250 Hz), BioGF materials showed slightly better insulation, potentially linked to their higher density (229.41–292.78 kg/m³) compared to mineral wool (55.00 kg/m³). In the mid-frequency range (315–800 Hz), BioGF15 and BioGF20 frequently exhibited the highest insulation values, exceeding 26 dB, likely influenced by their density and the specific fiberglass-biobinder proportions.

At higher frequencies (1000–4000 Hz), BioGF15 and particularly BioGF20 demonstrated significantly high transmission loss peaks, surpassing 30 dB at certain

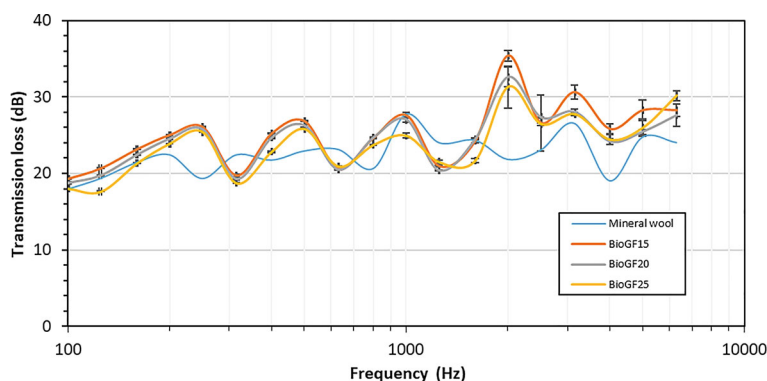


Fig. 4 The transmission loss dependence on frequency of the incident sound

points, suggesting an effective sound attenuation mechanism related to the interaction of their components. While BioGF25, with the highest bio-binder content, showed slightly lower high-frequency insulation, overall, the BioGF biocomposites exhibited considerable potential for acoustic insulation, especially in the mid and high ranges, with the bio-binder/GF ratio and higher density appearing as key determinants for their sound insulation properties, and BioGF20 showing promise for optimized performance.

4 Conclusions

The BioGF biocomposites (BioGF15, BioGF20, BioGF25) exhibited varying sound absorption based on their bio-binder/GF ratio. BioGF20 (20% binder) showed the highest NRC (0.45), indicating better average absorption than BioGF15 (15% binder, NRC 0.44) and BioGF25 (25% binder, NRC 0.38), highlighting the importance of binder concentration for optimal performance.

For sound insulation (STL), all BioGF materials generally outperformed mineral wool. BioGF15 and BioGF20 displayed the highest STL, particularly at mid and high frequencies, suggesting effective sound transmission reduction. The binder/fiberglass ratio also influenced STL, with lower binder percentages tending to favor better insulation at higher frequencies.

In summary, the bio-binder/GF ratio is a key factor determining the acoustic properties (absorption and insulation) of BioGF biocomposites. BioGF20 (20% binder) presented a favorable balance for overall acoustic performance, demonstrating the potential for tailored acoustic solutions using these sustainable materials derived from wind turbine blade waste.

Recognition of Use. The use of AI-assisted technologies, such as ChatGPT-4 (OpenAI, <https://chat.openai.com>), is acknowledged in the revision and translation process to enhance the readability and linguistic quality of this work.

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References

1. WindEurope. Global wind energy outlook 2023. <https://windeurope.org/intelligence-platform/product/wind-energy-in-europe-2023-statistics-and-the-outlook-for-2024-2030/>. Accessed on 2 Apr 2024
2. Sorte S, Martins N, Oliveira MSA, Vela GL, Relvas C (2023) Unlocking the potential of wind turbine blade recycling: assessing techniques and metrics for sustainability. *Energies* (Basel) 16. <https://doi.org/10.3390/en16227624>
3. Sorte S, Figueiredo A, Vela G, Oliveira MSA, Vicente R, Relvas C, et al. (2024) Evaluating the feasibility of shredded wind turbine blades for sustainable building components. *J Clean Prod* 434:139867. <https://doi.org/10.1016/j.jclepro.2023.139867>
4. Shen M-Y, Guo Z-H, Feng W-T (2023) A study on the characteristics and thermal properties of modified regenerated carbon fiber reinforced thermoplastic composite recycled from waste wind turbine blade spar. *Compos Part B Eng* 264:110878. <https://doi.org/10.1016/j.compositesb.2023.110878>
5. United Nations Environment Programme. United Nations environment programme GA for B and C. Global status report for buildings and construction—beyond foundations: mainstreaming sustainable solutions to cut emissions from the buildings sector (n.d.)
6. Environment Agency European (2024) Greenhouse gas emissions from energy use in buildings in Europe. <https://www.eea.europa.eu/en/analysis/indicators/greenhouse-gas-emissions-from-energy?activeAccordion=ecdb3bcf-bbe9-4978-b5cf-0b136399d9f8>. Accessed on 20 Dec 2024
7. European Commission (2024) Energy performance of buildings directive. https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficient-buildings/energy-performance-buildings-directive_en?prefLang=pt. Accessed on 14 Dec 2024
8. Muthuraj R, Lacoste C, Lacroix P, Bergeret A (2019) Sustainable thermal insulation biocomposites from rice husk, wheat husk, wood fibers and textile waste fibers: elaboration and performances evaluation. *Ind Crop Prod* 135:238–245. <https://doi.org/10.1016/j.indcrop.2019.04.053>
9. Mazor MH, Mutton JD, Russell DAM, Keoleian GA (2011) Life cycle greenhouse gas emissions reduction from rigid thermal insulation use in buildings. *J Ind Ecol* 15:284–299. <https://doi.org/10.1111/j.1530-9290.2010.00325.x>
10. Lacoste C, El Hage R, Bergeret A, Corn S, Lacroix P (2018) Sodium alginate adhesives as binders in wood fibers/textile waste fibers biocomposites for building insulation. *Carbohydr Polym* 184:1–8. <https://doi.org/10.1016/j.carbpol.2017.12.019>
11. Chen F (2021) Study on mechanical and thermal performance of building Energy-Saving Wall with insulation materials. E3S web of conferences, vol 242, EDP Sciences. <https://doi.org/10.1051/e3sconf/202124202005>

12. Zhou Y, Trabelsi A, El Mankibi EM (2022) View of development and characterization of thermal insulation materials based on rice straw and natural binder. *Clima*. <https://doi.org/10.34641/clima.2022.332>
13. Pianklang S, Muntongkaw S, Tangboriboon N (2022) Modified thermal- and sound-absorption properties of plaster sandwich panels with natural rubber-latex compounds for building construction. *J Appl Polym Sci*:139. <https://doi.org/10.1002/app.52068>
14. Rubino C, Bonet Aracil M, Liuzzi S, Stefanizzi P, Martellotta F (2021) Wool waste used as sustainable nonwoven for building applications. *J Clean Prod* 278:123905. <https://doi.org/10.1016/j.jclepro.2020.123905>
15. Vela G, Figueiredo A, Costa V, Vicente R (2024) Desenvolvimento de painéis produzidos a partir de resíduos de pás de turbinas eólicas em fim de vida: desempenho mecânico e acústico. *Construção Magazine* No 123:36–41
16. Standard SR. EN ISO 10534-2, Acoustics—determination of acoustic properties in impedance tubes 2023:32
17. Dissanayake DGK, Weerasinghe DU, Thebuwanage LM, Bandara UAAN (2021) An environmentally friendly sound insulation material from post-industrial textile waste and natural rubber. *J Build Eng* 33:101606. <https://doi.org/10.1016/j.job.2020.101606>
18. ASTM (2019) ASTM E1050–19—Standard test method for impedance and absorption of acoustical materials using a tube, two microphones and a digital frequency analysis system. <https://doi.org/10.1520/E1050-19>
19. Volcalis (2024) O isolamento e o mito da densidade. <https://volcalis.pt/artigos/o-isolamento-e-o-mito-da-densidade/>. Accessed on 5 Feb 2025

Nature-Based Solutions to Improve Water and Energy Efficiency and Social Equity in Low-Income Communities



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and Fernanda Rodrigues 

Abstract The urban water cycle is an essential component of cities but remains energy-intensive, accounting for a significant part of national electricity consumption and the operating costs of water utilities. This challenge is particularly acute in low-income communities, which often face resource inefficiencies, socio-economic inequality and environmental vulnerability. Nature-based Solutions (NbS) offers an opportunity to improve water and energy efficiency while promoting climate resilience and social equity. NbS can provide multifaceted benefits, including reducing energy consumption in water systems, mitigating climate risks and creating more liveable and inclusive urban spaces. This study examines the RECAREI Social Housing Complex in Matosinhos, Portugal, as a case study to assess the potential for improving water and energy efficiency through strategies implemented at the urban community level. Implementing water reuse systems, for example, in line with water efficiency strategies, the study estimates a 39–53% reduction in potable water consumption and a 16–23% reduction in wastewater production. These measures also result in significant energy savings, with a total reduction of 8313 kWh/year in urban water supply (WSS) and wastewater management (WWM) systems, equivalent to 1255 t of CO₂/year. In addition, the use of NbS can increase these benefits by up to 30%, while promoting urban greening, community well-being and social cohesion. The findings highlight the potential of NbS to transform social neighbourhoods into

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resilient, sustainable and equitable communities. By integrating blue-green infrastructure (BGI), NbS can help decarbonise urban systems and improve living conditions in low-income communities, aligned with national and international climate action and social inclusion objectives.

Keywords Nature-based solutions · Water efficiency · Energy efficiency · Social equity · Low-income communities · Urban water cycle

1 Introduction

The decarbonisation of cities is a global priority due to climate change and the need for urban sustainability [1]. The construction sector, a major contributor to greenhouse gas (GHG) emissions, must adopt strategies that integrate energy efficiency and reduce reliance on conventional resources. The urban water cycle is highly energy-intensive [2], impacting national electricity consumption and the operational costs of WSS and WWM systems [3, 4].

NbS offer an innovative approach, water and energy management, climate resilience, and social equity [5–7]. Measures like water reuse systems and rainwater harvesting reduce drinking water demand, lower energy costs, and improve access to services for vulnerable communities [5, 8–11]. The Water-Energy-Food-Ecosystems (WEFE) nexus helps understand connections between these resources and assess the benefits of NbS for more sustainable cities [12, 13].

Despite the benefits, challenges such as funding gaps and regulatory barriers remain [2, 5, 7]. This article proposes a methodology to assess the energy-saving potential of water conservation strategies in the built environment, with a focus on the RECAREI Social Housing Complex in Matosinhos. A literature review identified strategies such as water reuse systems to quantify their impact on energy savings and carbon emissions reduction. The methodology involves estimating reductions in water and wastewater consumption, calculating energy savings in water management systems, and analysing the benefits of NbS through the WEFE nexus. The financial impact on local residents and the role of NbS in affordable housing communities are also discussed. This study contributes to strategies integrating water efficiency, energy savings, and social justice.

2 Water-Energy-Food-Ecosystem Nexus

The WEFE nexus is a multi-sectoral approach recognising the interdependence between water, energy, and food, as well as the preservation of the ecosystems that sustain them [12]. This concept guides integrated and synergistic responses through sustainable management policies, ensuring ecological integrity [12]. NbS, by mimicking natural processes, offer multifunctional benefits such as improving

urban water management, increasing energy efficiency and climate resilience [8, 10]. They also contribute to addressing socio-economic disparities and strengthen community well-being, especially in areas vulnerable to water and food insecurity [14].

In low-income communities, energy poverty exacerbates social vulnerabilities, influencing food choices, as households often opt for less nutritious and less energy-demanding foods due to rising energy costs [15]. The concept of 'precarious consumption' helps to understand these fragilities in the urban WEFE context [15]. Thus, integrated solutions are essential for a just energy transition, balancing social equity, environmental sustainability, and economic development [13].

Among NbS, sustainable urban drainage systems (SUDS) stand out for their ability to integrate water and energy management, aligning with WEFE principles. Traditional wastewater treatment plants typically require 0.3–0.6 kWh/m³ [16], while alternatives such as SUDS and wastewater separation can reduce energy demand by up to 26% [17] and mitigate GHG emissions [4]. Rainwater harvesting and utilisation can also generate energy gains, reducing domestic drinking water consumption by up to 21.6% and savings of up to 138.6 kWh per household per year [18].

The urban water cycle is energy-intensive, with energy costs accounting for 25–40% of operating expenses [3]. About 90% of this energy is used during end use, while the remaining 10% is used for collection, treatment, distribution, and drainage [4]. In Portugal, water and waste sector energy consumption was 1.1 TWh in 2023, with 59.8% directed to WSS and 40.2% to WWM [19]. In WSS, 86% of energy is used for pumping, while 21% is used in WWM [19]. Indirect CO₂ emissions from the sector range from 0.04 to 0.10 kg CO₂ eq/m³ depending on operational intensity [19].

On an urban scale, water efficiency strategies in the housing, public and commercial sectors can save up to 8951.5 MWh/year, as observed in a Brazilian city with a population of over 500,000, where energy consumption in the urban water cycle was estimated at 0.69 kWh/m³ [20]. In Portugal, targeted measures focusing on domestic water heating systems could reduce energy use by around 423 kWh and CO₂ emissions by 100 kg per capita annually [4]. Specifically, building-level water heating systems contribute with 368 kWh and 88.3 kg CO₂ savings per capita per year, while WSS and WWM offer additional gains [4]. These water-efficient technologies, despite financial barriers in vulnerable communities, are essential to reduce dependency on energy-intensive water services and to promote resilience.

NbS applied to urban infrastructure can help mitigate climate change impacts. Green roofs, for example, can reduce air and surface temperatures by 3–16.5 °C [21], improving the urban microclimate and reducing buildings' energy demand. Energy savings vary from 3–90% for cooling and 0.58–60% for heating, depending on the type of NbS and climatic conditions [22]. During extreme weather events, infiltration systems and green roofs can reduce flood volumes by up to 33.5% [23], minimising damage to critical infrastructure and energy costs.

Despite the benefits, structural and socio-economic barriers hinder decarbonization. In low-income communities, financial constraints, lack of control over housing

conditions and limited access to information hinder the adoption of efficient technologies. Although decarbonisation is critical for sustainability, implementation must consider national and social contexts [1]. In Portugal, Decree-Law No.101-D/2020 [24] and Government Order No.138-I/2021 [25] define minimum energy performance requirements, directly influencing water and energy use. However, these standards can be difficult to meet in vulnerable communities without support mechanisms.

The integration of NbS with energy transition strategies can enhance urban resilience. Smart electricity grids combined with NbS may reduce energy use by 20–25% and GHG emissions by up to 35% [26]. These data reinforce the central role of NbS in promoting holistic approaches to energy efficiency and climate adaptation. Nonetheless, challenges remain, such as ecosystem degradation, which diminishes the natural capacity for water storage and filtration and increases energy demands. The recovery of resources like biogas and nutrients from wastewater exemplifies circular economy principles [9], offering opportunities for more sustainable and inclusive solutions. In low-income communities, the adoption of BGI, combined with sustainable management strategies, can improve energy efficiency, reduce GHG emissions and strengthen community resilience, promoting social equity and well-being.

The nexus between water and energy must be prioritised in public policies, ensuring not only technical feasibility but also socio-economic viability, particularly in contexts marked by inequality and limited access to infrastructure improvements.

3 NbS: Urban Decarbonisation and Community Wellbeing

NbS are a strategic approach to urban decarbonisation, integrating environmental sustainability, social equity, and climate resilience [10]. In low-income communities, these solutions mitigate environmental impacts and improve community well-being [5] by promoting efficient use of water and energy and replicating ecological processes. The implementation of BGI enhances access to green spaces, air quality, and energy efficiency [8], particularly benefiting vulnerable populations during extreme events. They also foster local economic development through green jobs and community engagement, supporting eco-innovation and circular economy principles [6].

NbS improve public health by reducing pollutant levels (e.g., ~ 10% NO₂) [27], and promoting active lifestyles, social cohesion, and mental well-being. Multifunctional NbS like green roofs can integrate urban agriculture, solar energy, and rainwater harvesting, contributing to reduced GHG emissions. For example, the “roof mosaic” approach can avoid up to 196 kg CO₂ eq/inhabitant/year, and achieve up to 50% self-sufficiency in water, energy, and food needs at the neighbourhood scale [28]. Table 1 summarises key NbS performance metrics in the water-energy-food nexus.

Table 1 NbS performance metrics in the water-energy-food nexus. Adapted from [11, 28]

Resource	Key performance metrics
Water	25–30% reduction in drinking water consumption; 230–700 m ³ /ha rainwater retention (water storage); 60–118 mm/h hydrological buffering capacity; 40–93% reduction in surface runoff; pollutants removed: 40% nitrogen, 60% phosphorus, 80% suspended solids; loads removed: 0.13 t/ha/year nitrogen, 3.9 t/ha/year dissolved organic carbon
Energy	10–30% reduction in energy consumption; 6.1–27 °C local temperature reduction; GHG reduction: (I) 13.9–18.6 kg CO ₂ eq/inhab/year (rainwater harvesting), (II) 177–196 kg CO ₂ eq/inhab/year (systems integrated with solar energy)
Food	Urban food production: (I) 0.932–20,000 kg/ha/year (by area), (II) 6.4 kg/m ³ of stored water used for production

Despite their potential, implementing NbS requires balancing temporal, spatial and functional aspects, and overcoming funding and knowledge gaps [5, 14]. Implementing NbS requires careful consideration of local contexts and community needs through transdisciplinary co-creation processes [29]. Less than 6% of NbS projects address poverty, and less than 25% support housing or neighbourhood regeneration [7]. To maximise their impact, NbS must be integrated into local policies and spatial planning frameworks, prioritising socio-economic equity [7].

Assessing NbS effectiveness depends on appropriate performance indicators, yet current methodologies often fail to capture their full range of co-benefits [2, 11]. A holistic evaluation approach is necessary to guide evidence-based planning and ensure targeted investments in BGI that promote more resilient and inclusive cities.

4 Methodology

This study proposes a methodology to estimate electricity savings and CO₂ reductions from water conservation strategies at an urban scale, specifically focusing on the impacts on WSS and WWM, as well as the economic benefits for inhabitants. The methodology was adapted from previous studies on effective water management in the built environment [20] and tailored to the context of a social urban community in Portugal. The method is divided into three stages:

1. **Water and wastewater reduction estimation:** The reduction in potable water consumption and wastewater production is calculated based on conservation strategies such as greywater use and rainwater harvesting.
2. **Electricity savings and CO₂ reduction:** Electricity savings are derived from the reduction in water consumption and wastewater production, using the average energy intensity of WSS and WWM.
3. **Analysis of NbS benefits:** Additional analyses assess the potential benefits of implementing NbS in urban environments, particularly in affordable housing contexts, considering their impact on the WEFE nexus. This methodology

allows the quantification of NbS benefits in improving the integrated management of resources, enhancing urban resilience, and promoting sustainability in low-income communities.

5 Case Study and Results

The RECAREI Social Housing Complex (41°12'09.6" N 8°38'00.2" W), located in Matosinhos, Portugal, was selected as a case study due to its representativeness as a social housing development facing key challenges in energy efficiency, water management, and socio-economic vulnerability—critical aspects for sustainable urban transitions. According to data provided by MatosinhosHabit, the municipal housing company, the complex was built in 2001 under the CDH/PER (Special Resettlement Programme) and comprises three buildings with a total of 154 dwellings: 54 one-bedroom, 16 two-bedroom, 79 three-bedroom, and 5 four-bedroom units, currently housing 311 residents. In addition to housing, the complex includes social facilities such as a Health Centre (Porta Sol Family Health Unit) with 569.5 m² of floor space and approximately 17,000 users, a nursery with 217 m² and capacity for 20 children, and a kindergarten with 773 m² and capacity for 45 children. The development also features 1064 m² of green space, a usable construction area of 10558.99 m², and a total built area of 15,952.65 m².

The methodology applied recognises the economic, environmental, and social relevance of RECAREI. Based on the reference methodology [9], the estimated total water demand—including approximately 248 social facility occupants—was around 86 m³/day of drinking water. This informed the local water balance, considering daily supplies of 20 m³ of light greywater (from washbasins, showers, and baths) and 8–19 m³ of rainwater collected from roof areas. Greywater was allocated exclusively to toilet flushing due to lower treatment requirements, while rainwater—estimated at 21 m³/day—was designated for washing, cleaning, and irrigating green spaces. Water-efficient equipment and components were included in the building systems.

The results demonstrate that water conservation strategies generate multiple benefits, including significant electricity savings and CO₂ emission reductions, supporting findings in the literature [4, 17, 18, 20, 26, 28]. The combined use of greywater and rainwater harvesting led to a 39% reduction in drinking water consumption (13,377 m³/year) and a 16% reduction in wastewater production (3317 m³/year), considering that only greywater contributes to wastewater [20]. When applied solely to residential use, these reductions increase to 53% (8962 m³/year) in water consumption and up to 23% (2372 m³/year) in wastewater. These results highlight the potential for resource sharing and redistribution in the built environment, improving overall efficiency in community-scale water management [9, 28]. The decrease in water consumption and wastewater generation also positively impacted energy use and CO₂ emissions. Annual energy savings were 6817 kWh in WSS and 1496 kWh in WWM, totalling 8313 kWh. This translates to an annual reduction of 1255 t of CO₂, or 2.019 kg CO₂ eq/person/year for residents and 2.529 kg CO₂ eq/person/year for

users of social facilities. Energy intensity values and emission factors were sourced from the 2024 Annual Report on Water and Waste Services in Portugal [19]. Financially, the measures produced notable savings: up to €73 per household annually (assuming two residents per unit) and €6095/year for the municipality, considering the health centre, nursery, and kindergarten. Water and wastewater tariffs (2025) were obtained from INDAQUA, the municipal utility company in Matosinhos.

Efficiency gains can be further enhanced by adopting water-efficient heating systems, which can reduce up to 88.3 kg CO₂ per capita annually [4]. Integration with NbS, such as rain gardens and SUDS [10], can boost benefits by 10–30% [11, 17, 28]. Additionally, using green areas for local food production supports the WEF nexus, fosters self-sufficiency, and reduces dependency on external resources. Urban greening also improves the microclimate, mitigates heat island effects, and enhances biodiversity. These interventions reinforce the environmental and social value of water and energy strategies, promoting community well-being and quality of life.

6 Conclusions

The study shows that water conservation strategies like use of greywater and rainwater harvesting can reduce potable water consumption by 53%, saving 8313 kWh/year in energy and reducing CO₂ emissions by 1255 kg CO₂ eq/year in urban environments, particularly at the community scale. These measures provide financial benefits, saving up to €73 per home annually (€11,213 for 154 homes), with additional savings of €6095 for local authorities. These strategies highlight the potential for public policy incentives, especially in social housing communities.

In the RECAREI Complex, NbS such as rain gardens and sustainable urban drainage systems enhance the benefits of the WEF nexus, contributing to urban agriculture, biodiversity, and community well-being. These findings reinforce the role of NbS in creating cities that are resilient, inclusive, and aligned with the Sustainable Development Goals (SDGs), particularly in sustainable water management (SDG 6), clean energy (SDG 7), sustainable cities (SDG 11), and poverty reduction (SDG 1). Further research is needed to quantify the specific benefits of different NbS techniques in diverse urban areas and socio-economic contexts. This work is essential for solidifying strategies that integrate water efficiency, energy transition, and social equity, contributing to urban decarbonisation and more resilient communities.

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References

1. Biswas N, Dey S, Srivastava RR (2023) Energy transition—building an understanding of the impacted communities. <https://doi.org/10.2139/ssrn.4397525>
2. Nika CE, Gusmaroli L, Ghafourian M, Atanasova N, Buttiglieri G, Katsou E (2020) Nature-based solutions as enablers of circularity in water systems. *Water Res* 183:115988. <https://doi.org/10.1016/J.WATRES.2020.115988>
3. Silva C, Loureiro D, Mamade A, Marabuto M, Rosa MJ (2020) Consumo de energia nos serviços urbanos de água em Portugal Continental. Resultados 2004–2017. *Águas e Resíduos* 9:5–16. <https://doi.org/10.22181/AER.2020.0901>
4. Silva-Afonso A, Pimentel-Rodrigues C (2017) Manual de Eficiência Hídrica em Edifícios. ANQIP: Associação Nacional para a Qualidade nas Instalações Prediais
5. Castelo S, Amado M, Ferreira F (2023) Challenges and opportunities in the use of nature-based solutions for urban adaptation. *Sustainability* 15(9):7243. <https://doi.org/10.3390/su15097243>
6. Chausson A et al (2024) Harnessing nature-based solutions for economic recovery. *PLOS Climate* 3(10):e0000281. <https://doi.org/10.1371/JOURNAL.PCLM.0000281>
7. Cooper C, Cunningham N, Bracken LJ, Collier M (2024) Distribution of nature-based solutions in cities across Europe. *Land Use Policy* 141:107160. <https://doi.org/10.1016/J.LANDUSPOL.2024.107160>
8. Bona S, Rodrigues F, Gomes R, Silva-Afonso A (2024) Nature-based solutions for water resilience in thriving European urban areas. *Urban Water J* 1–14. <https://doi.org/10.1080/1573062X.2024.2359661>
9. Bona S, Silva-Afonso A, Gomes R, Pimentel-Rodrigues C, Rodrigues F (2025) From nearly zero water buildings to urban water communities. *Appl Sci* 15(5):2566. <https://doi.org/10.3390/APP15052566>
10. Bona S, Silva-Afonso A, Gomes R, Matos R, Rodrigues F (2022) Nature-based solutions in urban areas: a European analysis. *Appl Sci* 13(1):168. <https://doi.org/10.3390/APP13010168>
11. Carvalho PN et al (2022) Nature-based solutions addressing the water-energy-food nexus: review of theoretical concepts and urban case studies. *J Clean Prod* 338:130652. <https://doi.org/10.1016/J.JCLEPRO.2022.130652>
12. European Commission. (2025). Water-energy-food-ecosystem Nexus. Last accessed on 2025/03/05. https://international-partnerships.ec.europa.eu/policies/climate-environment-and-energy/water-energy-food-ecosystem-nexus_en
13. Li Y, Zhang R (2023) A review of water-energy-food nexus development in a just energy transition. *Energies* 16(17):6253. <https://doi.org/10.3390/EN16176253>
14. Bush J, Doyon A (2019) Building urban resilience with nature-based solutions: cities 95:102483. <https://doi.org/10.1016/j.cities.2019.102483>
15. Mguni P et al (2020) What could go wrong with cooking? Exploring vulnerability at the water, energy and food nexus in Kampala through a social practices lens. *Glob Environ Chang* 63:102086. <https://doi.org/10.1016/J.GLOENVCHA.2020.102086>
16. Soares RB, Memelli MS, Roque RP, Gonçalves RF (2017) Comparative analysis of the energy consumption of different WTP. *Int J Arch Arts Appl* 3(6):79–86. <https://doi.org/10.11648/J.IJAAA.20170306.11>
17. Remy C, Jekel M (2012) Energy analysis of conventional and source-separation systems for urban wastewater management using life cycle assessment. *Water Sci Technol* 65(1):22–29. <https://doi.org/10.2166/WST.2011.766>
18. Chiu YR, Tsai YL, Chiang YC (2015) Designing rainwater harvesting systems cost-effectively in an urban water-energy saving scheme by using a GIS-simulation based design system. *Water* 7(11):6285–6300. <https://doi.org/10.3390/W7116285>
19. ERSAR (2025). Relatório Anual dos Serviços de Águas e Resíduos em Portugal (RASARP 2024). Volume 1—Caraterização do setor de águas e resíduos
20. Cureau RJ, Ghisi E (2020) Electricity savings by reducing water consumption in a whole city: a case study in Joinville, Southern Brazil. *J Clean Prod* 261:121194. <https://doi.org/10.1016/J.JCLEPRO.2020.121194>

21. Savić S, Krstić H, Šećerov I, Dunjić J (2024) Decreasing the energy demand in public buildings using nature-based solutions: Novi Sad and Osijek. *Energy Sustainability and Society* 14(1):1–15. <https://doi.org/10.1186/S13705-024-00455-2/FIGURES/7>
22. He Q, Tapia F, Reith A (2023) Quantifying the influence of nature-based solutions on building cooling and heating energy demand: a climate-specific review. *Renew Sust Energ Rev* 186:113660. <https://doi.org/10.1016/J.RSER.2023.113660>
23. Neumann J, Scheid C, Dittmer U (2024) Potential of decentral nature-based solutions for mitigation of pluvial floods in urban areas—a simulation study based on 1D/2D coupled modeling. *Water* 16(6):811. <https://doi.org/10.3390/W16060811>
24. Decree Law No. 101-D/2020—Defines the requirements applicable to the design and renovation of buildings. Republic Diary—Presidency of the Council of Ministers, 2020
25. Government Order No. 138-I/2021—Regulates minimum energy performance requirements. Republic Diary, 2021—Ambiente e Ação Climática e Infraestruturas e Habitação
26. Rasheed DH, Tambe SB (2024) Advancing energy efficiency with smart grids and IoT-based solutions for a sustainable future. *ESTIDAMAA* 2024:36–42. <https://doi.org/10.70470/ESTIDAMAA/2024/006>
27. Ascenso A et al (2021) Impacts of nature-based solutions on the urban atmospheric environment: a case study for Eindhoven, The Netherlands. *Urban For Urban Green* 57:126870. <https://doi.org/10.1016/J.UFUG.2020.126870>
28. Toboso-Chavero S et al (2019) Towards productive cities: environmental assessment of the food-energy-water nexus of the urban roof mosaic. *J Ind Ecol* 23(4):767–780. <https://doi.org/10.1111/JIEC.12829>
29. Skodra J, Zorita S, Garcia Perez I, Moebus S (2020) Co-creating nature-based solutions for healthy and sustainable cities: urban public health approach. *Eur J Pub Health* 30(supplement_5). <https://doi.org/10.1093/eurpub/ckaa165.234>

Green Roofs and Green Walls for Adapting to Urban Heat Islands and Reducing Building Energy Consumption



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Abstract The rapid growth of the urban population and the increasing densification of the built environment have led to a significant rise in urban air temperatures compared to rural areas, a phenomenon known as the urban heat island. During summer, this urban warming drives energy demand for cooling, as buildings strive to maintain comfortable indoor temperatures. Building Integrated Vegetation Technologies (BIVTs), such as green roofs and green walls, can mitigate extreme summer temperatures in urban environments and influence building energy use to varying extents, depending on the geometric characteristics of the buildings and the specific BIVT applied. This study investigates the effects of green roof-, green façade-, and living wall-based scenarios on urban air temperatures, aiming to identify which BIVT is most effective in reducing urban overheating under different conditions. Additionally, the study evaluates the potential of these BIVTs to influence building energy consumption. The research focuses on three Mediterranean cities: Rome, Bari, and Florence. Within these cities, urban areas with distinct building arrangements—scattered, arrayed, and enclosed—were selected to broaden the applicability of the findings. The urban areas share a similar background climate (Csa) according to the Köppen-Geiger classification. Two hundred and eighty-one BIVT-based scenarios were developed and modeled using ENVI-met software to explore which technologies and configurations offer the greatest urban air temperature reductions. Furthermore, the impact of BIVTs on building energy use was evaluated using Energy-Plus software. The results of this study will provide valuable insights into the most promising BIVTs for enhancing urban and building sustainability.

Keywords Urban heat island adaptation · Building energy efficiency · Building integrated vegetation technologies

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1 Introduction

Urban overheating, resulting from substituting natural materials with artificial ones and rural landscapes with urban settlements [1], is a significant global concern. Both large- and medium-sized cities (e.g., [2]) are increasingly affected by this phenomenon, and its consequences are well-documented: elevated mortality and morbidity rates, especially among vulnerable populations (e.g., [3]), increased building energy demand for cooling during summer (e.g., [4, 5]), and ecosystem degradation (e.g., [6]). A considerable body of research has already investigated the installation of building-integrated vegetation technologies (BIVTs), such as green roofs and green walls (GWs), as a strategy to mitigate the urban heat island (UHI) and its adverse impacts (e.g., [7–10]). However, the simultaneous effects of green roofs and GWs on urban microclimate and building energy use have received limited attention in the literature.

This gap is due to: (1) the requirement for specialized expertise in microclimate simulations, substantial computational resources, data, and time for running simulations, and (2) the lack of integrated tools within simulation software capable of assessing the impact of BIVT installation on building energy demand. For instance, EnergyPlus includes a module to assess the green roof installation effect but omits those related to GWs.

This study seeks to address these limitations and, most importantly, to provide valuable insights for urban planners and decision-makers interested in optimizing the benefits of BIVTs, either by reducing building energy needs or enhancing UHI adaptation.

2 Materials and Methods

2.1 Microclimate Evaluations

The impact of BIVTs on the urban microclimate was assessed using ENVI-met software, a dynamic microclimate simulation tool [11]. A total of 281 scenarios were developed and simulated to evaluate and compare the effects of BIVT installation on the urban climate during a typical summer day. Specifically, the study investigated the effects of extensive green roofs (EGR), green façades (GFs), and living walls (LWs). Simulations were conducted for three urban areas in three cities in the Mediterranean climate (i.e., Csa) [12]: Rome, Bari, and Florence. The three urban areas were characterized by different layouts: scattered (Rome), arrayed (Bari), and enclosed (Florence). These urban layouts were selected to represent the most common urban configurations, thus enhancing the generalizability of the results. The most influential factors for UHI adaptation were identified through a review of the published literature. The study found that building height (BH), leaf area index (LAI), and percentage of coverage (COP) of plant species are the most important

factors influencing UHI adaptation [13]. Scenarios were developed for each of the three areas, considering the application of a BIVT in each case, with variations in BH (5, 10, 20, 30, and 40 m), LAI (1.5, 3, and 5), and the COP of the green roof and wall plant species (25, 50, 75, and 100%). Detailed information on the developed scenarios and their results can be found in [13, 14].

First, the results of 117 scenarios—18 control scenarios and 99 adaptation scenarios—were analyzed to identify which factors among the three identified ones most significantly influence the UHI adaptation potential of the investigated BIVTs. The Analytic Hierarchy Process (AHP) methodology was employed to establish the hierarchy of the three factors. Subsequently, the number of simulations was increased from 117 to 281 to develop a simple tool capable of predicting UHI adaptation values. Specifically, all 281 simulation results were input into regression models, from which predictive indices were developed. The indices were developed for urban areas with an urban density ranging between 0.3 and 0.4, located in the Csa climate.

2.2 Energy Evaluations

To address the lack of tools with appropriate modules for calculating the impact of GW installation on building energy demand, we employed a Python-based module developed by Politecnico di Torino, which accounts for the effects of GW installation on building energy use. Further details can be found in [15]. DesignBuilder was used for urban area modeling and for modeling a specific building within the selected areas (see Fig. 1). EnergyPlus v23.2 was employed to simulate the building energy behavior within the urban areas.

For the modeling, materials for each building were first modeled and added to the database. These materials were consistent across both the climatic and energy models used in the simulations. Twelve scenarios were developed: three baseline scenarios—one for each urban area—and, for each selected building, one scenario with the EGR application, one with the application of GFs, and one with the application of LWs.

The energy behaviors of the three buildings were simulated using the Test Reference Year [16] climate file for Bari and Florence, and the IWEC climate file for Rome. For all the simulation scenarios, a year-round LAI equal to five and a COP of 100%

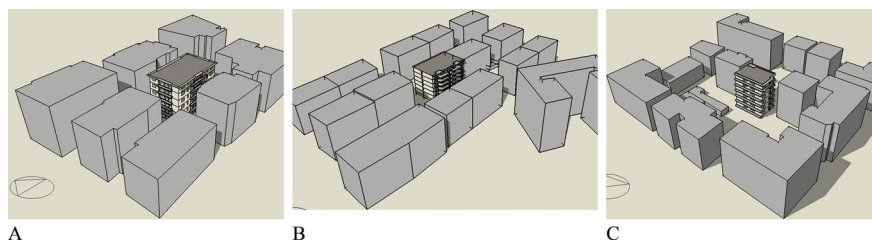


Fig. 1 Models of the urban areas in Rome (a), Bari (b), and Florence (c)

were applied to simulate the presence of perennial vegetation species. Furthermore, heating and cooling set-points of 20 °C and 25 °C, respectively, were selected.

3 Results

Comparing the results of the 99 UHI adaptation scenarios with the 18 baseline ones, the difference in spatial mean temperature was calculated for the three urban areas. Such data was used to define which factors, among BH, COP, and LAI, for each BIVT-based adaptation scenario, influence the adaptation potential the most (more details can be found in [13]). Specifically, the UHI mitigation potential of scenarios based on the application of EGR, GF, or LW was calculated at 2:00 pm, the time of the day when the UHI is the most pronounced in the three cities, and at pedestrian level (i.e., at 1.5 m above ground). It was found that the UHI adaptation potential of EGR-based scenarios in urban areas with a Csa climate decreases with increasing BH, while it rises with the increase in COP and LAI. The adaptation potential of GF-based scenarios increases with higher BH up to a height of 20 m; then, it grows further, but the growth is less steep. The adaptation potential increases linearly with the increase in the COP and LAI; however, the adaptation potential corresponding to LAI 1.5 is almost negligible. Regarding LW-based adaptation scenarios, their potential increases with increasing BH up to a height of 20 m, after which it plateaus. Furthermore, the adaptation potential of LW-based plans increases linearly with the increase in COP and LAI (see [13]).

Besides, the results of the 281 simulations were used for calculating the mean adaptation potential of the BIVT-based scenarios compared to the baseline ones, to feed a regression model, and to extract the following predictive indices (more details in [14]):

$$I_{EGR} = -0.0784 - 0.0016COP + 0.0722 \ln(BH) - 0.0177LAI \quad (1)$$

$$I_{GF} = -0.0269 - 0.0012COP + 123.3e^{-4.5LAI} \quad (2)$$

$$I_{LW} = -0.0014COP + 67.55e^{-4.5LAI} \quad (3)$$

Equation (1) encompasses all three factors (i.e., BH, COP, and LAI) because all of them are significant when considering the adaptation potential of EGR-based plans. In contrast, the predictive indices for the adaptation potential of GF and LW-based scenarios only include COP and LAI, as BH is not significant. The developed indices greatly ease the work of urban decision-makers since they need no specific knowledge and a limited amount of input data. From the energy perspective, we found that the BIVT application can reduce energy use to varying extents (Table 1).

Table 1 shows the normalized building energy needs with the limitations imposed by the Italian national law [17]: for Rome and Florence, the heating period starts on

Table 1 Normalized building energy need [kWh/m²] (“-” means energy needs for cooling “+” for heating)

Urban area	Scenario	Jan	Feb	March	April	May	June	July	Aug	Sept	Oct	Nov	Dec
Rome	Baseline	+ 10.53	+ 8.09	+ 6.12	+ 2.09	- 0.01	- 0.61	- 3.77	- 3.44	- 0.98	- 0.05	+ 4.82	+ 9.01
	EGR	+ 8.80	+ 6.59	+ 4.65	+ 1.41	- 0.03	- 0.97	- 4.43	- 4.04	- 1.41	- 0.15	+ 3.72	+ 7.47
	GF	+ 10.54	+ 8.09	+ 6.13	+ 2.10	- 0.01	- 0.60	- 3.76	- 3.43	- 0.98	- 0.05	+ 4.83	+ 9.01
	LW	+ 8.54	+ 6.38	+ 4.44	+ 1.31	- 0.20	- 1.84	- 5.51	- 5.38	- 2.13	- 0.37	+ 3.31	+ 7.19
Bari	Baseline	+ 10.75	+ 10.61	+ 8.54	0.00	0.00	- 0.17	- 1.05	- 0.75	- 0.20	0.00	+ 4.05	+ 9.79
	EGR	+ 8.51	+ 8.42	+ 6.42	0.00	0.00	- 0.35	- 1.61	- 1.29	- 0.31	0.00	+ 3.06	+ 7.66
	GF	+ 10.75	+ 10.61	+ 8.55	0.00	0.00	- 0.16	- 1.05	- 0.75	- 0.20	0.00	+ 4.05	+ 9.79
	LW	+ 8.78	+ 8.63	+ 6.42	0.00	- 0.13	- 1.34	- 3.66	- 3.19	- 0.92	0.00	+ 3.15	+ 7.87
Florence	Baseline	+ 15.25	+ 13.32	+ 9.12	+ 3.72	- 0.02	- 1.07	- 2.54	- 1.89	- 0.02	0.00	+ 8.07	+ 14.68
	EGR	+ 13.08	+ 11.36	+ 7.43	+ 2.89	- 0.04	- 1.36	- 3.30	- 2.46	- 0.04	0.00	+ 6.66	+ 12.71
	GF	+ 15.26	+ 13.33	+ 9.14	+ 3.73	- 0.02	- 1.05	- 2.51	- 1.87	- 0.02	0.00	+ 8.08	+ 14.69
	LW	+ 10.39	+ 8.77	+ 4.47	+ 1.46	- 1.87	- 5.40	- 9.15	- 8.05	- 1.93	- 0.09	+ 4.68	+ 9.95

November 1st and ends on April 15th, while for Bari, it starts on November 15th and ends on March 31st.

4 Discussion

To our knowledge, only a few studies have simultaneously focused on the interaction between BIVTs, pedestrian-level air temperature, and building energy demand using appropriate simulation tools. For instance, Costanzo et al. [18] and Mutani and Todeschi [19] limit their analysis to the effects of green roofs. Many studies separately investigate the urban and building scales (e.g., [20–24]). Furthermore, other studies examine both scales by reviewing the published literature (e.g., [8, 25–27]). In contrast, the proposed study reports on the mean UHI mitigation potential of EGR, GF, and LW-based adaptation scenarios and the effect on building energy needs. Regarding the urban scale, this study proposes a tool to assess the UHI mitigation potential of adaptation scenarios. To date, no tools like the one developed in this study have been created. Specifically, Djeddjig et al. [28] and Alexandri and Jones [29] report the development of tools to predict air temperature variation in urban canyons rather than the mean temperature variation across the entire urban area. Other studies limited the validity of the prediction tool to the rooftop level (e.g., [30–32]). Furthermore, the present study uses EnergyPlus, implemented with a Python module, to evaluate the effect of EGRs, GFs, and LWs on the building energy use of three buildings: one in Rome, one in Bari, and the last one in Florence. The results show that both EGRs and LWs reduce annual energy needs; besides, GF implementation slightly increases energy use for heating and reduces it for cooling, resulting in a net-zero variation. In literature, it has been found that EGRs can reduce both heating and cooling energy demand [8]. The difference between the thermal behavior of the EGR modeled in the present study and that reported in the literature is likely due to differences in EGR modeling, such as the amount of water used for irrigation, soil thickness, or vegetation type. The installation of LWs produces a decrease in heating energy needs ranging from about 20 to 40% and an increase in cooling energy demand from about 74 to 380%. The decrease in heating energy demand is consistent with the average values found for the Csa climate zone. Still, the increase in cooling energy needs is opposite to the results found in a literature review [25]. Regarding GFs, we found a negligible increase in heating energy demand ranging from 0.03 to 0.10% and a limited decrease in cooling energy demand, ranging from 0.4 to 1.1%. Such results are consistent with those shown in [25]. The lack of irrigation justifies the limited decrease in cooling energy demand. Further simulations will be carried out to investigate how the increase in watering can affect building energy demand.

5 Conclusions

The present study investigates the potential of BIVTs in affecting urban climate and building energy demand. The study focuses on the Csa climate, and three urban areas characterized by different arrangements. For the three urban areas, 281 scenarios were developed and run in ENVI-met. The scenarios were developed by modifying the BH, COP, and LAI parameters. The results were analyzed first using the AHP methodology and then with a regression model. Within the selected urban areas, three buildings were chosen, one for each area, and 12 scenarios (i.e., a baseline scenario and one scenario for the implementation of each BIVT) were developed and run in EnergyPlus. We obtained: (i) the weights related to the BH, COP, and LAI factors for plans based on a single BIVT application. The weights reflect the importance that each parameter assumes when BIVT-based scenarios are applied to urban areas to adapt to UHI; (ii) a parametric tool, easy to use, to assess the adaptation potential of BIVT-based plans; (iii) insights about the effect of BIVT implementation on buildings in Csa climate on their energy use. The results support urban planners and decision-makers who want to develop and implement efficient UHI adaptation plans providing guidance about the most effective BIVT to install depending on the urban context. For instance, EGR-based scenarios have a limited adaptation potential when buildings are 20 m or higher; in that case, GF and LW-based plans can be more successful. Also, the mean UHI adaptation is limited for plans based on a single BIVT implementation, thus, the application of plans based on multiple adaptation strategies can more successfully decrease urban overheating [33]. The energy analyses showed that EGRs can effectively reduce building energy use for heating and increase it for cooling. To optimize the effect of EGRs, plant watering should be increased in summer to transform sensible heat into latent heat. In contrast, GF implementation decreases building energy needs for summer cooling and increases heating energy demand. To improve the effect of GF implementation, deciduous plants should be preferred over evergreen ones. Lastly, the LW application entails a decrease and an increase in building energy needs for heating and cooling, respectively. LW optimization should focus on increasing plant watering in summer to decrease surface temperature and ease heat dissipation through the building envelope.

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References

1. Landsberg HE (1981) The urban climate. Academic Press
2. Susca T (2022) Nature-based solutions applied to the built environment to alleviate climate change: benefits, co-benefits, and trade-offs in a geographical multi-scale perspective. In:

- Lackner M, Sajjadi B, Chen W-Y (eds) Handbook of climate change mitigation and adaptation. Springer International Publishing, Cham, pp 2117–2167. https://doi.org/10.1007/978-3-030-72579-2_123
3. Huang WTK, Masselot P, Bou-Zeid E, Fatichi S, Paschalis A, Sun T et al (2023) Economic valuation of temperature-related mortality attributed to urban heat islands in European cities. *Nat Commun* 14:7438. <https://doi.org/10.1038/s41467-023-43135-z>
 4. Romitti Y, Sue Wing I (2022) Heterogeneous climate change impacts on electricity demand in world cities circa mid-century. *Sci Rep*:12. <https://doi.org/10.1038/s41598-022-07922-w>
 5. Santamouris M, Cartalis C, Synnefa A, Kolokotsa D (2015) On the impact of urban heat Island and global warming on the power demand and electricity consumption of buildings—a review. *Energ Build* 98:119–124. <https://doi.org/10.1016/j.enbuild.2014.09.052>
 6. Chessa C, Susca T (2023) Development of an LCA characterization factor to account UHI local effect on terrestrial ecosystems damage category: evaluation of European *Bombus* and *Onthophagus* genera heat-stress mortality. *Sci Total Environ* 897:165183. <https://doi.org/10.1016/j.scitotenv.2023.165183>
 7. Susca T, Zanghirella F, Del Fatto V (2023) Building integrated vegetation effect on micro-climate conditions for urban heat Island adaptation. Lesson learned from Turin and Rome case studies. *Energ Build* 295:113233. <https://doi.org/10.1016/j.enbuild.2023.113233>
 8. Susca T (2019) Green roofs to reduce building energy use? A review on key structural factors of green roofs and their effects on urban climate. *Build Environ* 162:106273. <https://doi.org/10.1016/j.buildenv.2019.106273>
 9. Adilkhanova I, Santamouris M, Yun GY (2024) Green roofs save energy in cities and fight regional climate change. *Nat Cities* 1:238–249. <https://doi.org/10.1038/s44284-024-00035-7>
 10. Visvanathan G, Patil K, Suryawanshi Y, Meshram V, Jadhav S (2024) Mitigating urban heat Island and enhancing indoor thermal comfort using terrace garden. *Sci Rep* 14:9697. <https://doi.org/10.1038/s41598-024-60546-0>
 11. ENVI_MET. ENVI_MET. Microclimate simulations | ENVI_MET 2019. <https://www.envi-met.com/intro/>. Accessed on 21 Jan 2019
 12. Kottek M, Grieser J, Beck C, Rudolf B, Rubel F (2006) World map of the Köppen-Geiger climate classification updated. *Metz* 15:259–263. <https://doi.org/10.1127/0941-2948/2006/0130>
 13. Iaria J, Susca T (2022) Analytic hierarchy processes (AHP) evaluation of green roof- and green wall- based UHI mitigation strategies via ENVI-met simulations. *Urban Clim* 46:101293. <https://doi.org/10.1016/j.uclim.2022.101293>
 14. Susca T, Iaria J, Zanghirella F (2024) Development of predictive indices for evaluating the UHI adaptation potential of green roof- and wall-based scenarios in the Mediterranean climate. *Sci Rep* 14:21675. <https://doi.org/10.1038/s41598-024-67567-9>
 15. Nesci V, Ballarini I, Rando Mazzarino P, Corrado V (2024) Living walls and green façades: an implementation code for energy simulation. *Buildings* 14:2040. <https://doi.org/10.3390/buildings14072040>
 16. CTI Comitato Termotecnico Italiano—Vendita documenti Normativi n.d. <https://try.cti2000.it/>. Accessed 6 Mar 2025
 17. Gazzetta Ufficiale. DECRETO DEL PRESIDENTE DELLA REPUBBLICA 16 aprile 2013, n. 74 2013. <https://www.gazzettaufficiale.it/eli/id/2013/06/27/13G00114/sq>. Accessed on 11 Mar 2025
 18. Costanzo V, Evola G, Marletta L (2016) Energy savings in buildings or UHI mitigation? Comparison between green roofs and cool roofs. *Energ Build* 114:247–255. <https://doi.org/10.1016/j.enbuild.2015.04.053>
 19. Mutani G, Todeschi V (2020) The effects of green roofs on outdoor thermal comfort, urban Heat Island mitigation and energy savings. *Atmosphere* 11:123. <https://doi.org/10.3390/atmos11020123>
 20. Abu QJ (2024) Energy efficiency evaluation of green roofs as a passive strategy in the mediterranean climate. *Results Eng* 23:102519. <https://doi.org/10.1016/j.rineng.2024.102519>
 21. Dahanayake KC, Chow CL (2018) Comparing reduction of building cooling load through green roofs and green walls by EnergyPlus simulations. *Build Simul* 11:421–434. <https://doi.org/10.1007/s12273-017-0415-7>

22. Barriuso F, Urbano B (2021) Green roofs and walls design intended to mitigate climate change in urban areas across all continents. *Sustainability* 13:2245. <https://doi.org/10.3390/su13042245>
23. Yang J, Mohan Kumar DL, Pyrgou A, Chong A, Santamouris M, Kolokotsa D et al (2018) Green and cool roofs' urban heat Island mitigation potential in tropical climate. *Sol Energy* 173:597–609. <https://doi.org/10.1016/j.solener.2018.08.006>
24. Susca T, Gaffin SR, Dell'Oso GR (2011) Positive effects of vegetation: urban heat Island and green roofs. *Environ Pollut* 159:2119–2126. <https://doi.org/10.1016/j.envpol.2011.03.007>
25. Susca T, Zanghirella F, Colasuonno L, Del Fatto V (2022) Effect of green wall installation on urban heat Island and building energy use: a climate-informed systematic literature review. *Renew Sust Energ Rev* 159:112100. <https://doi.org/10.1016/j.rser.2022.112100>
26. Nasr Y, El Zakhem H, Hamami AEA, El Bachawati M, Belarbi R (2024) Comprehensive assessment of the impact of green roofs and walls on building energy performance: a scientific review. *Energies* 17:5160. <https://doi.org/10.3390/en17205160>
27. Bevilacqua P (2021) The effectiveness of green roofs in reducing building energy consumptions across different climates. A summary of literature results. *Renew Sust Energ Rev* 151:111523. <https://doi.org/10.1016/j.rser.2021.111523>
28. Djedjig R, Bozonnet E, Belarbi R (2016) Modeling green wall interactions with street canyons for building energy simulation in urban context. *Urban Clim* 16:75–85. <https://doi.org/10.1016/j.uclim.2015.12.003>
29. Alexandri E, Jones P (2008) Temperature decreases in an urban canyon due to green walls and green roofs in diverse climates. *Build Environ* 43:480–493. <https://doi.org/10.1016/j.buildenv.2006.10.055>
30. Yang J, Wang Z-H (2014) Physical parameterization and sensitivity of urban hydrological models: application to green roof systems. *Build Environ* 75:250–263. <https://doi.org/10.1016/j.buildenv.2014.02.006>
31. Suter I, Maksimović Č, van Reeuwijk M (2017) A neighbourhood-scale estimate for the cooling potential of green roofs. *Urban Clim* 20:33–45. <https://doi.org/10.1016/j.uclim.2017.02.007>
32. Mazzeo D, Matera N, Peri G, Scaccianoce G (2023) Forecasting green roofs' potential in improving building thermal performance and mitigating urban heat Island in the Mediterranean area: an artificial intelligence-based approach. *Appl Therm Eng* 222:119879. <https://doi.org/10.1016/j.applthermaleng.2022.119879>
33. Zhao Y, Sen S, Susca T, Iaria J, Kubilay A, Gunawardena K et al (2023) Beating urban heat: multimeasure-centric solution sets and a complementary framework for decision-making. *Renew Sust Energ Rev* 186:113668. <https://doi.org/10.1016/j.rser.2023.113668>

Building Integrated Vegetation Technologies and Their Impact on Building Energy Consumption: The Role of Leaf Area Index (LAI)



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Abstract Urban overheating, a phenomenon primarily driven by the replacement of natural materials with artificial ones, disrupts the natural heat balance in both medium- and large-sized cities. In the European Union, approximately 75% of buildings exhibit poor energy performance, leading to increased energy demand for summer cooling. Consequently, the heat released by cooling systems further exacerbates the urban heat Island (UHI) effect, creating a vicious cycle. Numerous studies have shown that Building Integrated Vegetation Technologies (BIVTs), such as green roofs and green walls, can simultaneously reduce building energy consumption and mitigate the UHI effect. Vegetation reduces the solar energy absorbed by building surfaces by providing shade and reflecting incoming radiation. Additionally, evapotranspiration lowers near-surface air temperatures, reducing heat exchange between the air and building envelopes. However, the effectiveness of BIVTs in reducing building energy use, mainly in summer, is influenced by building geometry, orientation, local climate, substrate thickness, coverage percentage, and leaf area index (LAI). This study explores the impact of LAI variations on building energy consumption through detailed investigations of extensive green roofs, green façades, and living walls. Year-round energy simulations were conducted using EnergyPlus software, considering three different LAI levels: low, medium, and high. The simulations were performed for a single residential building in a Mediterranean climate. BIVTs can reduce the annual energy demand by ~ 20% and can be higher when deciduous plant species are used. The results emphasize the influence of LAI on cooling building energy, offering valuable insights for policymakers involved in developing adaptation and mitigation strategies.

Keywords Building energy efficiency · Leaf area index · Building integrated vegetation technologies

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1 Introduction

Building Integrated Vegetation Technologies (BIVTs), such as green roofs and green walls, are nature-based solutions applied to the building envelopes. BIVTs have been extensively studied due to the multiple benefits of their implementation within the built environment. For instance, green roofs were well-known and widespread in vernacular architecture; in Scandinavia, Turkey, and Iran, populations historically utilized turf as an inexpensive building material to cover the roofs of their houses and keep them warm. Subsequently, BIVTs gained momentum driven by ecological movements [1], since green roofs and walls can contribute to restoring ecosystem quality [2], provide ecosystem services [3], reduce urban overheating, and affect building energy demand [4, 5]. This latter topic is especially relevant today, as 75% of buildings in the EU exhibit poor energy performance [6], necessitating building retrofits. However, the increasing use of thermal insulation materials derived from petrochemical products can shift the impacts related to the life cycle of a building from the use phase to the refurbishment phase. A plethora of studies demonstrated that the deployment of BIVTs, if correctly designed, can reduce building energy use [4, 5] depending on several factors such as background climate [7], percentage of coverage, substrate composition and thickness, vegetation species, watering, and leaf area index (LAI) (e.g., [8–11]), to name a few. Furthermore, BIVTs can provide additional, often harder-to-quantify co-benefits, such as carbon sequestration and beautification (e.g., [11–15]).

The present study explores the effect of plant LAI implemented on extensive green roofs (EGRs), green façades (GFs), and living walls (LWs) on building energy use.

2 Materials and Methods

To evaluate the effect of the LAI of BIVTs on building energy needs, we simulated the energetic behavior of three buildings in a Csa climate zone. Specifically, three residential buildings in different urban layouts have been modeled and simulated in EnergyPlus using the Bari test reference year [16]. The three urban areas are characterized by different urban patterns: scattered, arrayed, and enclosed. These urban layouts were selected to represent the most common urban configurations, thus enhancing the generalizability of the results (Fig. 1).

EnergyPlus software was employed to assess the impact of BIVT installation on building energy use. Specifically, EnergyPlus was used to assess the effect of EGR implementation on buildings; however, the effect of green walls was assessed using a Python module implemented in EnergyPlus v23.2, developed by Politecnico di Torino (see [17]), since EnergyPlus *per se* does not account for the energetic impact of green walls. The effect of BIVT installation was assessed considering three different LAI: low (i.e., LAI 1.5), medium (i.e., LAI 3), and high (i.e., LAI 5). For the energy simulations, it was assumed that the plant species' coverage percentage was

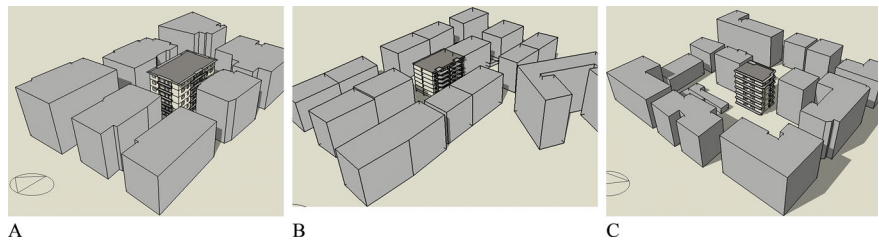


Fig. 1 Building models within their urban layouts: scattered (a), arrayed (b), and enclosed (c)

100%. A total of 30 scenarios were developed and run. For each selected building 10 scenarios were developed: a baseline scenario; three scenarios with the application of an EGR and LAI 1.5, 3, and 5; three scenarios with the application of GFs and LAI 1.5, 3, and 5; three scenarios with the application of LWs and LAI 1.5, 3, and 5. In all the BIVT-based scenarios, perennial plant species were considered, thus, the LAI was considered constant year-round. For the modeling process, materials for each building [18, 19] were first modeled and added to the database. For the simulations, heating and cooling set points of 20 °C and 25 °C, respectively, were selected. The selected buildings within the scattered and arrayed urban layouts are both 20 m high, while the chosen building, within the enclosed urban setting, is 15 m high. The stratigraphies and thermophysical characteristics of opaque envelopes were taken from the abacus published by UNI [20]. Table 1 reports the data related to the envelope surfaces of the selected buildings and the surface areas related to green wall and EGR implementation. The energy simulation was carried out year-round.

Table 1 Data related to the building envelope areas and the BIVT areas

Building	Net above-ground wall area ^a [m ²]	Window opening area [m ²]	Green wall area [m ²]	Green wall area/net above-ground wall area ratio (%)	Roof area [m ²]	EGR/roof area ratio (%)
Scattered	1828.11	471.00	1828.11	100	433.23	100
Arrayed	1983.88	332.94	1551.77	78	681.13	100
Enclosed	1164.86	187.17	936.06	80	176.43	100

^aThe net above-ground wall area is equal to the gross above-ground wall area minus the window opening area

3 Results

To evaluate the effect of BIVT implementation on building energy needs in Bari, cooling and heating energy demands were first calculated for the baseline scenario (i.e., a scenario without any BIVT). The annual heating period imposed by the Italian National law [21] was considered for the heating energy use calculation; for Bari, the heating period starts on November 15 and ends on March 31. Then, the energy needs, in terms of useful energy, related to the BIVT-implemented scenarios were compared with the baseline scenarios. Table 2 shows the difference in cooling and heating energy needs between the BIVT-implemented scenarios and the baseline ones.

4 Discussion

The results of the energy simulations for three buildings within three urban layouts in Bari—Csa climate zone—reported in Table 2, show that for all scenarios, the installation of EGR entails an increase in the building energy needs for cooling and a decrease in building energy needs for heating. Specifically, we found that EGR implementation increases building energy needs for cooling by approximately 30–65%; in winter, the heating energy needs are abated by 14–22%. The results related to the increase in building energy needs for cooling contrast with previous studies [22, 23] that show that green roof installation on buildings in the Mediterranean climate entails a decrease in energy consumption. However, the results depend on several factors that may differ among the studies, such as irrigation, precipitation, substrate thickness, plant selection, and software release. For instance, the increase in irrigation may play a crucial role in enhancing the thermal performance of the EGRs in Mediterranean climate cities [24]. The outcomes also show that, both in the cooling and in the heating period, the variation in LAI on EGRs does not impact building energy needs (Table 2).

Regarding GFs, the simulation results show that for all the investigated case studies, GF installation entails a decrease in building cooling energy needs ranging from approximately 0.3 to 0.9%. Besides, in winter, the shading provided by the leaves decreases solar gains, increasing the heating energy demand. Such an increase is modest, though, and ranges from 0.02 to 0.06%. For GFs, the results show that the increase in LAI impacts the energy demand; specifically, in winter, the increase in LAI increases the building energy needs for heating, and in summer, LAI 5 corresponds to the highest decrease in building cooling energy. Comparing the energy demeanor of green walls in literature is a tricky issue since no commercial software integrates green wall performance in energy balance; nevertheless, some attempts to implement modules in software capable of simulating the green wall thermal behavior have been made [25–28]. In accordance with the results in Table 2, Susca et al. [5] found that GFs decrease building energy demand for cooling by about 34%. In contrast, we found

Table 2 Percentage of the difference between the building energy needs of the scenarios implemented with BIVTs and the baseline ones

Scenario	LAI	$\Delta\%$ Cooling needs ^a (%)	$\Delta\%$ Heating needs (heating period) ^a (%)	$\Delta\%$ Total energy needs ^a (%)
Scattered EGR	5	+ 30.87	– 17.28	– 11.48
Scattered EGR	3	+ 31.45	– 17.21	– 11.35
Scattered EGR	1.5	+ 30.96	– 17.22	– 11.42
Scattered GF	5	– 0.49	+ 0.04	– 0.03
Scattered GF	3	– 0.44	+ 0.03	– 0.02
Scattered GF	1.5	– 0.34	+ 0.03	– 0.02
Scattered LW	5	+ 169.58	– 21.90	+ 1.17
Scattered LW	3	+ 165.56	– 21.75	+ 0.81
Scattered LW	1.5	+ 161.66	– 21.59	+ 0.48
Arrayed EGR	5	+ 63.63	– 22.11	– 18.05
Arrayed EGR	3	+ 61.41	– 21.94	– 17.99
Arrayed EGR	1.5	+ 64.56	– 22.00	– 17.90
Arrayed GF	5	– 0.73	+ 0.03	0.00
Arrayed GF	3	– 0.67	+ 0.03	0.00
Arrayed GF	1.5	– 0.53	+ 0.02	0.00
Arrayed LW	5	+ 324.74	– 20.32	– 3.99
Arrayed LW	3	+ 315.86	– 20.18	– 4.27
Arrayed LW	1.5	+ 306.89	– 20.02	– 4.55
Enclosed EGR	5	+ 29.51	– 14.32	– 10.55
Enclosed EGR	3	+ 30.12	– 14.28	– 10.45
Enclosed EGR	1.5	+ 29.43	– 14.29	– 10.52
Enclosed GF	5	– 0.91	+ 0.06	– 0.02
Enclosed GF	3	– 0.83	+ 0.06	– 0.02
Enclosed GF	1.5	– 0.64	+ 0.04	– 0.02
Enclosed LW	5	+ 349.00	– 31.09	+ 1.65

(continued)

Table 2 (continued)

Scenario	LAI	$\Delta\%$ Cooling needs ^a (%)	$\Delta\%$ Heating needs (heating period) ^a (%)	$\Delta\%$ Total energy needs ^a (%)
Enclosed LW	3	+ 340.05	– 30.88	+ 1.07
Enclosed LW	1.5	+ 331.38	– 30.72	+ 0.47

^a“–” means a decrease in energy need compared to the baseline scenario, besides “+” means an increase in energy need compared to the baseline scenario

that, in winter, the building energy needs slightly increase; previous research shows an average, although modest, decrease, equal to 0.8%, in building energy demand [5]. The increase in building energy for heating can be understandable, though, since the shadowing provided by the foliage limits the solar gains in winter, resulting in a penalty compared to the baseline scenario. A future study will look at the adoption of deciduous plants, with seasonal changes in LAI.

Lastly, the simulation results show that LW installation determines a high increase in the building energy demand for cooling, ranging from 160 to 350% (Table 2). This increase is proportional to the surface area covered with vegetation (Table 1). The increase in cooling energy demand found in the present study is in contrast with the experimental result found in a previous study focused on LWs in Puigverd de Lleida, Spain [29, 30], which shows a decrease in cooling energy demand ranging from about 31 to 59%. The discrepancy may be due to differences in setups. From the results of the present study, it seems that LW acts as an insulation layer that limits heat dissipation. Such an aspect might be enhanced by increasing summer irrigation. As far as the heating season is concerned, LW installation entails a decrease in heating energy needs, varying from approximately 20 to 30%. This is likely due to the increase in thermal resistance provided by the substrate. Such a result is in agreement with previous experimental research [29], although the experimental data are lower (i.e., about 3%) than those found in the present study. A simulation study focused on Athens [28], based on TRNSYS simulations, shows that LW installation decreases building heating energy demand by approximately 9%.

Altogether, the results show that EGR implementation on building in the Csa climate of Bari decreases year-round building energy needs by about 10.5–18% and the installation of GFs decreases the annual building energy demand by a maximum 0.03%, besides, LW installation can determine either a decrease or an increase in year-round building energy needs (Table 2). The results about LW and EGR thermal demeanor show that it is likely that the effect of evapotranspiration is residual compared to shading and thermal resistance. Such a result might be due to the irrigation schedule that is 1.68 mm/day and to the rainfall data related to the climate zone where Bari is located.

Although the study can provide insights for policymakers, some limits and possible sources of uncertainty also exist. In future work, simulations will be run with different software releases to verify whether different software releases can

produce differences in energy assessments. Furthermore, irrigation and LAI will be set at different levels during the year to investigate the effects on the GW thermal demeanor.

5 Conclusions

The present study investigated the effect of BIVT installation on building energy needs in the Csa climate zone. First, three buildings within three different urban layouts were selected. For each area, a building was chosen, and nine scenarios based on the application of a single BIVT with perennial vegetation species and on the variation of LAI (1.5, 3, and 5) and a baseline scenario were developed. The three areas were modeled in DesignBuilder and run in EnergyPlus; specifically, a Python module was implemented to account for the effect of GFs and LWs on building energy needs. The results indicate that EGR installation can decrease annual energy demand by 10–18%, while GFs have a negligible effect on energy demand. LW installation, however, may determine either a decrease or an increase in building energy demand. The study shows the impact of LAI in such thermal simulation and that to achieve a higher reduction in building energy demand, LAI must vary over the year, for instance, replacing perennial plant species with deciduous ones. In the future, more simulations will be carried out to investigate the role of irrigation, precipitation, and orientation.

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Disclosure of Interests The authors have no competing interests to declare.

References

1. Susca T (2022) Nature-based solutions applied to the built environment to alleviate climate change: benefits, co-benefits, and trade-offs in a geographical multi-scale perspective. In: Lackner M, Sajjadi B, Chen W-Y (eds) Handbook of climate change mitigation and adaptation. Springer International Publishing, Cham, pp 2117–2167. https://doi.org/10.1007/978-3-030-72579-2_123
2. Passaseo A, Pétremand G, Rochefort S, Castella E (2020) Pollinator emerging from extensive green roofs: wild bees (hymenoptera, Antophila) and hoverflies (Diptera, Syrphidae) in Geneva (Switzerland). Urban Ecosyst 23:1079–1086. <https://doi.org/10.1007/s11252-020-00973-9>
3. Aloisio JM, Tuininga AR, Lewis JD (2016) Crop species selection effects on stormwater runoff and edible biomass in an agricultural green roof microcosm. Ecol Eng 88:20–27. <https://doi.org/10.1016/j.ecoleng.2015.12.022>
4. Susca T (2019) Green roofs to reduce building energy use? A review on key structural factors of green roofs and their effects on urban climate. Build Environ 162:106273. <https://doi.org/10.1016/j.buildenv.2019.106273>

5. Susca T, Zanghirella F, Colasuonno L, Del Fatto V (2022) Effect of green wall installation on urban heat Island and building energy use: a climate-informed systematic literature review. *Renew Sust Energy Rev* 159:112100. <https://doi.org/10.1016/j.rser.2022.112100>
6. European Commission. Energy performance of buildings directive n.d. https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficient-buildings/energy-performance-buildings-directive_en. Accessed Mar 8 2024
7. Susca T (2020) Nature-based solutions applied to the built environment to alleviate climate change: a geographical multi-scale perspective. In: Lackner M, Sajjadi B, Chen W-Y (eds) *Handbook of climate change mitigation and adaptation*. Springer, New York, NY, pp 1–42. https://doi.org/10.1007/978-1-4614-6431-0_123-3
8. Durhman AK, Rowe DB, Rugh CL (2007) Effect of substrate depth on initial growth, coverage, and survival of 25 succulent green roof plant taxa. *HortScience* 42:588–595. <https://doi.org/10.21273/HORTSCI.42.3.588>
9. Bevilacqua P, Coma J, Pérez G, Chocarro C, Juárez A, Solé C et al (2015) Plant cover and floristic composition effect on thermal behaviour of extensive green roofs. *Build Environ* 92:305–316. <https://doi.org/10.1016/j.buildenv.2015.04.026>
10. Yaghoobian N, Srebric J (2015) Influence of plant coverage on the total green roof energy balance and building energy consumption. *Energ Buildings* 103:1–13. <https://doi.org/10.1016/j.enbuild.2015.05.052>
11. Bakhshoodeh R, Ocampo C, Oldham C (2022) Exploring the evapotranspirative cooling effect of a green façade. *Sustain Cities Soc* 81:103822. <https://doi.org/10.1016/j.scs.2022.103822>
12. Netusel NR, Lavelle L, Dissanayake S, Ando AW (2022) Valuing the public benefits of green roofs. *Landsc Urban Plan* 224:104426. <https://doi.org/10.1016/j.landurbplan.2022.104426>
13. Ode Sang Å, Thorpert P, Fransson A-M (2022) Planning, designing, and managing green roofs and green walls for public health—an ecosystem services approach. *Front Ecol Evol*:10. <https://doi.org/10.3389/fevo.2022.804500>
14. Choi C, Berry P, Smith A (2021) The climate benefits, co-benefits, and trade-offs of green infrastructure: a systematic literature review. *J Environ Manag* 291:112583. <https://doi.org/10.1016/j.jenvman.2021.112583>
15. Susca T (2021) Nature-based-solutions applied to the built environment to alleviate climate change. In: Lackner M, Sajjadi B, Chen W-Y (eds) *Handbook of climate change mitigation and adaptation*. Springer, New York, p 52
16. CTI Comitato Termotecnico Italiano- Vendita documenti Normativi n.d. <https://try.cti2000.it/>. Accessed Mar 6 2025
17. Nesci V, Ballarini I, Rando Mazzarino P, Corrado V (2024) Living walls and green façades: an implementation code for energy simulation. *Buildings* 14:2040. <https://doi.org/10.3390/buildings14072040>
18. Iaria J, Susca T (2022) Analytic hierarchy processes (AHP) evaluation of green roof- and green wall-based UHI mitigation strategies via ENVI-met simulations. *Urban Clim* 46:101293. <https://doi.org/10.1016/j.uclim.2022.101293>
19. Susca T, Iaria J, Zanghirella F (2024) Development of predictive indices for evaluating the UHI adaptation potential of green roof- and wall-based scenarios in the Mediterranean climate. *Sci Rep* 14:21675. <https://doi.org/10.1038/s41598-024-67567-9>
20. UNI/TR 11552:2014 (2014) Abaco delle strutture costituenti l'involucro opaco degli edifici. Parametri termofisici
21. Gazzetta Ufficiale. DECRETO DEL PRESIDENTE DELLA REPUBBLICA 16 aprile 2013, n. 74 (2013). <https://www.gazzettaufficiale.it/eli/id/2013/06/27/13G00114/sg>. Accessed Mar 11 2025
22. Martinelli A, Carlucci F, Fiorito F (2024) On the role of the building envelope on the urban Heat Island mitigation and building energy performance in Mediterranean cities: a case study in southern Italy. *Climate* 12:113. <https://doi.org/10.3390/cli12080113>
23. Zinzi M, Agnoli S (2012) Cool and green roofs. An energy and comfort comparison between passive cooling and mitigation urban heat Island techniques for residential buildings in the Mediterranean region. *Energ Build* 55:66–76. <https://doi.org/10.1016/j.enbuild.2011.09.024>

24. Borràs JG, Lerma C, Mas Á, Vercher J, Gil E (2023) Irrigation proposals for improving the energy performance of green roofs in Mediterranean climate. *J Build Eng* 75:107064. <https://doi.org/10.1016/j.jobe.2023.107064>
25. Arengi A, Perra C, Caffi M (2021) Simulating and comparing different vertical greenery systems grouped into categories using EnergyPlus. *Appl Sci* 11:4802. <https://doi.org/10.3390/app11114802>
26. Ramadhan AM, Mahmoud AH (2023) Evaluating the efficiency of a living wall facade as a sustainable energy-saving alternative in hot arid regions. *J Eng Appl Sci* 70:96. <https://doi.org/10.1186/s44147-023-00259-9>
27. García M, Vera S, Rouault F, Gironás J, Bustamante W (2022) Cooling potential of greenery systems for a stand-alone retail building under semiarid and humid subtropical climates. *Energ Build* 259:111897. <https://doi.org/10.1016/j.enbuild.2022.111897>
28. Djedjig R, Bozonnet E, Belarbi R (2015) Analysis of thermal effects of vegetated envelopes: integration of a validated model in a building energy simulation program. *Energ Build* 86:93–103. <https://doi.org/10.1016/j.enbuild.2014.09.057>
29. Coma J, Pérez G, de Gracia A, Burés S, Urrestarazu M, Cabeza LF (2017) Vertical greenery systems for energy savings in buildings: a comparative study between green walls and green facades. *Build Environ* 111:228–237. <https://doi.org/10.1016/j.buildenv.2016.11.014>
30. de Gracia A, Navarro L, Coma J, Serrano S, Romaní J, Pérez G et al (2018) Experimental set-up for testing active and passive systems for energy savings in buildings—lessons learnt. *Renew Sust Energ Rev* 82:1014–1026. <https://doi.org/10.1016/j.rser.2017.09.109>

PINN-Based Indoor Comfort Prediction for Residential Buildings in the Cooling Season



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Abstract Achieving global carbon neutrality targets requires innovative approaches to improve the energy performance and thermal comfort of buildings. This study investigates the application of Physics-Informed Neural Networks (PINNs) for predicting indoor thermal comfort conditions in residential buildings, combining physical modelling with Machine Learning (ML) strategies. A Multi-Storey Residential Building (MSRB) constructed in the 1980s in Bari, Southern Italy, is selected as a case study. A dynamic energy simulation is performed using DesignBuilder software, calibrated according to ASHRAE Guideline 14, using real weather data. The generated data set, including cooling loads, solar gains, occupancy, ventilation and outdoor air temperatures (OATs), is used as input to the PINN model, which directly incorporates the Energy Conservation Law during training. Hyperparameter Optimisation (HO) is performed using Optuna, and a PINN ensemble strategy further improves prediction accuracy. The final model achieves a Root Mean Square Error (RMSE) of 0.035 °C for the prediction of the operative temperature and allows the estimation of the Predicted Mean Vote (PMV) with a comfort compliance of 2.60%. Compared to the traditional PMV calculation based on measured temperatures only, the PINN-based approach shows a significant improvement of approximately + 0.66% in comfort hours. These results confirm the ability of PINNs to provide physically consistent, data-driven predictions of both thermal behaviour and occupant comfort, providing a robust framework to support energy-efficient and occupant-centred design strategies in the residential building sector.

Keywords Physics-informed neural network · Thermal comfort prediction · Energy simulation · PMV

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1 Introduction

Over the past decades, the European Union has prioritized reducing energy consumption in buildings, aiming for a 55% cut in emissions by 2030 and for climate neutrality by 2050 and. Buildings account for 40% of the EU's energy use and 36% of CO₂ emissions, with the residential sector alone responsible for 26.1% of energy consumption [1]. Much of the building stock is over 50 years old, underlining the need for retrofit interventions [2].

While reducing energy demand is a primary goal, ensuring indoor thermal comfort is equally crucial. Traditional models like the Predicted Mean Vote (PMV) [3], though widely used, assume steady-state and uniform environments, leading to limitations. Adaptive models incorporated into standards such as ASHRAE 55 and EN 15251 [4] address these gaps by considering occupant behavior.

Recent years have seen AI and Machine Learning (ML) techniques increasingly applied to predict comfort conditions. Methods like ANNs, SVMs [5], Deep Neural Networks (DNNs) [6], and Reinforcement Learning (RL) [7] offer powerful predictive capabilities, yet they often require large datasets and lack physical interpretability.

Physics-Informed Neural Networks (PINNs) offer a hybrid approach, embedding physical laws into ML models to improve robustness and reduce data needs [8]. Despite promising applications—such as predicting indoor temperature and optimizing HVAC operations—PINNs face challenges in validation against real-world residential data. Enhancements like hyperparameter optimization (HO) with Optuna [9] and hybrid edge-computing integrations [10] have been proposed to improve performance. However, the application of PINNs to predict thermal comfort in residential buildings remains limited, particularly in capturing uncertainties related to occupant behavior and dynamic boundary conditions.

This paper proposes a PINN-based framework to predict Indoor Operative Temperature (IOT) and estimate PMV during the summer season in a Multi-Storey Residential Building (MSRB) in Bari, Southern Italy. By embedding energy balance equations directly into the learning process and adopting an ensemble training strategy, the model aims to enhance predictive robustness and improve comfort prediction compared to traditional methods.

Section 2 outlines the methodology employed to construct the combined physics-based and ML framework. Section 3 presents the main results obtained through model evaluation and comparison with conventional calculation methods. Finally, Sect. 4 concludes with the implications, limitations, and future developments of the proposed approach.

2 Methodology

The methodology adopted in this paper develops a physics-based and ML framework to predict indoor thermal comfort conditions in residential buildings during summer period, based on dynamic simulation outputs and a PINN architecture.

The case study concerns a MSRB located within a social housing cluster in Bari, Southern Italy. Constructed in the late 1980s, the building consists of six stores, with two mirrored apartments of approximately 85 m² on each floor, for a total of ten residential units. The structural system is a reinforced concrete frame with latero-cement slabs. External walls, without thermal insulation, have a U-value of 1.15 W/m² K, the flat roof reaches 1.45 W/m² K, and windows with aluminum frames and double glazing have a U-value of 3.70 W/m² K with an SHGC of 0.75. The total net conditioned floor area is 814 m², corresponding to a conditioned volume of 2197.5 m³ and a surface-to-volume ratio of 0.38. Heating is provided by independent natural gas boilers ($\eta_H = 0.85$) through aluminum radiators operating at 80 °C, while cooling relies on split units with SEER 2.7. The Building Energy Model (BEM) is simulated on an hourly basis using IGDG weather data for Bari-Palese. The analysis focuses exclusively on the summer season (June–July–August). A constant cooling setpoint of 26 °C is maintained, in accordance with the Category II requirements reported in the UNI EN 16798-1 [11]. All systems—including cooling, mechanical and natural ventilation, domestic hot water (DHW), lighting, appliances, and PV generation—are modeled as operating continuously throughout the period. Occupancy schedules assume four occupants per apartment, consistent with standard residential internal gains. Lighting loads are defined with a Lighting Power Density (LPD) of 2.5 W/m² at 100 lux. Ventilation rates are modeled as 0.5 vol/h for mechanical ventilation, while natural ventilation is activated when indoor air temperatures range between 21 and 25 °C and the outdoor temperature is at least 1 °C cooler. Under these conditions, air exchange rates vary between 5 and 12 vol/h, as defined in the simulation.

The model is calibrated using three years of actual energy consumption data (electricity and gas) [12], following ASHRAE Guideline 14–2023, Option D. Calibration quality is assessed using the Root Mean Square Error (RMSE) metric, defined in Eq. (1):

$$\text{RMSE} = \left[\frac{1}{n} \sqrt{\sum_{i=1}^n (P_i - O_i)^2} \right] \quad (1)$$

where P_i and O_i are predicted and observed values, respectively. Once calibration is achieved, simulation outputs are prepared for training the predictive PINN model.

The selected input features are extracted from dynamic simulation outputs and include: Cooling Load, Solar Gains, Occupancy, Outdoor Dry-Bulb Temperature (OAT), Mean Radiant Temperature (MRT), and Air Velocity (AV). The target variable is the Indoor Operative Temperature (IOT). Table 1 summarizes the variables used as input and output in the model:

Table 1 PINN model input

Parameter	Unit	Typical range
OAT	°C	20–40
Solar gains	W m ^{−2}	0–250
Cooling load	W m ^{−2}	0–45
Occupancy	Persons	1–4 per apartment
Mean radiant temperature (MRT)	°C	22–32
Air velocity (AV)	m s ^{−1}	0.5–0.12
Indoor operative temp. (IOT)—target	°C	25–28

A three-hour centered rolling mean is applied to the target to smooth high-frequency noise related to thermal inertia. Subsequently, features and target are standardized using a StandardScaler, ensuring that variables with different units contribute equally to training. The dataset is then split into training (80%) and testing (20%) subsets to validate the model’s predictive performance.

The PINN employed in this study embeds physical laws directly within the learning process, ensuring that the predicted indoor conditions are consistent with the building underlying thermal dynamics. Specifically, the model integrates the first law of thermodynamics as a constraint, formulated to represent the energy balance of a single-zone indoor air volume during the summer season.

Equation (2) describes how the indoor operative temperature changes over time as a result of the interaction between internal heat gains and thermal exchange with the external environment. Mathematically, this is expressed as:

$$\alpha C \frac{\partial T_{op}}{\partial t} = \beta(Q_c + Q_s + Q_o) - \gamma H(T_{op} - T_o)$$

(2)

where α represents the system thermal inertia, β the influence of internal gains (cooling, solar, occupancy), and γ the effect of ventilation and envelope heat exchange. These coefficients were optimized using Optuna, resulting in $\alpha = 1.6878$, $\beta = 0.5692$, and $\gamma = 0.5761$. This ensures that the model predictions remain physically consistent while improving robustness during summer comfort evaluation.

The PINN architecture is a fully connected feed-forward neural network composed of three hidden layers with 32 neurons each, using ReLU activation functions for its computational efficiency, numerical stability, and ability to capture non-linear relationships essential for modeling thermal dynamics. The model is trained by minimizing a composite loss function that includes both a supervised Huber loss and a physics-based residual derived from the energy balance equation. Training is performed using the Adam optimizer over 3000 iterations, with a learning rate of 0.0001142 (Table 2).

Three models are trained independently using seeds 0, 42, and 123. Their predictions are averaged (ensemble strategy) and further refined with a linear regression to better align with ground truth values. Inputs and target are standardized using a

Table 2 Parameters for PINN model construction

Parameter	Description	Value
Framework	Library used to build the model	TensorFlow + DeepXDE
Number of trials	Number of optimization trials	3
Number of iterations	Total training iterations	3000 (Adam optimizer)
Batch size	Size of the training batch	Full-batch (PINN standard)
Number of hidden layers	Number of hidden layers	3
Neurons per layer	Neurons in each hidden layer	32
Activation function	Activation function in hidden layers	ReLU
Loss function	Loss type	Huber loss + PDE residual
Optimization framework	Hyperparameter tuning	Manual + Optuna pre-search
Overfitting prevention	Regularization technique	Physics-based PDE constraint

StandardScaler, smoothing the target IOT with a centered rolling mean over three hours to reduce high-frequency noise.

Once trained, the model predicts the IOT under summer conditions. Thermal comfort is then assessed using the PMV, computed from the predicted IOT using ISO 7730 assumptions: metabolic rate 1.1 met, clothing 0.4 clo, air velocity 0.12 m/s, and relative humidity 64%. Comfort performance is quantified as the percentage of hours where PMV lies within the optimal range $[-1.0, 1.0]$.

This comprehensive methodology ensures that both the physical plausibility and predictive accuracy of the model are robustly validated against the calibrated simulation dataset.

3 Results

This section presents the main results obtained from the evaluation of the PINN model. The performance is assessed based on the prediction accuracy of the IOT and the derived PMV index, both compared against the outputs of BEM.

3.1 Indoor Operative Temperature Prediction

The ability of the PINN model to predict the dynamic behavior of IOT is evaluated by comparing the predicted values to the reference temperatures obtained from the DesignBuilder simulation across the full summer dataset.

Figure 1 presents the comparison between the true and predicted IOT profiles. Visually, the predicted curve closely follows the reference trend, confirming the

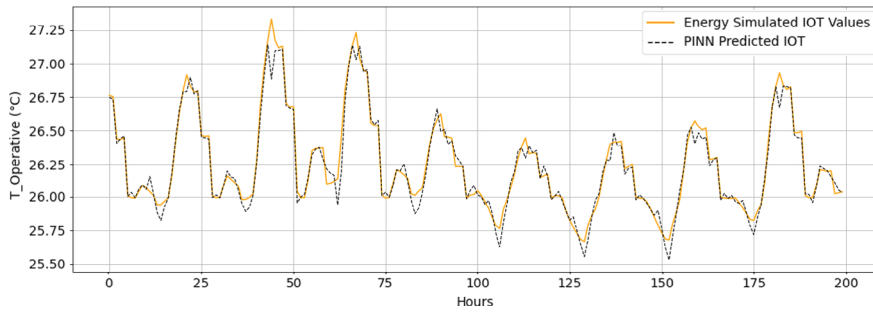


Fig. 1 Comparison of true and predicted IOT over the full summer (ensemble)

model capacity to reproduce the thermal behavior of the building envelope and systems throughout the summer period.

Quantitatively, the RMSE is 0.035 °C, indicating solid predictive accuracy of the PINN model under summer operating conditions. This result confirms the robustness of the physics-constrained learning approach, which effectively guides the model even with a relatively compact neural network architecture.

3.2 *PMV Prediction*

To further evaluate the model's performance in predicting indoor thermal comfort, the PMV index was calculated using both the PINN-predicted operative temperatures and the reference values from the building energy simulation. The computation follows ISO 7730 standards, adopting typical summer assumptions: a metabolic rate of 1.1 met, clothing insulation of 0.4 clo, and air velocity of 0.12 m/s. The relative humidity was set to 64%, a representative average value for the summer months extracted from the Bari-Palese EPW climate file, ensuring consistency with local weather conditions.

Figure 2 compares the distributions of PMV values obtained from the PINN-based prediction and the traditional simulation approach. The histogram reveals that the PINN model generates a more concentrated distribution within the comfort zone ($-1.0 \leq \text{PMV} \leq 1.0$), indicating enhanced alignment with human comfort perception.

Quantitatively, the PINN-based approach achieves a comfort percentage of 2.60%, while the traditional method only reaches 1.94% under the same simulation conditions.

Additionally, the RMSE between the PMV values derived from the PINN predictions and those computed from the DesignBuilder simulation outputs is 1.518 °C, confirming the model's strong capability not only in tracking indoor temperature dynamics but also in more accurately reproducing comfort indices under summer conditions.

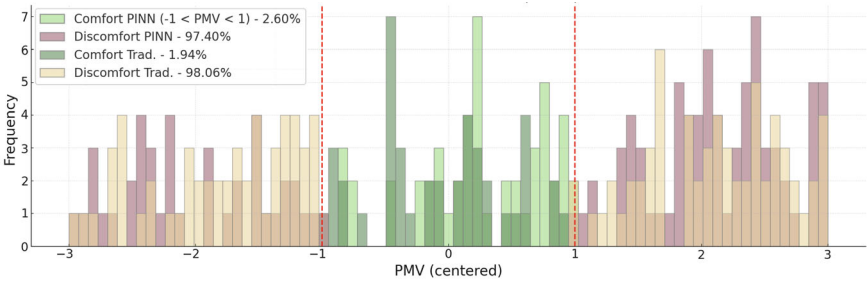


Fig. 2 Predicted PMV distributions: PINN and traditional approach (summer)

4 Discussion and Conclusions

The aim of this paper was to assess the application of PINNs for predicting IOTs and deriving thermal comfort conditions in a MSRB located in a Mediterranean climate. The proposed approach integrates a relatively simple fully connected neural network with first-principle thermodynamic laws embedded directly into the training process, enabling physically consistent predictions even under limited data availability. The methodology involved the dynamic simulation of a residential building for the summer season, the extraction and standardization of key environmental and operational features, and the training of an ensemble of PINNs optimized through hyperparameter search.

The prediction of IOT achieved a RMSE of 0.035 °C across the full summer dataset, confirming the model high predictive accuracy in capturing thermal dynamics. In terms of thermal comfort assessment, the PINN-based PMV prediction increased the comfort hours to 2.60% compared to 1.94% obtained using the traditional PMV calculation directly from simulation outputs, highlighting a substantial improvement of + 0.60% in predicting comfort conditions. This significant improvement suggests that integrating physical knowledge into the learning model enhances the reliability of comfort assessments, even when using limited or noisy input data. Moreover, the ensemble strategy and linear post-processing correction helped mitigate prediction biases and improved the model’s generalization capacity.

The results highlight the potential advantages of using physics-guided neural networks in early-stage design evaluations, retrofit analysis, and smart control strategies for occupant-centered building operation. However, several limitations can be identified in the current approach. First, the validation was carried out under simulated conditions, considering fixed values for clothing insulation and metabolic rate, without accounting for real occupant variability. Second, relative humidity, a key factor influencing perceived comfort, was assumed constant rather than dynamically modeled. Additionally, the study focused solely on the summer season in a Mediterranean context, without extending the analysis to other climatic conditions or seasonal behaviors.

Future work should focus on broadening the input features, integrating dynamic humidity and occupancy variability, and validating the framework against real-world measured datasets. Testing the model adaptability across different building types, seasons, and user profiles would also enhance its generalization capabilities. Alternative strategies such as the inclusion of adaptive thermal comfort models, or the integration of PINNs with real-time sensing and control systems, could further consolidate their role as a robust predictive tool in building performance simulation.

Overall, the findings confirm the potential of PINN to reliably predict both indoor thermal conditions and perceived comfort metrics, paving the way for their broader application in sustainable building design and operational optimization.

References

1. European Parliament, Towards climate neutrality: fit for 55 package, 2022
2. Stasi R, Ruggiero F, Berardi U (2024) Assessing the potential of phase-change materials in energy retrofitting of existing buildings in a Mediterranean climate. *Energies* (Basel). <https://doi.org/10.3390/en17194839>
3. Zhao Q, Lian Z, Lai D (2021) Thermal comfort models and their developments: a review. *Energy Built Environ* 2:21–33
4. Omoya T (2023) Thermal comfort in buildings: evaluation and semi-empirical modeling of occupant adaptation to environmental stimuli. Université de Bordeaux
5. Lu C, Li S, Lu Z (2022) Building energy prediction using artificial neural networks: a literature survey. *Energy Build* 262:111718
6. Qavidel Fard Z, Zomorodian ZS, Korsavi SS (2022) Application of machine learning in thermal comfort studies: a review of methods, performance and challenges. *Energy Build* 256:111771
7. Aruta G, Ascione F, Bianco N, Mauro GM, Vanoli GP (2023) Optimizing heating operation via GA- and ANN-based model predictive control: concept for a real nearly-zero energy building. *Energy Build* 292:113139
8. Olu-Ajayi R, Alaka H, Sulaimon I, Sunmola F, Ajayi S (2022) Building energy consumption prediction for residential buildings using deep learning and other machine learning techniques. *J Build Eng* 45:103406
9. Akiba T, Sano S, Yanase T, Ohta T, Koyama M (2019) Optuna: A next-generation hyperparameter optimization framework. In: *Proceedings of the ACM SIGKDD international conference on knowledge discovery and data mining*, pp 2623–2631
10. Chari A, Christodoulou S (2017) Building energy performance prediction using neural networks. *Energy Effic* 10:1315–1327
11. UNI EN 16798-1:2019
12. Stasi R, Ruggiero F, Berardi U (2025) From energy-intensive buildings to NetPlus targets: an innovative solar exoskeleton for the energy retrofitting of existing buildings. *Energy Build*. <https://doi.org/10.1016/j.enbuild.2025.115416>

Development of a Measuring Apparatus and Measurement of the Cooling Performance of Passive Daytime Radiative Cooling Materials for Buildings and Technical Applications



Michael Kamml, Christoph Sprengard, and Chiara Cucchi

Abstract The development and improvement of passive daytime radiative cooling materials (PDRC) have gained significant attention in recent years due to their ability to provide cooling without energy consumption. Climate change and rising temperatures are expected to increase the demand for electricity generation capacity, potentially leading to a “cold crunch”. Passive cooling materials can significantly reduce the energy demand of buildings and cooling systems, as well as industrial cooling processes, by reflecting solar radiation and emitting thermal energy into space through the transparent atmospheric window, achieving sub-ambient temperatures. The evaluation of their cooling capabilities is therefore crucial. This study presents an experimental setup enabling the measurement of the cooling power of four different passive radiative cooling materials under identical boundary conditions. The experimental setup was developed during the European Union funded 21GRD03 PaRaMetriC project. The design, supported by numerical simulation, is based on a liquid-filled temperature control plate that can be adjusted within a temperature range of 10–30 °C, allowing the testing of the PDRC materials at different temperatures. The cooling capacity is determined through the measurement of heat flux and temperature variations. The experimental setup includes a weather station to record and analyse the influence of environmental parameters such as humidity, cloud coverage, and ambient conditions on the performance of the materials. The robust design allows long-term measurements even in challenging weather conditions like rain and storms. It provides a systematic and precise methodology for evaluating PDRC materials.

Keywords Passive daytime radiative cooling (PDRC) · Emissivity · Selective emission · Thermal radiation · Performance assessment

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1 Introduction

The last two years, 2023 and 2024, have set new records in the increase of global temperatures. The year 2023 was marked by the hottest summer season ever recorded globally [1], and the global average temperature exceeded the pre-industrial level by 1.5 °C for the first time in 2024 [2]. The increase of the average surface temperature is one of the drivers in the growth of cooling energy demand besides growth in population, urbanization, and income [3]. The energy demand for cooling already more than tripled between 1990 and 2016, reaching 2000 TWh and accounting for 6% of the total final energy consumption in buildings globally [4]. Cooling has thus become the fastest-growing use of energy in buildings and, if no mitigation measures are implemented, it is projected to more than triple again by 2050 [4], largely driven by increasing demand in the residential sector with huge implications for electricity grids and GHG emissions. The technology for providing cooling has been based for over 100 years on the vapor-compression refrigeration cycle [3] and their use is expected to increase [5]. In this context, passive cooling solutions can help to mitigate heat gains and avoid overheating in building constructions [6]. Among the various solutions, passive daytime radiative cooling (PDRC) offers a promising approach for achieving sub-ambient cooling, without electricity needs and carbon emissions. This technology exploits radiative heat exchange to dissipate thermal energy into outer space through the so-called “Atmospheric Transparency Window” in the thermal infrared range between 8 and 13 μm . In this wavelength interval, the Earth’s atmosphere has reduced absorption properties, allowing the heat to be radiated directly into space.

While this physical phenomenon has been utilized since ancient times, e.g. to make ice in flat stone basins in cold clear nights and collect it for use in ancient cooling houses even in hot countries like Iran and India [7–9], recent advancements have enabled the development of materials capable of achieving cooling even during the day-time and under direct sunlight [10]. These materials must have specific optical properties. Besides a high emissivity (higher than 0.7) in the IR atmospheric window between 8 and 13 μm to enable heat dissipation, PRDC layers must have a high solar reflectance (typically higher than ~ 0.9) in the solar spectrum (0.25–2.5 μm) [11]. The emittance at wavelengths from 2.5 to 8 μm and above 13 μm should be adequately low to prevent overheating from the downwelling atmospheric irradiance and any residual solar irradiance [11].

The cooling performance of PRDC materials can either be expressed as a temperature drop in [K] below ambient temperature that is caused by the heat-dissipation into space or by the net heat flux in [W/m^2], which is referred to as the possible “cooling power”. Both values depend on different factors. Such as thermal radiation from the emitter into space, absorbed solar irradiance, absorbed atmospheric downward longwave radiation, and non-radiative heat transfer between the surface and the ambient environment (e.g. humidity, convection) [11]. Overall measurement accuracy depends on the ability to correctly measure all these terms. Therefore, this study proposes a design based on a liquid-filled temperature control plate that allows the

assessment of cooling power by measuring temperatures and heat flux. The research is about measuring the cooling capacity under real conditions with a high thermal load that can occur in various applications, e.g. in industrial heat exchangers, air conditioning systems, air-cooled condensers, and recooling units. These systems utilize higher temperatures to dissipate the heat energy into the environment. In most cases, heat transport is enhanced by convection using fans. Increasing the cooling power through radiation could contribute to lower energy consumption and higher system performance.

2 Methodology

2.1 Experimental Setup

The prototype (Fig. 1) is designed to evaluate the cooling performance of four PRDC materials by measuring the temperature and heat flux generated by a temperature gradient between the samples and a liquid-filled temperature control plate. The temperature control plate can be operated at temperatures between 10 and 30 °C with a temperature variation of less than ± 0.2 K. A thermally highly conductive levelling layer is placed between the temperature control plate and the carrier plate, where the PRDC samples are sealed. This layer is designed to compensate for the height variation caused by the sensor layer. It is highly flexible, ensuring all sensors are uniformly pressed down and perfectly thermally connected. The PRDC samples of 100×100 mm consist of three different PRDC films whose properties, such as emissivity and reflectivity, have been evaluated during the PaRaMetriC project [12], and one commercially available tape, glued to a highly reflective aluminium substrate. The samples are attached to an aluminium carrier plate of 5 mm thickness. The carrier plate is enclosed with a sealing compound to ensure a watertight seal, which can also accommodate thermal expansion due to temperature variation. A reflective sheet paired with a semi-transparent protective screen of 1.5 mm thickness surrounds the samples on the top of the setup to avoid solar gains and thereby heating of the carrier plate. To minimise the heat transfer to the surroundings, the system is wrapped on all sides in an XPS insulation material (approximately 0.035 W/(m K) and 100 mm thickness). Below the temperature control plate, the isolation of the system has been improved by adding a vacuum insulation panel (approximately 0.007 W/(m K) and 40 mm thickness) beside the XPS board. Calibrated and rolled (thickness 0.2 mm) thermocouples (TC) type T (within ± 0.1 K) are used to measure the temperature below each sample and to monitor the temperature of the carrier plate. Finally, heat flux sensors (accuracy within $\pm 3\%$) of the size 18 mm $\times$ 18 mm $\times$ 0.5 mm are positioned below each sample. The setup includes a high-precision weather station located near the specimens.

It is equipped with a multi-sensor system protected by a ventilated weather and radiation shield built at around 1.20 m above ground along with a pyranometer.

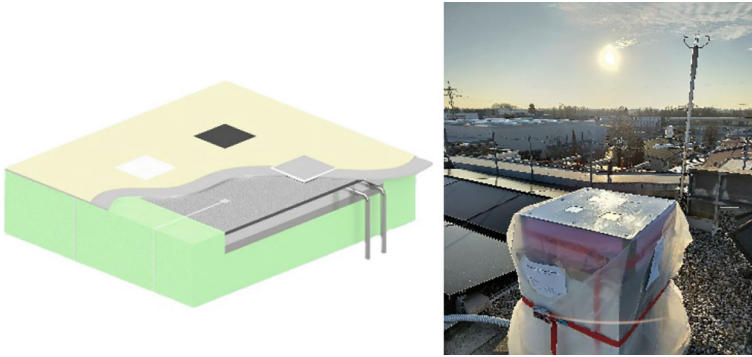


Fig. 1 Left: Schematic diagram of the experimental setup. Right: Experimental setup with weather station

Several environmental parameters, including particulate matter, atmospheric pressure (within ± 0.25 mbar), and air temperature (less than ± 0.1 K), are measured by the multi-sensor system. The pyranometer measures the incoming short-wave (from 0.3 to $2.8\ \mu\text{m}$ with an uncertainty less than 5%) and long-wave (from 4.5 to $42\ \mu\text{m}$ with an uncertainty less than 10%) Far Infrared (FIR) radiation and the surface-reflected short-wave and outgoing long-wave radiation. This instrument is also equipped with a temperature sensor (less than ± 0.3 K), which is used for the temperature compensation of the results as explained in Sect. 2.2. Finally, the weather station is equipped with an anemometer installed at 2.5 m above the ground and utilised to collect data on wind speed (within ± 0.1 m/s at $0\text{--}5$ m/s and $\pm 2\%$ of value higher than 5 m/s) and direction (within $\pm 1^\circ$). The apparatus is optimized to measure the cooling power but can be used to measure the temperature drop as well with small changes in the setup. Parallel to the iterative development and implementation of the system, an entity-relationship diagram was created to visualize functions and uncover dependencies. Critical areas, for example, the sealing of the samples and the associated heat conduction from the edges were also analysed and then optimized using 2-dimensional simulation software for analysing the heat transfer. Simulation results showed no interference between the samples and no parasitic heat-flux (or -loss) disturbing the measurement. One example of the simulation results is shown in Fig. 2. The black curved lines are the isotherms. A sample temperature of $10\ ^\circ\text{C}$ was used. The ambient temperature, as well as the temperature control plate temperature, were set to $20\ ^\circ\text{C}$. The parallel course of the isotherms below the sample shows, that the center of the sample in which the sensors are located is not affected by the connection to the other layers.

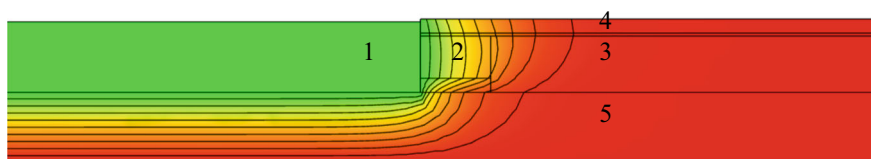


Fig. 2 Thermal simulation of the edge of the sample carrier (1) with the seal (2) and transition to the waterproof layer (3) and the protective screen (4). The leveling layer (5) is visible in the lower area of the heatmap

2.2 Acquisition and Processing of Measurement Data

The measurement data is recorded using two different systems. The analog signals are sampled one after the other via a precise data acquisition system (DAQ) with a time span of six seconds between the first and last reading. The second system is recording the digital signals of a bus system and therefore the values are already available in digital form and require no further conversion process. The DAQ measurement data is available in the form of voltage values (V) or resistance values (Ω). For thermocouples, the actual temperatures at the measuring point are determined by calculation from the voltages of the temperature sensors, taking into account the temperatures of the reference junction. Calibration is performed using individual fifth-degree polynomials for all 25 TC. These polynomials are valid for a temperature range of -20 to $+40$ °C and were measured and calculated using a block calibrator and a calibrated reference thermometer. The voltage values of the heat flux measuring plate are converted into the corresponding heat flux using the calibration factor and a temperature compensation factor. The voltage signals of the two solar radiation sensors and the two infrared radiation sensors are converted using individual calibration factors and the readings are compensated for temperature, using the temperature of the device. Furthermore, the difference between the incoming and outgoing radiation is calculated to create a balance—one for radiation of short and one of long wavelengths. The three voltage signals of the wind sensor correlate linearly with the wind speed, the wind direction, and the virtual temperature. Maximum temperature deviations between the respective TC of a layer are calculated to evaluate the measurement. This applies, for example, to the temperature distribution of the temperature control plate and in the measuring level. The sampling rate of all measurement signals is around 0.017 Hz, which corresponds to one measurement per minute. The data collected serves as the basis for calculating average values at five-minute intervals. The 5-min values reduce the amount of data and minimises random errors. However, they may not fully resolve short gusts in the wind, but it is fast enough to see relevant changes over the day. The ground and sky temperatures calculated for verification from the Pyregeometer data are plausible. In addition, the data was cross-checked with the measurement data from the LMU weather station in

Garching [13]. This station is located in a similar urban environment as the measurement setup at the FIW. The distance between FIW and Garching is around 25 km. Further validation of the results will be carried out later in the PaRaMetriC project.

3 Preliminary Measurement Data

To measure the cooling performance on 8 March 2025, the temperature control plate in the unit was set to 18 °C approx. 30 h before the test. The samples are subjected to a constant thermal load, as it would be the case with heat exchangers in cooling systems, for example. The weather was very mild for March in Munich with air temperatures around the freezing point at night and a maximum temperature of approx. 17 °C in the afternoon. There was plenty of sunshine and occasionally thin, high cloud fields. During the evening/night mostly clear. Weak winds (0.1–2.4 m/s) were blowing from different directions (Fig. 3). According to data from the German Meteorological Institute Deutscher Wetter Dienst (DWD), an average wind speed of 1.9–2.2 m/s at a height of 10 m can be considered average for the location of Munich [14]. The barometric pressure on this day was 951 hpa in the morning and dropped to 944 hpa during the course of the day.

The diagram (Fig. 4) shows the time (exactly 24 h) on the X-axis and the irradiance intensity in [W/m²] for long-wave (in red) and short-wave radiation (in yellow) on the left Y-axis. The blue dotted line shows the air temperature with the associated

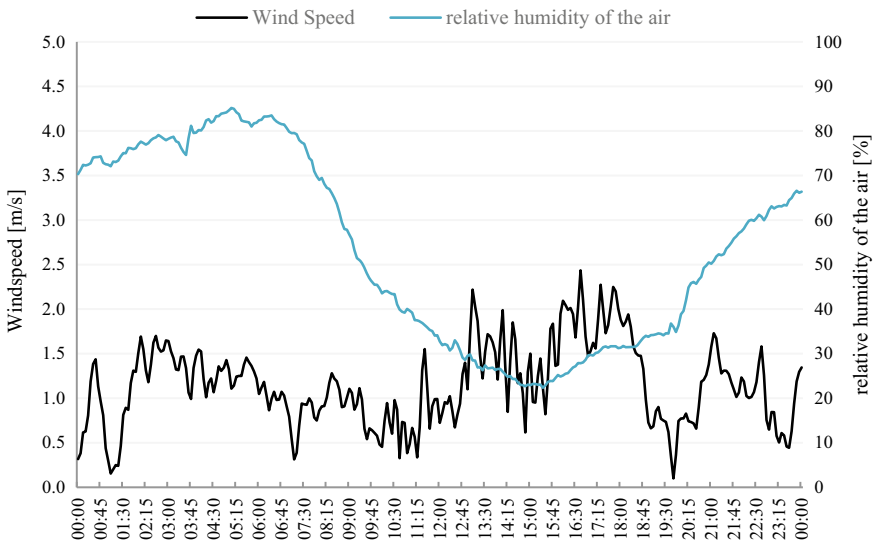


Fig. 3 Measured wind speed and relative humidity of the air in the close surrounding of the samples

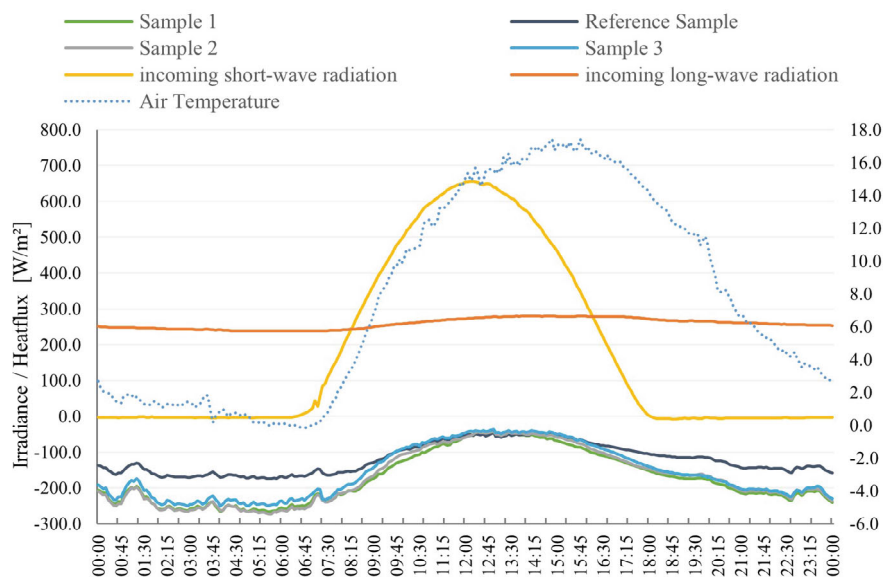


Fig. 4 Results of the cooling power measurement test on 08 March 2025 with temperature control plate set to 20 °C

right Y-axis in [°C]. The heat flux (cooling power) of the samples is plotted in [W/m^2].

The short-wave radiation shows the typical circadian cycle for a cloudless spring day. The long-wave radiation is constant with a slight increase during the day. The samples show a strongly increased cooling power at night, which reaches $-270 \text{ W}/\text{m}^2$. With the increase in short-wave radiation (sunrise), the cooling capacity of the samples is reduced. At the time of maximum energy gain (12:30) with a short-wave irradiation of $650 \text{ W}/\text{m}^2$ plus the incoming long-wave radiation of $280 \text{ W}/\text{m}^2$. The coatings achieve cooling capacities of -40 to $50 \text{ W}/\text{m}^2$. As the solar radiation decreases, the cooling power increases again. On average, over 24 h, including convective cooling, Reference Sample achieves a cooling power of approx. $-120 \text{ W}/\text{m}^2$. The Sample 2 and Sample 3 coating are around $-160 \text{ W}/\text{m}^2$ and Sample 1 achieves approx. $-170 \text{ W}/\text{m}^2$. It is important to mention that these cooling capacities are not only the result of radiation. Convection is a key part of this cooling power. The Reference Sample consists of the same layer arrangement as the other samples (highly reflective aluminum + thin polypropylene film). But instead of a PRC Material, a regular transparent adhesive Scotch Tape without any specific optimized emissivity properties is glued to the highly reflective aluminum substrate. It could be used as the baseline cooling capacity. By calculating the difference between the baseline and the other substrates, the difference should be assigned to the advanced radiative properties. The 24-h average additional radiative cooling power for this day would be around $-38 \text{ W}/\text{m}^2$ for Sample 3 and $-50 \text{ W}/\text{m}^2$ for the Sample 2 coating. The Sample 1 achieves approx. $-53 \text{ W}/\text{m}^2$.

4 Conclusion

The measurement setup is optimised for measuring the cooling performance under increased thermal load, as is the case with technical systems such as air-cooled condensers and recooling units. For the use of this provided data, it is important to recognize that this is the first measurement data from a completely newly developed device the data needs further validation, and improvements on the setup are pending. The resistance of the structure to environmental influences observed to date can be evaluated positively due to the weatherproof installation. Future measurements during the spring and summer months will analyse the actual benefit of the coatings. Furthermore, it is planned to identify the meteorological parameters that influence the cooling capacity, and the temperature drop, to determine the application areas of the products more precisely. Optimisation of the measurement device like small improvements in the thermal management of the measurement technology will enhance the stability of the measurements. Further improvement will be achieved by replacing the currently used levelling layer with a mat with higher heat conductivity to reduce thermal inertia while measuring the cooling capacity. The installation of a camera to improve the observation of ice formation on the surface would be beneficial for the interpretation of the results. Further options for future measurements include the installation of a large sample (700 × 700 mm) to determine the influence of sample size. A wind shield could also be installed to reduce the convective cooling effect. A strategically planned set of tests will be carried out as soon as the optimisations have been implemented.

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References

1. Copernicus Climate Change Service. <https://climate.copernicus.eu/summer-2023-hottest-record>. Last accessed 7 Mar 2025
2. Copernicus Climate Change Service (2025) The 2024 annual climate summary—global climate highlights 2024. Report
3. Campbell I, Kalanki A, Sachar S (2018) Solving the global cooling challenge—how to counter the climate threat from room air conditioners. Global Cooling Prize, Rocky Mountain Institute
4. International Energy Agency (2018) The future of cooling: opportunities for energy-efficient air conditioning. IEA, Paris
5. Statista. <https://www.statista.com/outlook/cmo/household-appliances/major-appliances/air-conditioners/worldwide>. Last accessed 7 Mar 2025
6. Directive (EU) 2024/1275 of the European parliament and of the council of 24 April 2024 on the energy performance of buildings (recast) (Text with EEA relevance) (2024)

7. Barker R (1775 XXII) The process of making ice in the East Indies. By sir Rober Barker, F.R.S. In a letter to Dr Brocklesby. *Phill Trans R Soc* 65:252–257
8. Bahadori M (1978) Passive cooling systems in Iranian architecture. *Scientific American*, Springer Science and Business Media LLC
9. Mahdavinejad M, Javanrudi K (2012) Assessment of ancient fridges: a sustainable method to storage ice in hot-arid climates. *Asian Cult Hist* 4(2)
10. Raman A, Anoma M, Zhu L, Rephaeli E, Fan S (2014) Passive radiative cooling below ambient air temperature under direct sunlight. *Nature* 515:540–544
11. Tichý D, Kapouněk Š, Voldán M et al (2023) Report on the collection and production of candidate passive radiative cooling materials, and identification of figures of merit to evaluate their cooling performance. *Zenodo*
12. Adibekyan A, Schumacher J, Pattelli L et al (2025) Emissivity and reflectivity measurements for passive radiative cooling technologies. *Int J Thermophys* 46:66. <https://doi.org/10.1007/s10765-025-03532-6>
13. Ludwig-Maximilians-Universität München. <https://www.meteo.physik.uni-muenchen.de/DokuWiki/doku.php?id=wetter:garching:neu:zeitreihe>. Last accessed 8 May 2025
14. Deutscher Wetterdienst. http://www.wind-of-change.org/files/helix_files/news/160823_Bergedorfer/Windkarte-Deutschland-10m.pdf. Last accessed 8 May 2025

Cooling Potential Assessment of PRC Materials: Findings from a Full-Scale Prototype Study



Eduardo M. González-Cruz, Gloria Pérez, Fruto Borja, Carmen Alonso, Fernando Martín-Consuegra, and Lorenzo Pattelli

Abstract A full-scale radiant-capacitive cooling system (RCCS) was implemented in Arganda del Rey, Spain, to evaluate passive radiative cooling (PRC) materials. The hydronic system includes sky-exposed radiators, indoor radiant ceiling panels, and thermal energy storage. The thermal performance of the radiators was evaluated under two conditions: with and without PRC material. The cooling potential was assessed based on the water temperature difference between the radiator inlet and outlet. Multiple correlation models, incorporating the most influential climatic and operational factors, were developed to comparatively analyze the experimental series. Their application enabled the identification of the best-performing configurations and the conditions under which they are most effective. The application of PRC material increased cooling hours and maintained the daily cooling potential between 52.4 and 68.1 W/m². This cooling effect ensured that operating temperatures remained within the thermal comfort range, even under extreme conditions (~ 40 °C). These findings highlight the potential of PRC materials to enhance sustainable cooling solutions for buildings and improve energy efficiency.

Keywords Passive radiative cooling · Full-scale test cells · Performance assessment · Experimental study · Radiant-capacity cooling system · Building

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1 Introduction

The escalating demand for cooling energy, driven by global warming and increased urbanization, poses a significant challenge to the sustainability of the built environment [1, 2]. As traditional air conditioning systems contribute to greenhouse gas emissions and high energy consumption, passive cooling technologies have gained considerable attention as viable alternatives for mitigating thermal loads in buildings [3]. Among these, passive radiative cooling (PRC) has emerged as a promising solution due to its ability to dissipate heat directly into outer space without requiring external energy input [4, 5]. This process takes advantage of the atmospheric transparency window in the mid-infrared spectrum, allowing surfaces engineered with PRC materials to achieve sub-ambient temperatures both during nighttime and, more recently, under direct solar radiation [6].

Significant advancements in photonic and nanomaterial technologies have enabled the development of high-performance PRC materials with enhanced cooling capabilities. These materials exhibit selective emissivity properties that maximize radiative heat loss while minimizing solar absorption, promising to improve energy efficiency and reducing cooling loads in buildings [7, 8]. However, despite the theoretical and laboratory-scale successes of PRC technologies, their real-world applicability remains underexplored, particularly in full-scale architectural settings where multiple environmental variables interact.

To address this gap, the EURAMET research project “Metrological framework for passive radiative cooling technologies” (PaRaMetriC) has implemented a full-scale prototype study to assess the performance of PRC materials in an operational building system. This study, conducted in Arganda del Rey, Spain, integrates PRC-coated radiators with a radiant-capacitive cooling system (RCCS) [9].

By monitoring the system’s thermal performance under various meteorological conditions and operational configurations, this study aims to quantify the cooling potential of the sky radiator with and without PRC material. To achieve this, a methodology based on multiple correlation models is proposed, incorporating the most influential factors in determining the cooling potential of sky radiators (CP_{SR}).

The primary aim is to establish a practical methodology for comparatively assessing the cooling capacity of sky radiator arrays across experiments conducted under diverse climatic conditions.

2 Methodology

Nine experimental series were conducted during the summer of 2024 to evaluate the thermal performance of the cooling system under various operating configurations. These configurations involved modifications to the water flow rate, energy storage capacity, and the number of radiant-capacity modules in both radiator conditions: without and with PRC material. The first four series were designated as the A series,

while the remaining five were designated as the B series. The first four series used polypropylene radiators exposed to the sky in their original state, while the following five series employed radiators coated with SPACECOOL Film Silver PRC material [10].

After describing the characteristics of the radiant-capacitive cooling system, its components, and operating conditions, the procedure for generating multiple regression models will be explained. These models will be applied to compare the thermal performance of four experimental series based on one of the key figures of merit: the cooling potential of sky radiators.

2.1 The Experimental Setup

The experimental setup is conducted at the IETCC-CSIC facility in Arganda del Rey, Madrid, which has favorable climatic conditions for radiative cooling applications. The study is based on the hydronic “Radiant-Capacitive Cooling System” (RCCS). The system consists of three main components: (a) Sky Radiators (SRs) exposed to the sky, (b) indoor Radiant-Capacity Modules (RCMs), and (c) a Thermal Energy Storage (TES) water tank (Fig. 1). A controlled closed-loop water circuit enables heat exchange between these components. The system operates by dissipating heat via long-wave radiation to the sky, achieving water-cooling at night and, in specific conditions, also during the day using passive radiative cooling (PRC) materials. The cooled water then circulates through ceiling-mounted RCMs, providing radiant cooling for indoor spaces.

The full-scale test facility consists of two twin thermally insulated test cells, each measuring 15.2 m². The walls, ceiling, and floor are built with highly insulating modular panels ($U = 0.0552 \text{ W/m}^2 \text{ K}$), minimizing external heat transfer. Each cell includes a south-facing high-performance window (Fig. 2a). The sky radiator comprises polypropylene panels coated with a 110 μm thick SPACECOOL Film-Silver, a PRC material with high reflectivity and emissivity (Fig. 2b, c). The RCMs are made of steel sheets containing a copper pipe coil for heat exchange and water storage, offering a high thermal capacity (216.6 kJ/K) (Fig. 2d, e).

The thermal energy storage system includes two polyethylene water tanks (1000 and 50 L). A hydropneumatic control system regulates water circulation through four different circuits, adjusting flow rates via solenoid valves. Data acquisition and control rely on a Raspberry Pi 4B, connected to sensors monitoring temperature, humidity, water flow, and weather conditions. The system was tested during summer with and without PRC materials to evaluate its cooling performance.

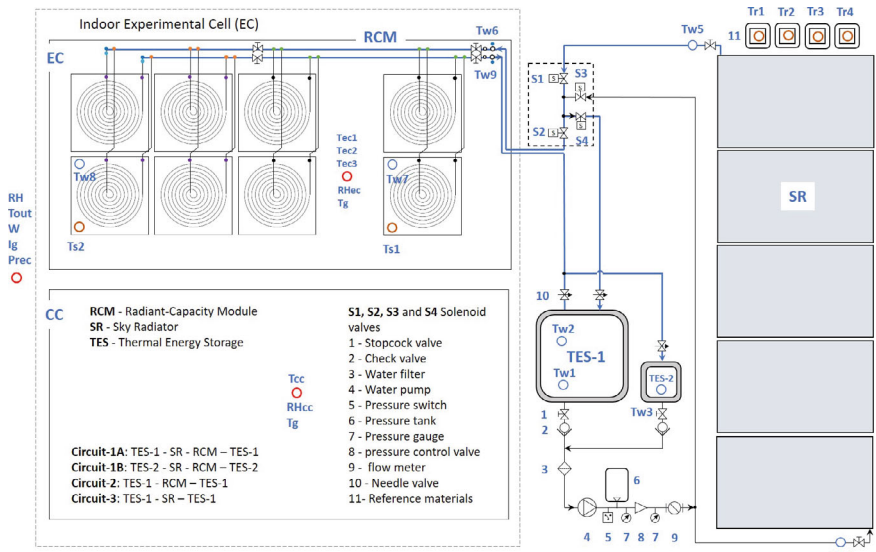


Fig. 1 Diagram of components, sensors and water flow circuits of the radiant-capacitive cooling system using PRC material coated on the radiators



Fig. 2 a The full-scale experimental setup with two twin test cells, b sky radiators with PRC material, c cross and longitudinal sections of the sky radiator, d top view of an RCM with its connections to the heat exchanger, e array of RCMs as roof panels in the experimental cell

2.2 On the Regression Models

The multiple regression method is used to analyze and predict the relationship between one dependent variable and two or more independent variables [11]. In the present case, the aim is to predict the water temperature difference between the radiator inlet and outlet (DTw-the temperature drop required to calculate the cooling potential of the radiators, as will be discussed later), based on climatic variables and other factors related to the system's operating mode.

The variables that directly or indirectly affect the thermal balance of sky-exposed radiators and therefore the difference in water temperature difference between the inlet and outlet were identified. A correlation matrix was then generated to determine and select the most influential factors. These include ambient air temperature, sky temperature, reference temperature (Tr3, the equilibrium or stagnation temperature measured on the PRC-coated radiator sample), and the temperature difference between the radiator inlet water temperature (Tw4) and the surface temperature of the sample made of the same material (Tr3).

From these parameters, multiple regression models were developed for experimental series B1 and B4. These models are used to predict DTw values in experimental series A3 and A2, respectively, as they share the same operating configurations. These series were selected to compare results from series A3 (radiators without PRC material) with the results that could have been obtained under the same conditions with PRC-coated radiators, corresponding to series B1. Thus, a predictive model from series B1 allows for this comparison. Similarly, a predictive model from series B4 enables a comparison with series A2.

3 Results and Discussion

3.1 ES-B1 Model

A multiple regression model incorporating four independent variables (Tamb, Tsky, Tr3, and Tw4-Tr3) was developed for ES-B1, expressed as follows:

$$\begin{aligned} Y &= 0.58236 - 0.09564 \cdot T_{amb} - 0.01407 \cdot T_{sky} \\ &\quad + 0.10853 \cdot Tr3 + 0.11621 \cdot (Tw4 - Tr3) \end{aligned} \quad (1)$$

$CC = 0.9374; R^2 = 0.8787; RMSE = 0.092 \text{ } ^\circ C$

This model was developed using the monitored data of the first four nights (from 22:30 to 8:00 h) of the experimental series B1 and validated against data of the last three nights of the experimental series (Fig. 3), yielding a result of: $CC = 0.8972$ and $R^2 = 0.805$.

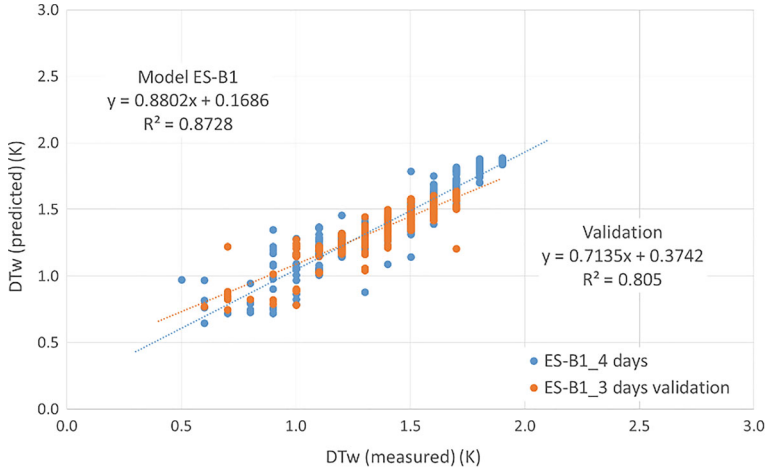


Fig. 3 ES-B1 model validation. DTw measured versus predicted

3.2 ES-B4 Model

A multiple regression model was also developed based on the first four nights of ES-B4, incorporating four independent variables (T_{amb} , T_{sky} , Tr_3 , Tw_4-Tr_3). The resulting model is expressed as follows:

$$\begin{aligned}
 Y &= 0.24725 - 0.13482 \cdot T_{amb} - 0.02919 \cdot T_{sky} \\
 &\quad + 0.16729 \cdot Tr_3 + 0.15197 \cdot (Tw_4 - Tr_3) \\
 CC &= 0.9719; R^2 = 0.9446; RMSE = 0.119 \text{ } ^\circ\text{C}; MAPE = 6.20\%
 \end{aligned}
 \tag{2}$$

This model was validated against data of the last three nights of the experimental series B4 (Fig. 4), yielding a result of: $CC = 0.943$ and $R^2 = 0.8893$.

3.3 Comparative Analysis of Cooling Potential in Series B1-A3 and B4-A2

The generated models allow us to estimate the water temperature drop as it passes through the radiators, i.e., the temperature difference between the inlet and outlet of the radiators, expressed as DTw. Based on this temperature drop, we determine the **cooling potential per unit area of the sky radiators** (CP_{SR}) as follows:

$$CP_{SR} = \dot{m} \times cp \times DTw/A \tag{3}$$

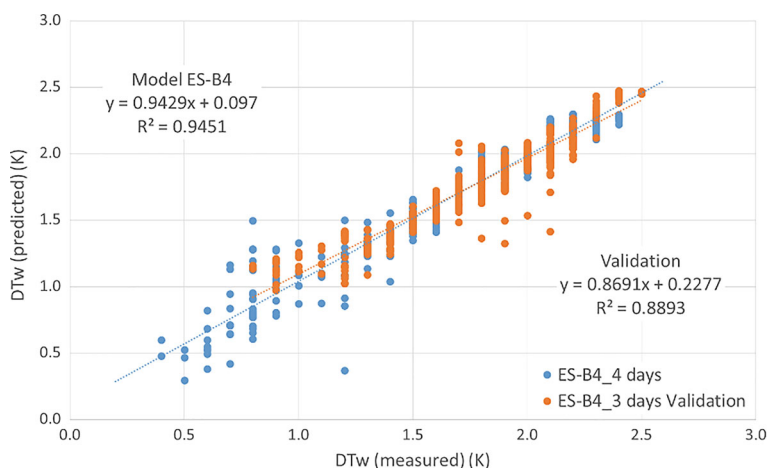


Fig. 4 ES-B4 model validation. DTw measured versus predicted

where: CP_{SR} (W/m^2) is the instantaneous cooling power of the sky radiator per unit area; $\dot{m}$ (kg/s) is the mass flow rate of water; c_p ($J/kg\ K$) is the specific heat of the water; DTw (K) is the difference in water temperature between the inlet and outlet of the radiator and A (m^2) is the area of the sky radiator.

The models for series B1 and B4 were used to predict DTw values for series A3 and A2, respectively. This enabled the calculation of the average cooling potential for series B1 and B4 under the same conditions observed in series A3 and A2.

B1-A3 application model In both experimental series B1 and A3, water flow rates were kept relatively similar: 363 l/h in ES-B1 and 396 l/h in ES-A3; Circuit 1 operated using TES-2 (50 l) with 8 RCMs in both cases.

The ES-B1 regression model was used to predict DTw using the data from series A3. The obtained values were lower than those measured during the A3 experimental series (1.65 K Vs. 1.87 K) (Table 1). As a result, the average predicted CP_{SR} for series B1, based on A3 data, was $61.3\ W/m^2$, which is 19% lower than the average value experimentally determined in series A3. The predicted average CP_{SR} increased from 52.4 to $61.3\ W/m^2$, representing a 17% increase compared to the values observed during the monitoring period. However, this increase remained below the CP_{SR} determined for series A3 ($75.8\ W/m^2$). This increase may be attributed to more favorable climatic conditions in series A3 compared to series B1. The results also suggest a better thermal performance of the system in series A3 than in series B1. It is important to highlight that the water flow rate in series A3 was 33 l/h higher than in series B1. While this difference alone may not fully explain the variation in results, it should still be considered in the analysis. One of the limitations observed during system monitoring was the need to establish a specific water flow rate (WFR). Achieving this precisely proved challenging, so we accepted having relatively similar values

between experimental series when identical values were intended, as this consistency was necessary for future comparisons between them.

B4-A2 application model In both experimental series B4 and A2, the water flow rates remained virtually the same: 376 l/h in ES-B4 and 387 l/h in ES-A3; Circuit 1 was operated with TES-1 (1000 l) and 8 RCMs in both cases.

Applying the ES-B4 regression model to the ES-A2 data results in higher predicted values than those recorded during the experimental series. Both the measured DT_w values (series averages) and the cooling potentials calculated from the actual data are presented for each series in Table 1. The average CP_{SR} for ES-A2 is 63.8 W/m², while for ES-B4, it is 68.1 W/m².

When applying the ES-B4 model to the corresponding ES-A2 data, the predicted average CP_{SR} increases from 68.1 to 77 W/m², representing a 12% increase compared to the observed values during the monitoring period. This increase can be interpreted not only as a result of more favorable climatic conditions but also as an indication of improved thermal performance in the configuration with TES-1 and PRC material compared to the A2 configuration without PRC material.

The present results do not allow for a definitive conclusion on whether polypropylene sky radiators with or without PRC material are more effective during nighttime hours (10:30 p.m.–8:00 a.m.). This is likely because both surfaces exhibit very similar emissivity values, explaining why the equilibrium temperatures of the two radiator material samples (Tr2 and Tr3) remained nearly identical throughout the night. However, the experimental series clearly demonstrated an increase in the number of daily cooling hours when the radiators were covered with PRC material. Based on the experimental results, the use of PRC material in sky radiators is estimated to extend the duration of effective water cooling by an additional two to five hours per day, depending on climatic conditions. Further investigation is required as part of the ongoing study.

Table 1 Average temperature differences between the radiator inlet and outlet and corresponding measured and predicted CP_{SR} values

Dates	Series	Real data		Predicted w/data A2 and A3		TES	WFR	8-RCM
		DT _w (K)	CP _{SR} (W/m ²)	DT _w (K)	CP _{SR} (W/m ²)			
		Avg	Avg	Avg	Avg			
09/08 to 12/08	A2	1.61	63.8			1	387	X
10/09 to 16/09	B4	1.77	68.1	2	77.0	1	376	X
13/08 to 16/08	A3	1.87	75.8			2	396	X
20/08 to 27/08	B1	1.41	52.4	1.65	61.3	2	363	X

4 Conclusions

The development and application of multiple correlation models, integrating some of the most influential climatic and operational factors, allowed for a comparative analysis of the experimental series.

The application of the developed and validated multiple correlation models has demonstrated improved system performance in series B1 and B4 compared to A3 and A2, respectively. The climatic conditions during A2 and A3 were more favorable for radiative cooling than those observed in B1 and B4.

However, applying the ES-B1 predictive model under ES-A3 conditions does not result in a higher average cooling potential, unlike the ES-B4 prediction using ES-A2 data. These findings prevent us from definitively determining which configuration exhibits superior thermal performance. It is important to note that ES-A3 had a water flow rate 33 l/h higher than ES-B1, which may have influenced the results.

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References

1. IEA (2018) The future of cooling, IEA, Paris. <https://www.iea.org/reports/the-future-of-cooling>
2. Santamouris M (2018) Cooling the buildings—past, present and future. *Energy Build* 128(1):617–638
3. Santamouris M, Kolokotsa D (2016) Passive cooling dissipation techniques for buildings and other structures: the state of the art. *Energy Build* 140:121–137
4. Givoni B (1994) *Passive low energy cooling of buildings*. Wiley
5. González-Cruz EM, Krüger EL (2022a) Experimental study on a low energy radiant-capacitive heating and cooling system. *Energy Build* 255:111674
6. Raman A, Anoma M, Zhu L, Rephaeli E, Fan S (2014) Passive radiative cooling below ambient air temperature under direct sunlight. *Nature* 515:540–544
7. Zhao B, Hu M, Ao X, Chen N, Pei G (2019) Radiative cooling: a review of fundamentals, materials, applications, and prospects. *Appl Energy* 236:489–513
8. Zhang Q, Wang S, Wang X, Jiang Y, Li J, Xu W, Zhu B, Zhu J (2022) Recent progress in daytime radiative cooling: advanced material designs and applications. *Small Methods* 6(4):2101379
9. Gonzalez E, Perez G, Borja F, Alonso C, Martin-Consuegra F, Kruger E, Gutierrez A, Arranz B (2024) Full-scale facility for the assessment of night and daytime passive radiative cooling. In: Fernandez J, Dominguez S, Roaf S (eds) *Proceedings of 2024 CATE conference*, 20–22 November 2024 Seville, Spain
10. SPACECOOL. Homepage, <https://spacecool.jp/en/product/film/>. Last accessed 14 Mar 2024
11. Keith TZ (2019) *Multiple regression and beyond*. Routledge, Taylor & Francis Group, NY

Unlocking Deep Renovation Potential: A Systems Thinking-Driven Socio-economic and Circular Economy Analysis of Housing Sector in Bologna



Shantanu Raut, Roisin Cahill, Jacopo Gaspari, and Lia Marchi

Abstract The European Union's housing sector is a major contributor to energy consumption and emissions, making deep renovation essential for achieving energy efficiency and circular economy goals. However, 85% of EU buildings were constructed before 2001, and large-scale retrofitting faces barriers such as high costs, fragmented policies, and stakeholder misalignment. Bologna exemplifies these challenges due to aging buildings, socio-economic disparities, and inconsistent policies. This study employs a qualitative approach, integrating secondary data analysis and a Systems Thinking framework to examine deep renovation barriers. A Causal Loop Diagram (CLD) analysis identifies reinforcing market mechanisms and constraints such as high costs and policy instability. A Multi-Dimensional Matrix links these barriers to targeted interventions, including financial incentives, regulatory stability, and circular material adoption. By embedding circular economy principles, stable financing, and stakeholder coordination, this research presents a scalable policy framework to accelerate deep renovation across the EU, supporting climate targets, resource efficiency, and energy equity.

Keywords Energy efficiency · Policy barriers · Financial incentives · Housing sector · Systems thinking · Stakeholder engagement

1 Introduction

The European Union's building sector accounts for 40% of total energy use and 36% of greenhouse gas emissions, making deep renovation a critical strategy for achieving decarbonization and energy efficiency goals [1]. With 85% of EU buildings constructed before 2001, renovation efforts must go beyond incremental improvements to achieve substantial reductions in energy demand. The EU Renovation

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Wave Strategy (2020) aims to double renovation rates by 2030, emphasizing deep renovation as a key carbon reduction and sustainability mechanism.

Deep renovation reduces primary energy consumption by at least 60% and typically involves upgrading building envelopes, modernizing HVAC systems, and integrating renewable energy [2]. It also lowers energy costs, improves indoor air quality, and enhances housing affordability [3]. However, widespread adoption remains limited due to high upfront costs, long payback periods, fragmented policies, and regulatory barriers. Additionally, while policies prioritize operational energy efficiency, they often neglect material circularity, leading to high embodied carbon emissions and inefficient resource use [4].

Bologna, a major urban center, exemplifies these EU-wide challenges as it faces significant renovation barriers, including an aging building stock, high energy demand, and limited material reuse [5]. Research calls for an integrated approach that aligns financial mechanisms, regulatory support, and circular economic principles.

2 Context and Background

2.1 Barriers to Deep Renovation

Despite its benefits, deep renovation adoption is constrained by financial, regulatory, and material inefficiencies. High upfront costs and uncertain returns deter property owners, while inconsistent subsidies and abrupt policy changes further undermine investor confidence [6]. The issue is particularly pronounced in the housing sector, where landlords bear renovation costs while tenants benefit from energy savings, discouraging private-sector investment [7].

Furthermore, regulatory barriers such as Inconsistent building codes, complex permitting processes, and fragmented decision-making across governance levels delay implementation [4]. Without standardized EU-wide renovation guidelines, retrofitting efforts remain inefficient and uncoordinated.

While inefficiency also hinders progress, policies emphasize operational energy savings but often overlook the environmental impact of construction materials. The lack of circular economy integration results in significant waste generation and high embodied carbon [8]. Addressing these barriers requires a systemic approach that aligns financial, regulatory, and material strategies.

2.2 Emerging Solutions and Trends

Deep renovation is advancing through new approaches integrating circular economy principles, financial innovation, and policy reform. Strategies like design for disassembly, material reuse, and prefabrication cut costs and lower embodied carbon

[9]. Digital tools like Building Information Modelling (BIM) and material passports enhance material traceability, optimizing renovation planning and execution.

Innovative financial models such as Energy Service Company contracts, green bonds, and performance-based financing mechanisms enable larger-scale investments. Cities like Amsterdam and Copenhagen have successfully combined public subsidies with private capital to create scalable renovation funding structures [2].

Policy reforms are streamlining renovation efforts by simplifying permitting procedures, enforcing minimum energy efficiency standards, and ensuring long-term financial stability for property owners. Some models advocate for phased subsidy reductions rather than abrupt removals to maintain market stability. By aligning financial incentives, regulatory support, and stakeholder engagement, these renovation strategies can serve as a model for accelerating deep renovation across the EU while balancing energy efficiency, resource sustainability, and social equity.

2.3 *System Thinking in Deep Renovation*

Deep renovation is a multi-faceted process shaped by financial, regulatory, technical, and social factors. Conventional energy efficiency policies often tackle these barriers in isolation, failing to account for their dynamic interdependencies [10]. A Systems Thinking approach offers a holistic analytical framework to analyse these complex interdependencies, allowing for the identification of feedback loops, unintended consequences, and key leverage points.

For example, the Superbonus 110% scheme exemplifies how linear policy interventions can create unintended effects. While the scheme temporarily boosted renovation activity, it also led to supply chain bottlenecks, inflated costs, and failed to establish a self-sustaining market a classic “Fixes That Fail” archetype [6].

A multi-stakeholder collaboration can lead to a successful deep renovation initiative, but conflicting priorities often slow progress [7]. Financial institutions and Energy Service Companies offer green loans and energy contracts, but long return-on-investment periods deter large-scale investments. Meanwhile, developers and the construction sector influence material choices and workforce capacity but prioritize affordability over sustainability.

Building owners and tenants face affordability constraints and renovation disruptions, limiting adoption. The landlord-tenant split incentive remains a significant barrier, as landlords lack the motivation to retrofit properties when tenants benefit from energy savings. Addressing this issue through tax incentives, cost-sharing models, and rental efficiency standards could improve adoption.

In Bologna’s San Donato district, community-led renovation projects have demonstrated how strategic densification enhances energy efficiency and property value. However, inconsistent incentives and weak regulations continue to limit large-scale adoption.

3 Methodology

This study employs a qualitative approach, integrating secondary data analysis and a Systems Thinking framework to examine the financial, social, and technical barriers affecting deep renovation in Bologna’s housing sector. Given the complexity of these challenges, a holistic perspective is essential to understanding how policies, market dynamics, and stakeholder interactions shape renovation efforts.

A Systems Thinking framework moves beyond traditional reductionist methods by capturing feedback loops and interdependencies rather than treating barriers in isolation. Policy measures, financial mechanisms, and technical constraints interact in ways that influence renovation adoption, making it crucial to identify leverage points for intervention. By mapping these relationships, this approach provides a structured and scalable pathway for accelerating deep renovation.

The study synthesizes scientific literature, policy reports, and empirical studies to support this analysis, drawing from sources such as the EU Renovation Wave Strategy, Italy Buildings Climate Tracker, and national policy frameworks. Research selection prioritized key themes, including financial constraints, circular economy integration, energy efficiency policies, and stakeholder engagement, ensuring a comprehensive evaluation of the renovation landscape. A workflow diagram (Fig. 1) illustrates the methodological approach.

3.1 System Analysis and Causal Loop Diagram (CLD) Development

A Causal Loop Diagram (CLD) is developed using Vensim software to analyse deep renovation dynamics systematically. The CLD maps out reinforcing (R-loops) and balancing (B-loops) that influence renovation adoption, highlighting key leverage points. Reinforcing loops (R-loops) identify positive feedback mechanisms, such as

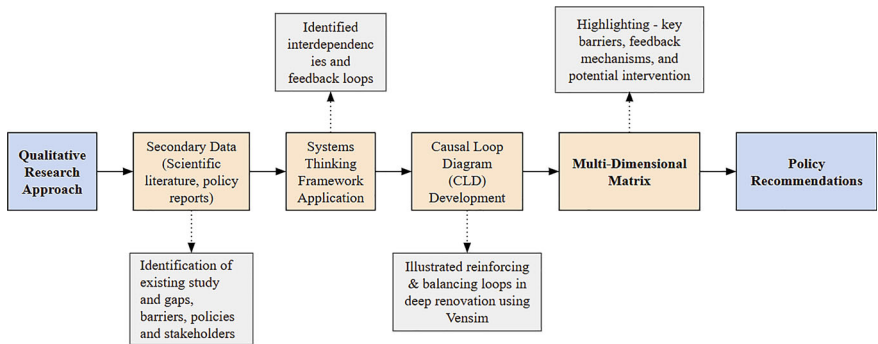


Fig. 1 Methodology workflow diagram

how financial incentives increase renovation activity, boosting market demand and investment confidence. Balancing loops (B-loops) represent systemic constraints, such as high upfront costs, policy instability, and supply chain limitations, which slow down renovation efforts.

The CLD construction process involved categorizing key variables, mapping cause-and effect relationships, and identifying leverage points where targeted interventions could improve renovation rates. The relationships are established based on empirical findings from the literature. Building on the CLD findings, a multi-dimensional matrix is developed to align barriers, systemic causes, and policy solutions.

4 Results

The systemic insights derived from the Causal Loop Diagram (CLD) analysis and the Multi-Dimensional Matrix, highlighting the key barriers, feedback mechanisms, and potential intervention in Bologna's housing sector. The Causal Loop Diagram (CLD) analysis (Fig. 2) highlights the interplay between reinforcing loops (R-loops) that drive deep renovation adoption and balancing loops (B-loops) that create systemic barriers. These feedback mechanisms shape the effectiveness of renovation strategies, influencing investment flows, stakeholder engagement, and policy implementation. The reinforcing loops show how positive interventions can lead to market expansion and increased renovation activity.

The Investment-Driven Growth Loop (R1) demonstrates that financial incentives and government subsidies can enhance market confidence, attracting private investment and stimulating demand for deep renovation. Similarly, the Circular Economy Adoption Loop (R2) highlights that increasing material reuse and prefabrication techniques can reduce renovation costs and emissions, reinforcing circular construction's economic and environmental benefits. Another key enabler is the Public Awareness and Homeowner Engagement Loop (R3), which shows that as residents experience lower energy bills and improved comfort, their willingness to invest in deep renovation increases, further stimulating demand.

On the other hand, balancing loops reveal systemic barriers that slow or prevent deep renovation. The High Renovation Costs and Long ROI Loop (B1) identifies the financial challenges associated with deep retrofitting, where upfront costs and long return-on-investment (ROI) periods discourage homeowners and investors. This issue is exacerbated by material price inflation and labor shortages, necessitating expanded ESCO financing, green loans, and phased incentives to make renovations more financially viable. The Policy Uncertainty and Market Instability Loop (B2) illustrates how frequent changes in subsidy programs and regulatory frameworks create investment risks, leading to hesitation among private sector stakeholders. Ensuring long-term financial stability, gradual phase-outs of subsidies, and structured policy roadmaps can help address these concerns.

4.1 Multi-dimensional Matrix: Linking Barriers to Policy Interventions

The Multi-Dimensional Matrix (Table 1) provides a structured approach to aligning deep renovation challenges with targeted policy and financial interventions. It identifies systemic barriers and connects them to specific interventions and responsible stakeholders. For example, the high renovation cost and longer ROI (B1) can be mitigated by introducing energy service companies' financing mechanisms, green loans, and phased financial incentives, reducing the burden on homeowners and investors. A more structured approach is needed to address policy uncertainty market instability (B2), including long-term financial frameworks, gradual phase-outs of subsidies, and investment-friendly policies.

One of the key gaps identified in the analysis is the limited adoption of circular economy principles (R2) due to high upfront costs and a lack of incentives for material reuse. Implementing material passports, financial incentives for reused materials, and digital tracking tools such as Building Information Modelling (BIM) could significantly enhance circular renovation practices. Additionally, addressing the landlord-tenant misalignment (B3) through tax deductions, co-financing models, and efficiency requirements for rental properties can help bridge the financial gap in rental housing retrofits.

By linking barriers, systemic causes, and solutions, the matrix is a decision-support tool for policymakers, financial institutions, and industry stakeholders. It ensures that deep renovation strategies are conceptually strong and practically viable within Bologna's housing sector.

5 Key Findings and Conclusion

Deep renovation in Bologna faces financial, regulatory, technical, and stakeholder-related challenges, requiring an integrated approach to scale adoption effectively. A significant barrier is financial accessibility, as high upfront costs and long ROI periods discourage investment. Expanding Energy Service Company financing, tax incentives, and structured subsidies can improve affordability, but long-term investor confidence remains weak without regulatory stability. Establishing policy continuity and phased subsidy reductions is essential to maintaining market trust.

The circular economy principles are not fully embedded in renovation practices. While efforts focus on operational energy efficiency, material reuse, and embodied carbon reduction remain largely overlooked. Strengthening reuse mandates, financial incentives, and digital tracking tools (e.g., BIM) can enhance sustainability. The landlord-tenant split incentive further complicates renovation efforts in the rental sector, requiring tax benefits and shared renovation funding to align stakeholder interests.

Table 1 Multi-dimensional matrix to reinforce deep renovation and circularity

Identified barrier	Systemic cause (CLD links)	Proposed interventions	Expected impact	Stakeholders
High Renovation Costs	Balancing Loop (B1)—High upfront costs discourage investment	Expand Energy Service Company financing, green loans, and phased incentives	Reduces upfront costs, attracts private investors and shorten return on investments	Financial Institutions, Energy service companies
Policy Uncertainty and Market Instability	Balancing Loop (B2)—Frequent changes in government incentives reduce investor confidence	Implement gradual phase-out mechanisms for subsidies instead of abrupt removals	Maintains long-term private investment in renovation and ensures stability renovation market	Policymakers, Regulatory Authorities
Tenant-Landlord Split Incentive Problem in Rental Housing	Balancing Loop (B3)—Landlords lack financial motivation to invest in renovations because tenants benefit from energy savings	Introduce tax reductions for landlords who renovate rental properties, shared renovation funding schemes, and minimum energy efficiency standards for rental housing	Increase renovation rates in rental housing, reduces energy poverty, and improves energy efficiency	Government Authorities, Rental Housing Associations, Real Estate Developers
Low Private Investment in Deep Renovation	Reinforcing Loop (R1)—Stable financial incentives attract investors, increasing deep renovation adoption	Establish long-term subsidy frameworks, introduce tax credits for private sector investments, and ensure stable regulatory policies	Increases investor confidence, ensures sustainable market growth for deep renovation, and attracts long-term private sector investment	Government Authorities, Financial Institutions, Private Sector Stakeholders

(continued)

Table 1 (continued)

Identified barrier	Systemic cause (CLD links)	Proposed interventions	Expected impact	Stakeholders
Limited Adoption of Circular Economy Practices in Renovation	Reinforcing Loop (R2)—High cost of circular construction materials limits adoption	Mandate material passports, provide tax incentives for circular materials, and promote digital tracking tools such as BIM	Encourages material reuse, reduces renovation costs, and aligns renovation practices with circular economy principles	Construction Industry, European Union Policymakers, Sustainability Agencies
Lack of Public Awareness and Homeowner Engagement	Reinforcing Loop (R3)—Homeowners are unaware of the financial and energy benefits of deep renovation	Launch awareness campaigns, introduce transparent energy labelling systems, and promote green building certification programs	Increases homeowner willingness to invest in deep renovation and improves public understanding of long-term cost savings	Government Agencies, Non-Governmental Organizations, Media Organizations

The Causal Loop Diagram (CLD) analysis demonstrated how investment-driven market growth and circular material adoption can reinforce renovation progress while high costs and regulatory instability act as constraints. The Multi-Dimensional Matrix linked these barriers to targeted policy solutions, including financial incentives, tax benefits, and circular material mandates.

For Bologna to successfully scale deep renovation, it must prioritize long-term financial stability, regulatory consistency, and stronger stakeholder coordination. Expanding financing mechanisms, structured subsidies, and public engagement will be critical. Bologna can serve as a replicable model for sustainable renovation across the EU by embedding circular economy principles and ensuring policy coherence.

References

1. Buildings Performance Institute Europe (BPIE) (2024) Accelerating deep renovation in the EU with renovation passports: EU roadmap proposing concrete measures to maximise the uptake of iBRoad2EPC schemes. BPIE, Brussels
2. D’Oca S, Ferrante A, Ferrer C, Perneti R, Gralka A, Sebastian R, Op ’t Veld P (2018) Technical, financial, and social barriers and challenges in deep building renovation: integration of lessons

- learned from the H2020 cluster projects. *Buildings* 8(12):174. <https://doi.org/10.3390/buildings8120174>
3. Barrella R, Linares JI, Romero JC, Arenas E (2023) Evaluating the impact of energy efficiency strategies on households' energy affordability: a Spanish case study. *Energy Build* 295:113289. <https://doi.org/10.1016/j.enbuild.2023.113289>
 4. Amoah C, Smith J (2024) Barriers to the green retrofitting of existing residential buildings. *J Facilities Manag* 22(2):194–209. <https://doi.org/10.1108/JFM-12-2021-0155>
 5. Fabbri K, Gaspari J (2021) Mapping the energy poverty: a case study based on the energy performance certificates in the city of Bologna. *Energy Build* 234:110718. <https://doi.org/10.1016/j.enbuild.2021.110718>
 6. Buildings Performance Institute Europe (BPIE) (2025) Italy buildings climate tracker: is Italy on track to decarbonise its building stock? BPIE, Brussels
 7. Fořt J, Černý R (2022) Limited interdisciplinary knowledge transfer as a missing link for sustainable building retrofits in the residential sector. *J Clean Prod* 343:131079. <https://doi.org/10.1016/j.jclepro.2022.131079>
 8. Pomponi F, Moncaster A (2017) Circular economy for the built environment: a research framework. *J Clean Prod* 143:710–718. <https://doi.org/10.1016/j.jclepro.2016.12.055>
 9. Rahla KM, Mateus R, Bragança L (2021) Implementing circular economy strategies in buildings—from theory to practice. *Appl Syst Innov* 4(2):26. <https://doi.org/10.3390/asi4020026>
 10. Meadows DH (2008) *Thinking in systems: a primer*, 2nd edn. Earthscan, London

Scaling Renewable Energy Communities: A Critical Analysis of Mechanisms to Accelerate the Energy Transition



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Abstract Renewable Energy Communities (REC) offer a promising pathway towards a global energy system transformation. Although EU member states have developed enabling frameworks to accelerate the growth of REC, the consequences of ‘scaling’ energy communities remain under explored. This study asks which aspects of REC are being scaled and how, through a literature review with qualitative content analysis. We develop an indicative mapping of REC scaling and amplification literature categorised by amplification typologies, whether scaling increases impacts within the community, external to the community, or at institutional levels beyond the community. The findings suggest the need for further research in ‘amplifying beyond’: scaling that changes mindsets and values, to unlock the full potential of REC as deep levers of the energy system transformation.

Keywords Renewable Energy Community · Energy transition · Scaling · Amplifying

1 Introduction

1.1 Purpose

In 2018 the Intergovernmental Panel on Climate Change (IPCC) called for a transformation of the global energy system at a rate and scale with “no documented precedent” [1]. Yet, the global energy system remains a source of political conflict, environmental destruction and economic inequality. Renewable Energy Communities (REC) offer a promising pathway to a democratic, climate neutral future. REC as defined by Renewable Energy Directive (RED) II (part of the 2016 EU Clean Energy Package), are legal entities of citizen renewable energy prosumer collectives. Their

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primary objective is “to provide environmental, economic or social community benefits for its members or local areas”. ‘Community’ is a core characteristic of REC due to their purpose of adding regional value, and the relationship structure between members and the energy generation facilities. A characteristic at odds with the scale of transformation called for by the IPCC [1].

To address this challenge, the emerging interdisciplinary field of ‘Scaling and Amplifying’ investigates the ‘shift in scales’ from local sustainability actions to global impact [2]. ‘Scaling’ and ‘amplifying’ refer to the process of increasing impact. This study examines academic literature that advances REC amplification processes, strategies, and mechanisms [3]. REC scaling and amplification processes tend to take an instrumentalized approach, encouraged by the politics of urgency. This raises concerns regarding how scaling impacts the intrinsic value of community initiatives [2, 4].

This paper aims to identify what impact REC scaling processes strive to increase, and how. It contributes to identifying gaps that are potentially restricting the transformational agency of REC in the energy transition. Section 1 provides context and purpose, Sect. 2 details the method, Sect. 3 describes the resulting data which is discussed in Sect. 4.

1.2 Literature Context

Despite inconsistent applications of the term ‘scale’ due to concerns of hierarchical and geographical connotations, and the diversity of the research field, amplification and scaling research shares a purpose: examining how small-scale initiatives can have large-scale impact [2]. Systems thinker Meadows (1999) proposes a hierarchy of intervention for transforming a system. She finds that altering the goal of a system, or the mindset or paradigm in which the system exists to be amongst the most efficient levers for system change, they are ‘deep leverage points’ for transformation [5]. An agreed purpose, or shared vision, is a key precursor of a paradigm shift, or energy system transformation [6]. RED II provides REC with a defined role in the energy transition at an EU level. Yet, at an individual REC level, the flexibility of REC forms is noted as an advantage over conventional energy generation methods [7]. REC have the potential to simultaneously address social, economic and environmental issues at a local and global level [2].

As this paper seeks to investigate the increase in impact sought by REC amplification and scaling literature, it utilizes Lam et al. (2020) amplification typology to develop a theoretical framework. In contrast to Meadows hierarchy of intervention, Lam et al. argues processes from each of the proposed amplification categories; *amplify within*, *amplify out* and *amplify beyond* are required to achieve a sustainable transformation (See Table 2) [3]. The type of scaling and amplification used to increase REC impact is an important consideration as not all elements of a community are scalable. Studies show instrumentalization of community initiatives may amplify one element at the cost of another [4]. For example, *up-scaling* can damage

community bonds [2], while the external provision of a short-term output driven agenda reduces bottom-up initiatives' transformative potential. Yet, energy community studies continue to investigate 'how to' scale with little consideration on the impact of scaling [4].

2 Method

To address the research question, "what does REC scaling seek to increase?" we carried out a scoping review and qualitative content analysis (QCA) of REC scaling and amplification literature. The study design is based on the PICO framework, to increase relevance of material collection, within the PRISMA guidelines for systematic reviews. A manifest QCA method is used to assess and extract meaning from the collected material, identifying the authors' explicit meaning [9]. The review and analysis are directed by two sub-research questions:

- (1) What is the primary amplification objective?
- (2) What amplification process is proposed or advanced?

2.1 Material Collection

We utilized the Scopus database to identify relevant REC scaling and amplification literature, as Scopus has both a broad range of disciplines and one of the largest collections of peer reviewed scientific literature. By setting search field criteria for title, abstract and keywords and limiting results to articles and reviews published since the publishing of RED II, within RED II jurisdiction, and containing terminology of the eight sustainability amplification typologies, in addition to alternative terminology used to discuss amplification processes: strategies, patterns and mechanisms [3]. The following search string was resulted in 66 documents in the Scopus database on 2025-03-04: TITLE-ABS-KEY ("renewable energy communi*" and (scaling OR amplify* OR (scal* and (out OR up OR deep)) OR upscal* OR outscal* OR replicat* OR partner* OR instrument* OR embed* OR deepen* OR broaden* OR grow* OR accumulat* OR transform* OR mechanism* OR strateg* OR pattern*)) and PUBYEAR > 2018 and (LIMIT-TO (AFFILCOUNTRY, "Country xxx")) and (LIMIT-TO (SUBJAREA, "xxx")) and (LIMIT-TO (DOCTYPE, "ar")) OR LIMIT-TO (DOCTYPE, "re")) and (LIMIT-TO (LANGUAGE, "English")).

After a primary screening of the resulting documents against the study's eligibility criteria; 12 papers that do not explicitly state an amplification objective, and propose or advance an amplification process are excluded. This study differentiates between precursors to scaling, such as papers focused on identification or advancement of enabling conditions for REC, and those advancing a scaling process or method [3]. Which resulted in the exclusion of 9 papers that focused on REC enabling conditions,

and 15 descriptive analytic papers on REC characteristics or performance. Descriptive analytic papers are outside the scope of this study as they do not directly propose an amplification method. One paper is excluded at the analysis stage due to full paper access restrictions. The effects of this study boundary are discussed in Sect. 4.

2.2 Data Extraction and Analysis

The remaining 27 papers are manually analysed. Following the QCA methodology of Bengtsson (2016), data answering the research sub questions are extracted and format-*ted* as meaning units and collated as an inventory of analysis schedules (see Table 3) [9]. Using the theoretical framework (see Tables 1 and 2) a coding agenda is developed and applied to the meaning units in three coding phases.

Phase 1, the explicit primary amplification objectives of each paper are recorded as quotes, and categorised based on the theoretical framework which utilizes the six energy community objectives of Bauwens et al. (2022) (see Table 1). Through an iterative inductive coding process, the community objectives are expanded to include ‘Energy Efficiency’ and ‘REC Establishment’ [8].

Phase 2, the amplification processes proposed or advanced by the reviewed papers are analysed and categorised using an iterative inductive coding process resulting in three categories; *Design and Initiation Methods*—processes that seek to support the establishment of new REC or REC activities. *Controls and Operations Strategies*—processes that seek to increase REC operational performance such as power sharing methods or growth protocols. *Configuration Strategies*—processes that seek to increase REC performance through the organisation of its components.

Phase 3, the amplification typology categories (see Table 2) are employed as a deductive category framework to analyze the amplification objectives and processes of the collected literature. While this study extracts data on both the amplification

Table 1 Amplification objectives. Theoretical framework

Category	Description
Environmental	Improve environmental conditions
Energy efficiency	Towards balancing energy consumption and production
Infrastructural	Improvement of energy system
Social	Increase social capital
Political	Reduce power imbalances
Energy autonomy	Increase in energy prosumership
Economic gain	Receive financial benefit
Establishment	Create additional REC

Source Author’s elaboration based on references [8]

Table 2 Typology of amplification. Theoretical framework

Category	Sub-category	Description
Amplifying within <i>Description</i> seeks to prolong or accelerate the impact	Stabilizing	Aims to strengthen, embed, increase resilience etc. of an existing initiative
	Speeding up	Aims to accelerate rate of impact E.g. increase efficiency, optimize
Amplifying Out <i>Description</i> seeks to increase the impact range	Growing	Aims to expand the impact range co-dependent initiatives
	Replicating	Aims to copy an initiative into a dissimilar context
	Transferring	Aims to adapt an initiative and implement it in a similar but independent context
	Spreading	Aims to share core principles and approaches to dissimilar contexts
Amplifying Beyond <i>Description</i> seeks to alter regimes or mindsets	Scaling up	Aims to impact higher institutional levels by changing regime rules
	Scaling deep	Aims to change mindsets and values

Source Author’s elaboration based on references [3]

Table 3 Analysis schedule extract

Meaning unit	Coding phase		Code
“This paper aims at reducing both electricity and space heating demands of residential districts.....this research proposes an energy efficiency measure that can be easily implemented without a major refurbishment of the buildings, addressing a common barrier as residents often resist invasive construction....This paper proposes an innovative solution ... a novel layout that combines the renewable energy community paradigm with Power-to-Heat technology, specifically tailored for existing residential areas”	1	Amplification objective category	Energy efficiency
	2	Amplification process	Configuration strategies
	3	Amplification typology	Speeding up Growing
		Amplification category	Within Out

Source Author

objective and process, analysis is carried out with awareness of complex relationship of process and objective [10].

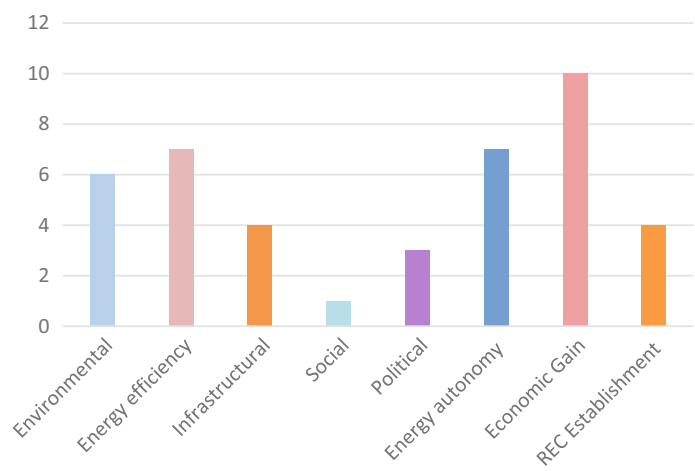


Fig. 1 Primary amplification objectives of REC scaling and amplifying publications. *Source* Author. *Note* 42 amplification objectives are recorded from 27 publications, this is due to papers that explicitly state more than one amplification objective without clear prioritization

3 Results

The QCA results are formatted to address the two-sub research question. Figure 1. addresses ‘What is the primary amplification objective?’ Fig. 2. addresses ‘What amplification process is proposed or advanced?’.

4 Discussion

Amplification Processes. This study finds that REC scaling processes are distributed across the categories of amplifying within (22) and amplifying out (17), with no literature seeking amplification beyond. Suggesting a gap that may restrict REC transformational potential as transformation requires processes in all three amplification categories [3]. It is essential this finding is read in context of the study’s limitations. The study scope excluded reviewing descriptive analytic publications, which could themselves be classified as an amplification process—as they disseminate learnings of REC, changing mindsets or support policy recommendations, therefore altering the regime. The lack of literature supporting ‘Replicating’ processes is understood in the context that the flexibility and adaptability of the REC model is one of its valued characteristics [7].

Amplification Objectives. The study found ‘Economic Gain’ to be the most frequently explicitly sought objective. A contradiction to the shared vision set by RED II, which states financial profit is to be a secondary priority for REC. The finding

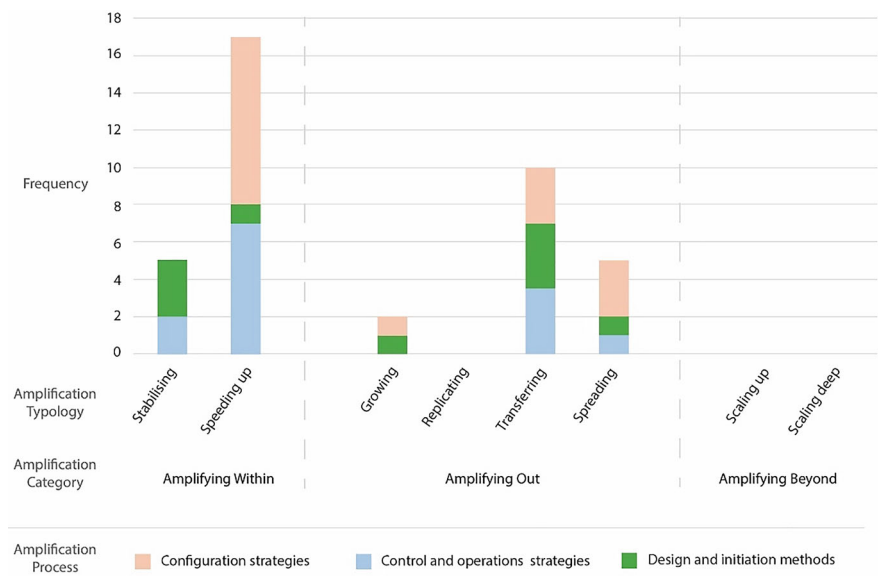


Fig. 2 The amplification processes, typology and categories supported by REC scaling and amplifying publications. *Source* Author. *Note* 39 amplification processes are recorded from 27 publications, this is due to papers that advance or propose processes that can be classified as more than one amplification typology

corresponds with the leading motivation of individuals joining an energy community, to reduce energy costs. Combined with the finding that ‘Speeding Up’ amplification processes, which seek optimization and efficiency, are the most frequently advanced scaling typology. This strengthens concerns that scaling of community initiatives is primarily through instrumentalization, and fuels debate that a techno-optimistic western mindset dominates the climate action strategies [4].

Contribution and Limitations.

This study contributes to mapping the REC scaling and amplification field and therefore to the call for a more conscious scaling of REC [2]. The study scope limits the mapping to a proportion of REC scaling and amplification literature as the material analysed is limited to those which explicitly state an amplification objective, and advance or propose an amplifying process. Further research is therefore required to comprehensively assess REC scaling and amplification processes. Additionally, as with any QCA analysis this study has limitation of human error and biases, which was mitigated through use of a coding agenda but does not claim to be comprehensive.

5 Conclusion

This study maps REC scaling processes by analyzing the amplification objectives and processes of relevant academic literature. The results support findings that instrumentalization of community initiatives is the leading form of REC scaling and amplification. As is evidenced by both the most frequently found primary amplification objective, '*Economic Gain*' and amplification process, '*Speeding Up*' (processes to increase efficiency).

To further detail the literature landscape map, future research may expand the scope of this study to include assessment of implied amplification objectives and descriptive analytic literature. This may aid in addressing the indicated gap in '*amplifying beyond*' research (scaling through impacting higher system levels), which may limit the true transformational potential of REC. All findings must be considered within the scope of the study which solely reviewed the explicit amplification objectives of REC literature focused on amplification processes.

Disclosure of Interests The author has no competing interests to declare that are relevant to the content of this article.

References

1. Masson-Delmotte V et al (2019) Global warming of 1.5°C an IPCC special report on the impacts of global warming of 1.5°C [Online]. Available: www.environmentalgraphiti.org
2. Schmid B, Taylor Aiken G (2023) A critical view on the role of scale and instrumental imaginaries within community sustainability transitions research. *Area* 55(4):506–513. <https://doi.org/10.1111/area.12884>
3. Lam DPM et al (2020) Scaling the impact of sustainability initiatives: a typology of amplification processes. *Urban Transformations* 2(1):1–24. <https://doi.org/10.1186/S42854-020-00007-9>
4. Koga H, Petrova S, Bouzarovski S (2024) Community-based energy governance and the political: towards a post-foundational energy democracy. In: *Progress in environmental geography*. <https://doi.org/10.1177/27539687241307955>
5. Meadows D (1999) Leverage points places to intervene in a system. The Sustainability Institute
6. Voulvoulis N et al (2022) Systems thinking as a paradigm shift for sustainability transformation, 01 Jul 2022. Elsevier Ltd. <https://doi.org/10.1016/j.gloenvcha.2022.102544>
7. Reis IFG, Gonçalves I, Lopes MAR, Henggeler Antunes C (2021) Business models for energy communities: a review of key issues and trends, 01 Jul 2021. Elsevier Ltd. <https://doi.org/10.1016/j.rser.2021.111013>
8. Bauwens T et al (2022) Conceptualizing community in energy systems: a systematic review of 183 definitions. In: *Renewable and sustainable energy reviews*, vol 156, Mar 2022. <https://doi.org/10.1016/J.RSER.2021.111999>
9. Bengtsson M (2016) How to plan and perform a qualitative study using content analysis. *NursingPlus Open* 2:8–14. <https://doi.org/10.1016/J.NPLS.2016.01.001>
10. Creamer E, Taylor Aiken G, van Veelen B, Walker G, Devine-Wright P (2019) Community renewable energy: what does it do? Walker and Devine-Wright (2008) ten years on. *Energy Res Soc Sci* 57:101223. <https://doi.org/10.1016/j.erss.2019.101223>

Dynamic Shading Device with Phase Change Materials: Optimized Performance for Resilient and Sustainable Building Stock



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Abstract Dynamic façades (DF) represent a promising approach to decarbonize the building sector, offering adaptability to environmental changes and users' habits. This research focuses on the design, manufacturing, and performance analysis of a Dynamic Shading Device incorporating Phase Change Materials (DS-PCM), targeted to passively improve the indoor thermal environment. A performance-based design tool is under analysis to streamline and evaluate the performance of this dynamic shading device across different conditions. Therefore, this paper presents the research methodology, workflow, and preliminary results of a numerical simulation aimed at comprehensively characterizing the dynamic shading device with PCM and evaluating the influence of building location (i.e., climate zone) on thermal performance. The numerical model was developed and validated based on the experimental data obtained from real-scale prototype testing in two test rooms: one equipped with a conventional curtain as the reference case and the other featuring the dynamic shading device incorporating PCM. Dynamic building simulations demonstrated that the DS-PCM device reduced thermal discomfort by up to 8% compared to a traditional curtain, with its impact being most significant in Portugal's moderate summer

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climate. These findings highlight the potential of this innovative dynamic shading system and emphasize the need for the development of a design tool for the sizing and optimizing of the dynamic shading system to aid designers and architects and offer a user-friendly interface for design purposes.

Keywords Dynamic indoor shading device • Phase change materials • Numerical model • Thermal comfort • Energy efficiency

1 Introduction

The revised Energy Performance of Buildings Directive (EPBD) sets that all new residential and non-residential buildings must meet zero-emission standards, which refers to high energy performance without on-site fossil fuel emissions [1] aligning with the European Union's (EU's) climate neutrality target for 2050 [2]. As the built environment contributes significantly to carbon emissions, a fundamental change in building envelope design is essential.

Building energy demand is greatly influenced by the translucent envelope [3]. While solar gains can reduce heating needs in colder months, they also pose challenges during warmer months by increasing overheating risks and cooling loads. Effectively balancing these opposing effects requires a careful design of glazing and solar shading elements. Shading systems are widely used as passive design strategies to mitigate excessive solar radiation. However, static shading solutions often fail to adapt to changing climatic conditions, and in response, dynamic shading systems have emerged [4, 5]. Another key strategy for enhancing energy savings, indoor thermal comfort, and reducing reliance on fossil fuels involves integrating Thermal Energy Storage (TES) systems into building components—such as Phase Change Materials (PCM). These materials can store and release thermal energy during both their sensible and latent phases [6], offering a passive means of temperature regulation.

The *PCM enhanced building envelope: optimized performance for resilient and sustainable building stock* doctoral research work plan emerges within this context, whose main objective is to design, develop, and study the performance of an innovative dynamic shading device for buildings, incorporating PCM, addressed to enhance energy efficiency and indoor thermal comfort. Since building energy simulation models provide accurate predictions of energy consumption and indoor thermal comfort, this paper presents the preliminary findings from a parametric analysis assessing the impact of different building locations on the test compartments' thermal performance. The findings of this doctoral research will contribute to defining a novel, replicable solution for diverse building applications, supporting the decarbonization of the building stock, promoting resource efficiency, and addressing the challenges of climate change.

2 Methodology

The methodology for the *PCM enhanced building envelope* doctoral research follows a holistic approach to designing, developing, testing, simulating, and evaluating the replicability potential of a novel dynamic shading device incorporating PCM (DS-PCM) device, and it is structured into three main research areas (Fig. 1).

The research methodology begins with designing and developing the DS-PCM device for glazed envelopes, aimed at mitigating indoor overheating (Research Task 1). The proposed system consists of an internal movable shading device with PCM (more detail in Sect. 3.2). A reference solution was also constructed for comparison and control purposes. The PCM's thermal properties were first analyzed using the Differential Scanning Calorimetry (DSC) method, and then, an experimental campaign tested the system in two real-scale, comparable Light Steel Framing (LSF) buildings. The DS-PCM's performance, evaluated through indoor temperature comparisons and thermal discomfort analysis, was thoroughly analyzed using different operational strategies to optimize its potential. To extend the experimental hypotheses through numerical simulation (Research Task 2) and achieve a comprehensive characterization of the DS-PCM device, the experimental results served as the basis for developing, calibrating, and validating numerical models. Subsequently, a dynamic simulation of the system will explore the impact of various parameters and scenarios on energy and thermal performances for both the reference and dynamic solutions. Once the analysis of experimental and simulation data has been completed, a performance-based design tool will be developed and refined (Research Task 3), targeted for replicating the DS-PCM device across various scenarios, to aid designers and architects and offer a user-friendly interface for optimizing the design of the proposed system. A methodology based on Artificial Neural Networks (ANN) is planned for the creation of this tool. As previously mentioned, this article builds on the initial steps and findings of the Numerical Simulation and Data Generation task (Research Task 2).

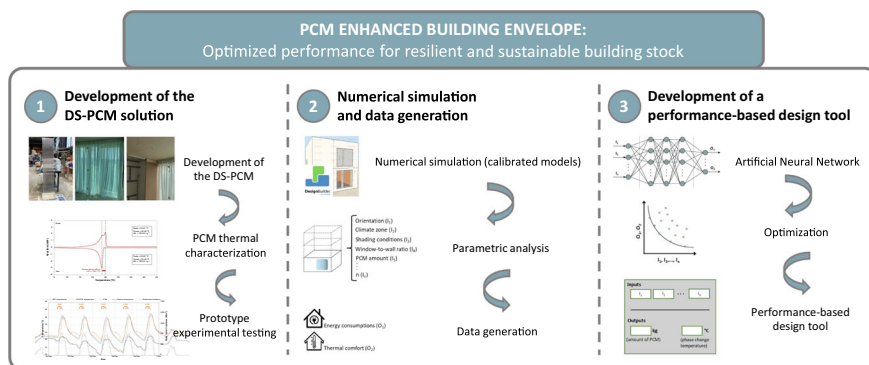
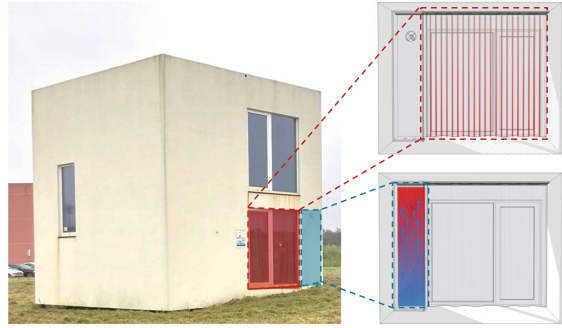


Fig. 1 Main tasks of the research methodology

Fig. 2 Case study and schematic view of the DS-PCM device



3 Model Development

3.1 Case Study

The performance of the DS-PCM device was experimentally evaluated in real-scale applications. A prototype was developed, installed, and tested in a compartment of full-scale LSF buildings—one featuring a conventional fabric curtain (REF) and the other integrating the DS-PCM device (Fig. 2). The case study is located on the University of Aveiro Campus, along Portugal's northern coast, and consists of two floors, a treated floor area of 35 m², a volume of 125 m³, and a glazed area of 13 m². The DS-PCM and REF systems were installed on the largest glazed surface of the buildings, measuring 2.07 × 2.08 m², and south-oriented to maximize solar heat gains ($U_{\text{Aluminium-frame}} = 2.40 \text{ W m}^{-2} \text{ }^{\circ}\text{C}^{-1}$; $U_{\text{Glass}} = 1.00 \text{ W m}^{-2} \text{ }^{\circ}\text{C}^{-1}$; SHGC = 0.21). A detailed characterization of these buildings was previously published by Gonçalves et al. [7]. The U -values of the LSF solutions were calculated using the analytical approach for non-homogeneous elements defined in ISO 6946 [8]: $U_{\text{Ground-floor-slab}} = 0.51 \text{ W m}^{-2} \text{ }^{\circ}\text{C}^{-1}$; $U_{\text{Walls}} = 0.47 \text{ W m}^{-2} \text{ }^{\circ}\text{C}^{-1}$; $U_{\text{Ceiling}} = 0.60 \text{ W m}^{-2} \text{ }^{\circ}\text{C}^{-1}$; $U_{\text{Internal-floor}} = 1.52 \text{ W m}^{-2} \text{ }^{\circ}\text{C}^{-1}$; $U_{\text{Compartment-walls}} = 0.40 \text{ W m}^{-2} \text{ }^{\circ}\text{C}^{-1}$.

3.2 Prototype Description

The PCM-integrated shading device absorbs heat from solar radiation when positioned in front of the window, reducing heat gains through the glazed areas during the cooling season (marked in red in Fig. 2). Once the PCM reaches a fully liquid state, the device moves to a discharging chamber connected to the outdoor environment, where crystallization occurs, rejecting the stored heat to the outdoor environment (marked in blue in Fig. 2). The prototype container was a PolyMethylMethAcrylate tube (PMMA, thermal conductivity: 0.19 W m⁻¹ °C⁻¹; density: 1190 kg m⁻³) with an outer diameter of 20 mm, an inner diameter of 16 mm, and a length of 2000 mm. A

paraffin-based PCM (Rubitherm RT25HC, thermal conductivity: $0.20 \text{ W m}^{-1} \text{ }^{\circ}\text{C}^{-1}$; density: 825 kg m^{-3}) was selected, with a peak melting temperature of $25 \text{ }^{\circ}\text{C}$ and a peak crystallization temperature of $23.6 \text{ }^{\circ}\text{C}$, requiring a thermal range of $20\text{--}25.6 \text{ }^{\circ}\text{C}$ for full charge and discharge. The material exhibits an enthalpy of 155.99 J g^{-1} during melting and 130.89 J g^{-1} during crystallization. Additionally, a traditional white indoor fabric curtain—identical to those used in the REF building—was incorporated into the solution.

3.3 Dynamic Thermal Simulation Model Definition

The dynamic simulation model was developed using *DesignBuilder/EnergyPlus*TM software and calibrated with data collected during an experimental campaign conducted in September 2024, based on indoor temperatures recorded in the test compartment and hourly outdoor climate data collected from a local weather station. The numerical model replicates the real building's characteristics and consists of three thermal zones: test compartment, discharging chamber, and remaining building zone. This study intends to evaluate the performance of the DS-PCM device in terms of thermal comfort enhancement. In this preliminary phase, the DS-PCM device follows a static approach, where the system remains continuously positioned in front of the window.

4 Results and Discussion

4.1 Model Validation

To validate the numerical model, a calibration process was conducted using real data to assess the model's accuracy against monitored values. Figure 3 shows the residuals (difference between real and simulated values) versus indoor air temperature.

The results indicate good agreement, with an average difference between real and simulated data below $3 \text{ }^{\circ}\text{C}$.

4.2 Influence of Building Location on Thermal Performance

Portugal is divided into three summer climate zones (V1, V2, V3), where higher index numbers correspond to more extreme seasonal conditions. Thus, to assess the impact of the DS-PCM device on thermal performance across different climate zones, three locations were selected: Aveiro (V1) with mild summer conditions, Bragança (V2) with a moderate summer climate, and Beja (V3) with an intense summer

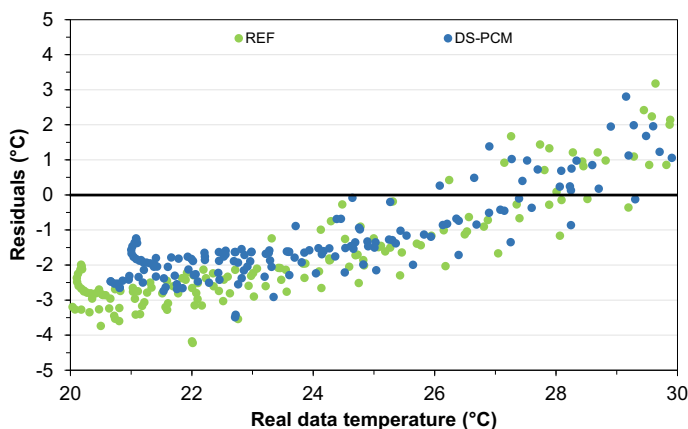


Fig. 3 Residuals values for the period under calibration in REF and DS-PCM compartments

climate. An annual numerical simulation was conducted for these locations, and the results of the thermal discomfort analysis are presented for the summer months (June–September). Figure 4 illustrates the thermal analysis results, the Degree-Hours Discomfort value (DHD, which quantifies the sum of positive differences between hourly indoor temperature and Portugal’s standard summer indoor comfort temperature limit of 25 °C), along with the thermal discomfort periods for each selected location.

The results confirm the significant role of both the latent and sensible heat capacity of the PCM in regulating indoor temperatures since the DS-PCM compartment consistently outperformed the REF compartment, achieving reductions of up to 8% in DHD and up to 3% in the thermal discomfort period. In Aveiro (Fig. 4a, V1), a city with a mild summer climate and average outdoor temperatures ranging from 14.8 °C to 26.5 °C, the DS-PCM device reduced DHD by 6% and the overheating period by 3%. The most favorable results were observed in Bragança (Fig. 4b, V2), a moderate summer climate zone, where slightly lower minimum (13.4 °C) and maximum (25.6 °C) outdoor temperatures facilitated PCM charging and discharging, effectively mitigating overheating. Conversely, in Beja (Fig. 4c, V3), characterized by more intense summer conditions with higher minimum (16.4 °C) and maximum (28.1 °C) outdoor temperatures, the shading device was less effective. While it still achieved a 5% reduction in DHD and a 3% decrease in the discomfort period, the elevated temperatures limited the PCM’s thermal regulation capacity due to its low melting temperature. The results validate the expected outcome, highlighting the need to optimize the PCM phase change temperature range for each climate zone due to variations in daily outdoor thermal amplitudes.

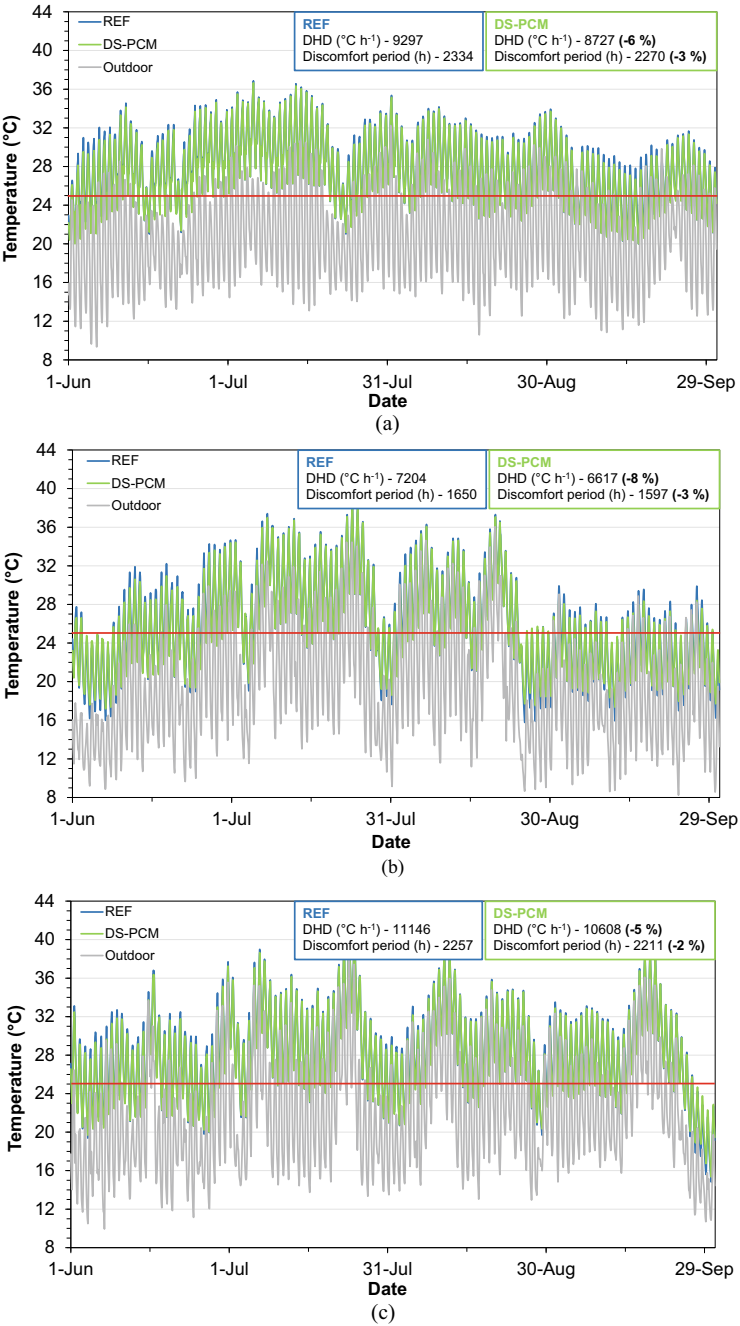


Fig. 4 Thermal performance results for: **a** Aveiro (V1), **b** Bragança (V2), and **c** Beja (V3)

5 Conclusions

This research presents preliminary results from a calibrated and validated numerical simulation based on real-scale monitored data. The developed numerical model provides a comprehensive characterization of a novel DS-PCM prototype, assessing its thermal performance across different Portuguese summer climate zones and comparing it to a reference case. The results demonstrate the system's potential to mitigate indoor overheating and promote energy efficiency, achieving reductions of up to 8% in Degree-Hours Discomfort and up to 3% in overheating periods. Notably, the moderate summer climate zone showed the greatest improvement due to the significant daily temperature variations required to drive the PCM phase change. Future work will involve extensive dynamic simulations to evaluate various parameters and scenarios in the solution performance, culminating in the development of a performance-based design tool to enable the replication and optimization of the DS-PCM system.

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References

1. Official Journal of the European Union (2024) Directive (EU) 2024/1275 of the European Parliament and of the council of 24 April 2024 on the energy performance of buildings (recast)
2. Mikropoulos E, Roelfsema M, Chen HH, Staffell I, Oreggioni G, Hdidouan D, Thellufsen JZ, Chang MA, Fragkos P, Giannousakis A, Chatterjee S, Ürges-Vorsatz D, Pfenninger S, Pickering B, Victoria M, Brown T, van Vuuren DP (2025) Examining pathways for a climate neutral Europe by 2050; A model comparison analysis including integrated assessment models and energy system models. *Energy* 319:134809. <https://doi.org/10.1016/J.ENERGY.2025.134809>
3. Hassan MM, Refat KH, Baten MZ, Sajjad RN (2022) Energy saving potential of photovoltaic windows: impact of shading, geography and climate. *Sol Energy* 240:342–353. <https://doi.org/10.1016/J.SOLENER.2022.05.034>
4. He Y, Zhou H, Fahimi F (2022) Modeling and demand-based control of responsive building envelope with integrated thermal mass and active thermal insulations. *Energy Build* 276:112495. <https://doi.org/10.1016/J.ENBUILD.2022.112495>
5. Wu H, Zhang T (2022) Optimal design of complex dynamic shadings: towards sustainable built environment. *Sustain Cities Soc* 86:104109. <https://doi.org/10.1016/J.SCS.2022.104109>
6. Kalidasan B, Pandey AK (2025) Next generation phase change materials: state-of-the-art towards sustainable future. *Prog Mater Sci* 148:101380. <https://doi.org/10.1016/J.PMATSCI.2024.101380>
7. Gonçalves M, Figueiredo A, Almeida RMSF, Vicente R, Samagaio A, Košny J (2024) Thermal performance evaluation of a light steel framing building with macroencapsulated phase change materials in a Mediterranean climate. *Energy Build* 323:114837. <https://doi.org/10.1016/J.ENBUILD.2024.114837>
8. International Organization for Standardization, ISO 6946 (2017) Building components and building elements—thermal resistance and thermal transmittance—calculation methods

Determination of Thermal Performance of Building Walls Insulated with Biobased Material by Active Method (Preliminary Results)



Alain Koenen, Damien Marquis, and Kamel Zibouche

Abstract To improve the energy efficiency of buildings, the thermal performance of opaque walls has traditionally been laboratory-tested samples under controlled conditions. However, these methods often fail in accurately reflecting real-world conditions, highlighting a need for the development of in situ measurement techniques. This study presents a novel device designed to measure the thermal transmission coefficient of building envelopes using an active thermal excitation method. The approach addresses critical challenges, including the impact of environmental factors, especially moisture, and the behavior of bio-based insulation materials. These materials are particularly sensitive to moisture variations, making it essential to assess their thermal conductivity under actual operating conditions. Thermal resistance remains crucial for improving energy efficiency throughout a building's lifecycle, from construction to renovation. Existing methods, whether conducted in laboratories or experimental settings, often lack universal applicability across different wall types and fail to adequately consider moisture effects. The developed in situ device combines active thermal techniques with advanced data processing to account for environmental influences. Validation involves multiple strategies, including laboratory characterizations using a guarded hot plate, tests in climate-controlled chambers, and a prototype incorporating heating elements and conventional sensors. This paper details the device's development and its real-world applications, with a focus on bio-based materials and the critical role of moisture in thermal conductivity.

Keywords Hygrothermal performance · Energy efficiency · Building pathologies · Diagnostic

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1 Introduction

The quality of thermal insulation in solid walls is crucial for enhancing the energy efficiency of buildings. Effective management of thermal performance is essential during construction, renovations, delivery, and throughout the lifespan of the insulation. Currently, the energy efficiency of buildings and the performance of construction materials are verified using specimens extracted and tested under controlled laboratory conditions. These assessments are based on conventional climate scenarios and the thermal performance of construction products, typically determined through standardized methods such as the heat flow meter and guarded hot plate.

However, the thermal performance values derived from normative calculations can significantly differ from those observed in real-world conditions, particularly since these calculations assume defect-free installations [1]. To address this discrepancy, validating conventional calculations with large-scale measurements is necessary for a reliable evaluation of a building envelope's thermal performance. Three primary approaches can achieve this validation, the energy-consuming approach (Co-heating), the infrared thermography [2] and the instrumenting walls with temperature and heat flow sensors as described in ISO 9869-1 [3] but with an uncertainty greater than 25%.

Additionally, there is a need for a reliable method to determine the thermal performance of buildings along with the associated uncertainty. In response, an instrument has been developed that measures the coefficient of thermal transmission of the building envelope using an active method to heat the wall.

2 Laboratory Apparatus and Test Method

The test bench is a prototype designed to determine the thermal resistance of buildings walls. Measurements were carried out in different laboratories test benches with thermal controlled conditions. Before using the active model prototype in order to validate the concept, the thermal properties of the components of the wall were determined by a Guarded Hot Plate, and the wall thermal performances were determined in a bi-climate chamber which is clause to a Guarded Hot Box method [4].

2.1 *The Active Method Prototype*

The prototype was developed by the French company THEMACS. It consists of a circular plate with a diameter of 60 cm. This plate incorporates three heat flow sensors, positioned in the center of the disk and along two diameters, along with a heating system. During testing, the device is positioned in contact with the wall to be evaluate (Fig. 5 left).

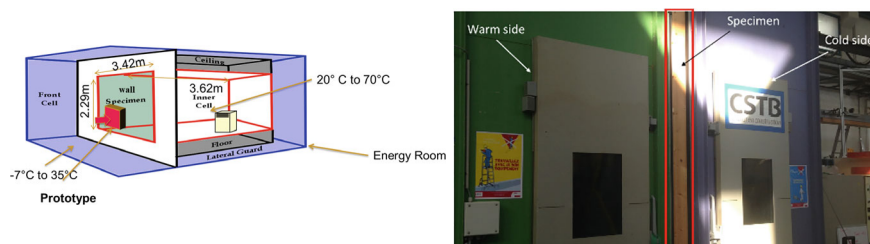


Fig. 1 Schematic diagram of both bi climatic device (left LNE, right CSTB)

2.2 The Guarded Hot Plate

The guarded-hot-plate method (ISO 8302 [5]) determines steady-state thermal transmission properties of flat slab specimens having a low thermal conductivity. It uses the one-dimensional steady-state thermal conductivity equation. The apparatus is a two specimen devices with a overall dimensions of 600×600 mm. The apparatus used at LNE is the double specimen apparatus.

All measurement for this study were conducted at a mean temperature of 10°C , with a temperature difference of 15°C between hot and the cold plate. The influence of moisture on wood fiber as also determined. Before measurement, the specimens were dried at 70°C , then conditioned at 23°C and 50%RH, followed by 23°C and 85%RH. Thermal conductivity measurements were performed under each condition.

3 Methods of Determination of Thermal Resistance

Two different walls (2×2 m) were constructed and mounted between two controlled environments: one at LNE, called REBECCA, and the second at CSTB, known as the bi-climate chamber (Fig. 1).

After the installation in the climatic chamber, their thermal resistances were determined using a steady state method define in the standard ISO 9869-1. The active prototype was positioned to the wall surface for evaluation.

4 Description of the Test Materials (Wall Specimen) for Tests at Laboratories

The overall dimension of the walls were 1950×1950 mm. The wall at LNE represent an external thermal insulation system using high-density wood fiber (Fig. 2, left). The wall at CSTB represents a timber frame system insulated with hem concrete (Fig. 2, right).

Fig. 2 Scheme of both walls (left LNE wood fiber, right CSTB hemp concrete)

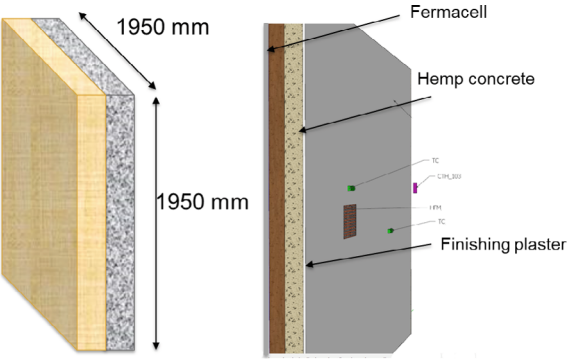


Table 1 Thermophysical properties of the component of the walls at CSTB (hemp concrete)

Hemp concrete wall					
Material (from inside to outside)	Thickness (mm)	Density (kg/m ³)	Thermal conductivity (W/(m K))	Thermal resistance (m ² K/W)	Time constant (s)
Fermacell	12	1000	0.2–0.3	0.04	480
Hemp concrete	300	280	0.1–0.105	2.8–3	252,000
Finishing plaster	20	1600	0.5	0.04	1280
Wood fiber wall					
Plaster board	12.5	750	0.2–0.3	0.04	390
Cinderblock	150	875	0.9	0.2	21,875
Wood fiber	120	150	0.04		81,000

Table 1 summarizes the thermophysical properties of the different components.

5 Experimental Validation at Laboratory

The thermal resistance of wall components was measured using a guarded hot plate. Overall wall resistance was then assessed in both bi-climatic chambers under steady-state conditions, with constant temperatures maintained on each side throughout the tests. Finally, measurements were conducted using the active method prototype.

5.1 Measurements with Mean of Guarded Hot Plate

To conduct the measurement, two specimen (600 × 600 mm) were cut from wood fiber panel and hemp, both taken from the same batch used to construct the test

Table 2 Measured thermal performance on guarded hot plate on wood fiber

	Specimen conditioning	Thermal conductivity (W/(m K))	Thermal resistance (m ² K/W)	Mass of water intake (%)
Wood fiber	Dry	0.0380	3.09	0
	23 °C/50%RH	0.0395	3.02	9.3
	23 °C/85%RH	0.0419	2.91	13.7
Concrete hemp	23 °C/50%RH	0.105	2.8	

Table 3 R values at both environnements

	Conditioning	Thermal resistance (m ² K/W)	Thermal conductivity (W/(m K))
Wood fibre	Dried at 70 °C	2.95	0.0407
	23 °C 85%RH	2.80	0.0429
Hemp concrete	Standard laboratory	3	

walls. Guarded hot plate measurements were conducted at a mean temperature of 10 °C with a 10 °C temperature difference (ΔT). Wood fiber specimens were tested at 3 moisture levels: dry state (dried at 70 °C until mass stabilization), 23 °C/50% RH (conditioned in a climatic chamber), 23 °C/85% RH (see Table 3). The hemp concrete specimen was measured at 10 °C after conditioning at 23 °C and 50%RH (Table 2).

5.2 Bi-Climatic Chamber (Thermal Resistance of the Walls)

The thermal performance complete 2 × 2 m walls were determined in both bi-climatic chambers before measurements with the active prototype.

The wall with external thermal insulation made of wood fiber was tested under dry conditions (dried at 70 °C and subsequently conditioned at 23 °C and 85% RH). The measurement was conducted under steady-state conditions over a period of three days. Using the same methodology, the thermal resistance of the hemp concrete insulated wall was evaluated after conditioning in a standard laboratory environment (Table 3).

5.3 Measurements with the Active Method Prototype

Wood Fiber

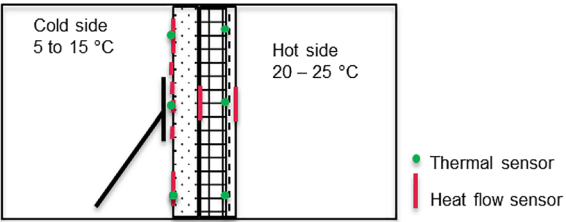
The active method prototype was placed against the cold-side wall surface (Fig. 3). Temperatures on each wall surface were measured at nine positions, and heat flux was recorded at five locations: three on the cold-side surface, one on the cinder block, and one on the hot-side surface (Fig. 4). Four tests were conducted to evaluate the effects of temperature difference and moisture (Table 4).

The evolution of heat flux and temperature was recorded at all measurement locations every 30 s throughout the test (Fig. 5). The thermal resistance was determined using Fourier’s law on the cold side, combined with a superposition method. This approach assumes that the temperature increase on the hot side is negligible and that the cold-side temperatures correlate with the total heat flux from the active prototype. Moreover, all analysis were done after a long period of heating when the temperature and heat stay constant. These assumptions are valid here, because we do mainly a comparative analysis between the different configurations.



Fig. 3 Wall installed in the Rebecca climatic chamber (left cold side with the prototype, right hot side)

Fig. 4 Position of thermal and heat flow sensor



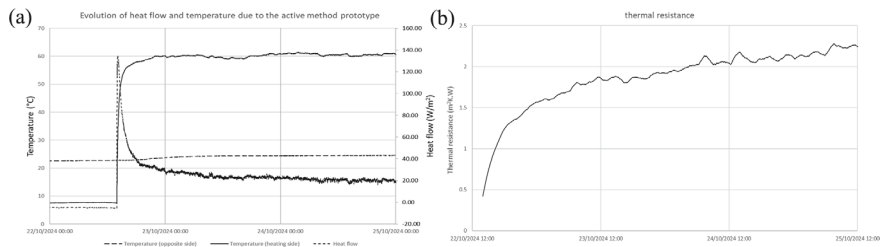


Fig. 5 **a** Measured heat flow on cold side and temperature on both side (dry wall ΔT 5–25) on wood fiber wall **b** thermal resistance evolution

Table 4 Parameters of tests

Conditioning	Cold side temperature (°C)	Hot side temperature (°C)	ΔT (°C)
Dried at 70 °C	5 and 15	25	20 and 10
Conditioned at 23 °C and 85%RH	5 and 15	25	20 and 10

The thermal resistance was calculated using the following equation:

$$R = \frac{(T_{coldside,final} - T_{coldside,initial})}{Q_{proto}} + \varepsilon \text{ with } \varepsilon = \frac{(T_{hotside,initial} - T_{hotside,final})}{Q_{proto}}$$

where:

- Q_{proto}: heat flow measured by the prototype,
- T_{cold side, x}: surface temperature before heating and a the end of heating on cold side.
- T_{hot side, x}: surface temperature before heating and a the end of heating on hot-side.

In all our tests, ε was approximately 0.05 m²K/W. The temperature increase on the hot side was around 1 °C, while the heat flux was about 18 W/m².

The results obtained by the test device using the active method are in Table 5.

The measured thermal resistance was approximately 2.4 m²K/W, which is lower than the expected value of 3 m²K/W. The variation in ΔT and moisture content had no significant impact on the results.

Table 5 Parameter of the test

Conditioning	T _{cold} –T _{hot} (°C)	R (m²K/W)	T _{proto} –T _{cold} (°C)	Heat flows Q ₂ /Q ₁ (W/m²)
Dried at 70 °C	5–25	2.3	53.4	19.4/–5.0
	15–25	2.5	53.0	18.0/–3.3
23 °C 85%RH	5–25	2.4	53.3	16.8/–5.8
	15–25	2.4	51.8	16.9/–4.3

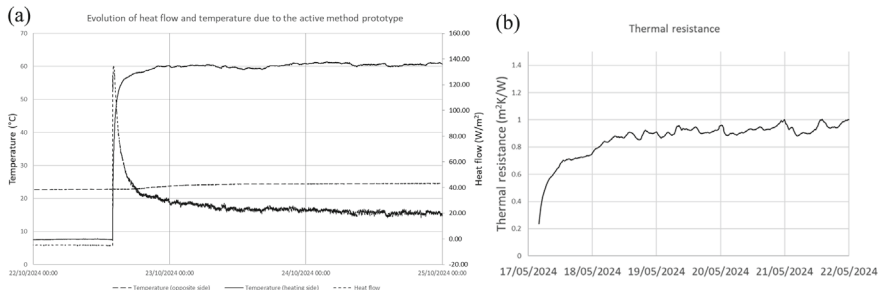


Fig. 6 **a** Example of measured heat flow on the cold side and temperature on both side on hemp concrete **b** example of thermal resistance evaluation over the time

Table 6 Result of the test

Conditioning	$T_{\text{cold}}-T_{\text{hot}}$ (°C)	R (m²K/W)	$T_{\text{proto}}-T_{\text{hot}}$ (°C)	Heat flow (W/m²)
Standard laboratory condition	2–22	0.8	28.8	27.9

Hemp Concrete Wall

Similar to the wood fiber wall, the active method prototype was placed against the wall surface, but in this case, on the hot side. Temperatures were measured at three positions on each surface, and heat flux was recorded at two locations (one on each side of the wall). A single test was conducted to evaluate the effect of the high heat capacity of hemp concrete.

The evolution of heat flux and temperature was recorded every 60 s throughout the test (Fig. 6). The thermal resistance was determined using Fourier’s law on the hot side, combined with a superposition method.

The measured data are presented in Table 6. The thermal resistance was evaluated at 1.0 m²K/W, which is significantly lower than the expected value of 2.8 m²K/W. This wall exhibited a time constant of 252,000 s, which is three times higher than that of the wood fiber wall.

6 Conclusion

This study presents a new method for determining the thermal resistance of building walls using an active heating method applied to a small wall area over several hours. The method was tested on two different walls: one insulated with wood fiber and the other with hemp concrete. The influence of three parameters was evaluated: the temperature difference between both sides of the walls, moisture content, and time constant. The temperature difference and moisture content did not significantly affect

the measured thermal resistance. However, the time constant, which is linked to heat capacity, density, and thickness, had a considerable impact on the results.

The aim of the project was to develop a device capable of providing reliable thermal resistance measurements for walls insulated with bio-based materials, whose moisture content varies between summer and winter. For walls insulated with low time constant, this method appears to be effective. However, for walls insulated with high thermal constant, further development is ongoing to determine thermal resistance using inverse method.

References

1. Doran (2000) Fields investigations of the thermal performance of construction elements as built, Nov 2000, pp 15–16. Report BRE n° 78132. <http://projects.bre.co.uk/uvalues/U-values.pdf>
2. Monchau JP (2013) Mesure d'émissivité pour la thermographie infrarouge appliquée au diagnostic quantitatif des structures, Thèse de doctorat, Université Paris Est
3. ISO 9869-1:2014 Thermal insulation—building elements—in-situ measurement of thermal resistance and thermal transmittance—part 1: heat flow meter method
4. ISO 8990 Thermal insulation—determination of steady-state thermal transmission properties—calibrated and guarded hot box
5. ISO 8302. Thermal insulation—determination of steady-state thermal resistance and related properties—guarded hot plate apparatus. International Organization for Standardization

Simulation-Based Assessment of the Thermal Performance of Radiant Floor Systems



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Ricardo M. S. F. Almeida , and Victor M. Ferreira 

Abstract The literature highlights that design and composition of hydronic Radiant Floor Systems (RFS) are critical for an adequate thermal behaviour, ultimately providing high indoor thermal comfort. The thermal performance of RFS is strongly influenced by the thermophysical properties of the heat transfer medium embedding the water pipes. In these systems, mortars with high conductive properties enable faster thermal responses. However, this can lead to peak heating loads and significant thermal fluctuations, potentially compromising thermal comfort and increasing the energy demand. The objective of this study is to investigate the impact of mortar thermal conductivity on the thermal performance of RFS. A 3D numerical simulation model was developed in Ansys Fluent®, replicating an experimental setup of conventional heavyweight hydronic RFS. The performance indicators used in the parametric analysis were surface temperature and total heat flux. The results obtained provide theoretical support for the improvement of the thermophysical properties of the heat transfer medium in RFS during the design phase.

Keywords Radiant floor system · Numerical simulation · Heating · Thermal performance

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1 Introduction

The building sector remains accountable for about a third of global energy consumption and a quarter of CO₂ emissions [1]. Of the different end-uses contributing for energy consumption in buildings, indoor heating and cooling loads still represent the largest share [2].

From the different heating and cooling technologies in buildings, the advantages of radiant floors have led to increased interest in these systems, as well as their widespread use on the market [3, 4]. However, as highlighted in the literature, the configuration and composition of RFS are key parameters, critical for improved thermal performance and energy efficiency [5]. Ding et al. [6] investigated the effect of surface material, surface heat transfer coefficient, filling and pipe materials on the heating capacity and surface temperature of RFS. Zhang et al. [7] studied the influence of water supply temperatures, flow rates and pipe pitch on the heating capacity of a prefabricated RFS under different operating conditions. The authors observed water supply temperature as the parameter that most influenced the heating capacity of the RFS, while flow rate revealed to have little impact. Fu et al. [3] established a numerical simulation model of a RFS to analyze the influence of pipe pitch, finishing layers and the material surrounding the heating pipes on the surface temperature and heat flux of RFS. Kang et al. [8] developed a simplified 2D numerical model to study the impact of different thermophysical properties on the performance of Phase Change Materials (PCMs) incorporated in RFS. Wang et al. [9] studied the effect of the water pipe position within a PCM encasement on the thermal performance of RFS, while in [10] the same authors used numerical simulation to analyze three different PCM incorporation modes on RFS. Wang et al. [11] proposed a steady-state simplified method to calculate the thermal performance of RFS, carrying a sensitivity analysis on the influence of different parameters. Almeida et al. [12] studied the influence of different mortar compositions and floor finishing materials on RFS efficiency through an experimental campaign and a 3D numerical model using FEMIX. Thermal conductivity of the mortar and of the finishing material strongly impacted the surface temperature and operating hours of the RFS.

One of the parameters with the greatest impact on the thermal performance of RFS is the thermal conductivity of the layer embedding the heating pipes [11]. In fact, the thermophysical properties of the heat transfer medium surrounding the heating pipes strongly influence the thermal performance and efficiency of hydronic RFS, which in conventional heavyweight systems is typically a mortar [6, 13]. Mortars with high conductive properties enable faster thermal responses of the RFS. However, this can lead to peak heating loads and significant thermal fluctuations, potentially compromising thermal comfort and increasing the energy demand. Additionally, it is still unclear how, and to what extent, increasing the thermal conductivity leads to improving the thermal performance of RFS, in terms of increasing surface floor temperature and total heat flux. The objective of this study is to investigate the impact of using different mortar compositions and corresponding thermal conductivity on the thermal performance of RFS using a 3D steady-state numerical simulation model

developed in the computational fluid dynamics (CFD) software Ansys Fluent® 2024 R2.

2 Numerical Method

2.1 Physical Model

The physical model is representative of a conventional heavyweight hydronic RFS, and was created using Ansys SpaceClaim 3D modeling software. Mortar is used as the heat transfer medium embedding the water pipes, which are displaced in serpentine configuration having 200 mm of pitch and $\text{Ø}16 \times 2$ mm. The mortar layer measures $1.20 \text{ m} \times 1.50 \text{ m}$ of horizontal dimensions and 60 mm of total thickness. A volume of thermal insulation (EPS) was considered and modeled under the mortar domain with 80 mm of thickness. To simulate indoor air environment, a fluid domain (air) measuring 1.20 m (width) $\times 1.50 \text{ m}$ (length) $\times 1.80 \text{ m}$ (height) is modeled on top of the mortar domain. The air domain is limited by an enclosure structure composed of plasterboard walls and EPS roof, which were modeled as well. Supply water temperature was considered 36.45°C at the inlet of the fluid domain modeled within the pipes, with a water flow rate fixed to $2 \text{ l}\cdot\text{min}^{-1}$. External ambient air temperature was defined as 10°C and considered constant throughout the calculations.

2.2 Mesh Quality

The mesh for the CFD simulation was generated using the Watertight Geometry Workflow in Ansys Fluent Meshing software. All the domains were volume meshed using poly-hexcore elements as observed in Fig. 1, totaling 2,305,648 cells. Mixed cell type was adopted for each domain, achieving a minimum orthogonal quality of 0.25. The generated volume mesh of the 3D numerical model is presented in Fig. 1.

2.3 Numerical Model

The study was conducted, as mentioned, using the CFD software Ansys Fluent® 2024 R2. A 3D steady-state numerical model was generated to simulate the thermal performance of the theoretical hydronic RFS. The thermal characteristics of the materials used in the numerical model are summarized in Table 1.

In the benefit of computational efficiency and to save resources during calculations, the following simplification assumptions were adopted:

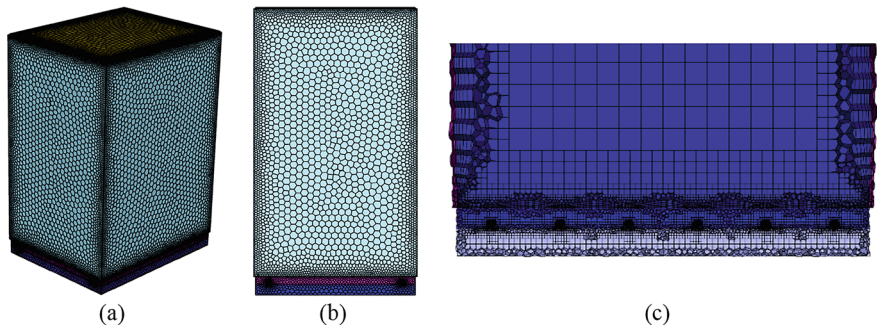


Fig. 1 Mesh of the 3D model: **a** volume mesh of poly-hexcore elements displayed in isometric perspective; **b** front view of the 3D numerical model; **c** cross-section of the 3D model showing internal details

Table 1 Material thermal characteristics of each domain

Domain	Material	Thermal conductivity – $k(\text{W m}^{-1} \text{K}^{-1})$
Fluid	Water-liquid	0.6
Fluid	Air	0.024
Solid	Thermal insulation (EPS)	0.036
Solid	Mortar	<i>Parameter</i>
Boundary condition (wall)	Pipes	0.42
Solid	Gypsum plasterboards	0.25

- Materials of each layer are homogeneous and isotropic with constant thermal conductivity;
- Peripheral surfaces of the mortar domain are adiabatic boundary conditions;
- Pipe walls were not 3D modeled. Thickness and material of the pipe walls were input values, in a liquid–solid boundary condition (wall);
- All internal interfaces were defined as coupling surfaces.

In Ansys Fluent® the energy model was first enabled. The radiation model Surface to Surface (S2S) was activated for the calculations, and computed. The Coupled scheme was employed for the solution method. As mentioned, the external ambient temperature was kept constant throughout the calculations, and the infiltration of external air was neglected. During the simulation, residuals were set under 10^{-7} as convergence criterion.

Thermal conductivity (k) of the mortar domain was the parameterized variable in this study. A baseline thermal conductivity value of $0.71 \text{ W m}^{-1} \text{K}^{-1}$ was considered for the mortar medium embedding the heating pipes of the RFS, in line with previous research [5]. Starting from this baseline, the effect of increasing its value was studied through increments of 20%. A total of 16 cases were calculated starting from the

initial thermal conductivity value, up to the maximum of $2.84 \text{ W m}^{-1} \text{ K}^{-1}$, which corresponds to a total increase of 300% from the baseline.

3 Results and Discussion

This section presents and discusses the results obtained from the parametric analysis. Average floor surface temperature and heat flux were the selected output performance indicators. In Fig. 2 are presented the resulting contour maps from the floor surface corresponding to the thermal conductivities of $0.71 \text{ W m}^{-1} \text{ K}^{-1}$, $1.85 \text{ W m}^{-1} \text{ K}^{-1}$ and $2.84 \text{ W m}^{-1} \text{ K}^{-1}$. Figure 2a–c represent the resulting contours of average surface floor temperature, and Fig. 2d–f shows heat flux.

The results of the relationship between thermal conductivity of the mortar domain and the average surface temperature of the RFS are shown in Fig. 3, and in Fig. 4 are presented the percentage differences in increasing surface temperature, corresponding to each thermal conductivity case, in relation to the previous value.

As observed in Fig. 3, the linear increase in the thermal conductivity of the mortar domain did not result in a corresponding linear behaviour increasing the floor surface temperature. In fact, for higher values of thermal conductivity, the increase in temperature at the floor surface tends to stabilize after a given value. It is possible to observe this relationship in Fig. 4, which shows the percentage difference in increasing surface temperature corresponding to each thermal conductivity case, in relation to the previous value. Surface floor temperature reaches a maximum of 28.29°C , under the regulatory limit of 29°C for thermal comfort [14]. However, despite the total increase in surface temperature of 6.29°C , which corresponds to the

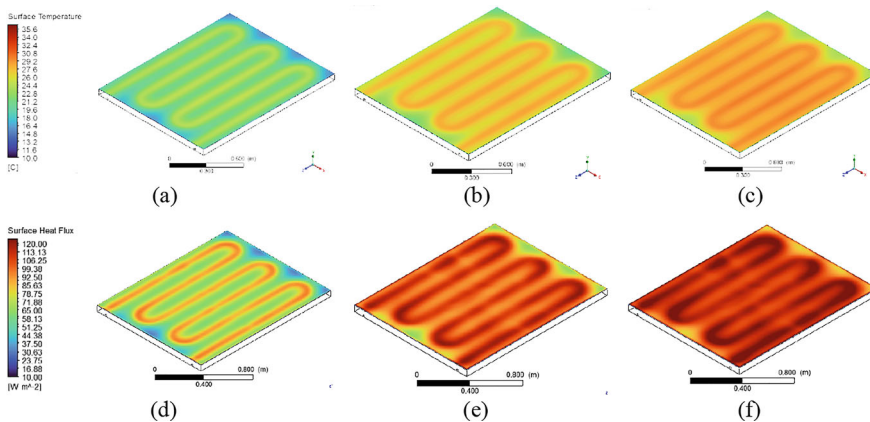


Fig. 2 Contour maps of surface floor temperature and heat flux: **a** surface floor temperature for $k = 0.71 \text{ W m}^{-1} \text{ K}^{-1}$; **b** surface floor temperature for $k = 1.85 \text{ W m}^{-1} \text{ K}^{-1}$; **c** surface floor temperature for $k = 2.84 \text{ W m}^{-1} \text{ K}^{-1}$; **d** surface floor heat flux for $k = 0.71 \text{ W m}^{-1} \text{ K}^{-1}$; **e** surface floor heat flux for $k = 1.85 \text{ W m}^{-1} \text{ K}^{-1}$; **f** surface floor heat flux for $k = 2.84 \text{ W m}^{-1} \text{ K}^{-1}$

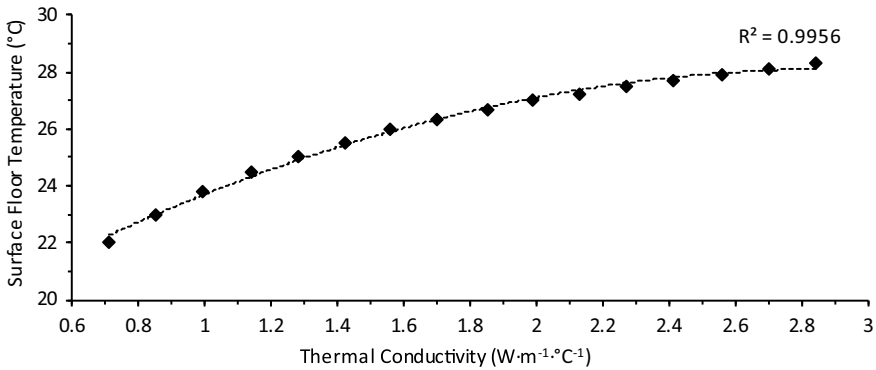


Fig. 3 Impact of the thermal conductivity of the mortar medium (x-axis) on the surface weighted average floor temperature (y-axis)

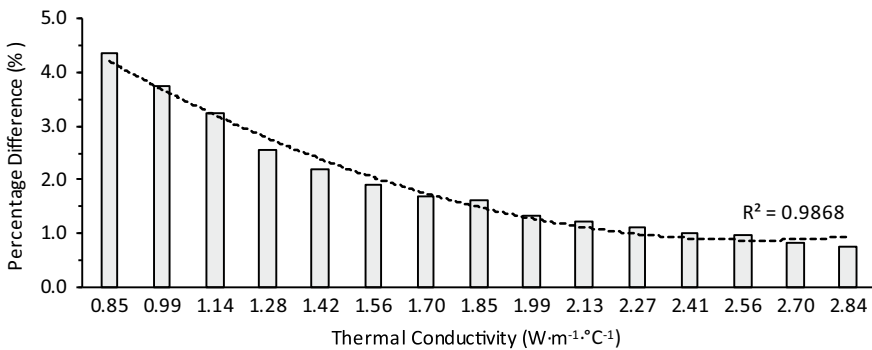


Fig. 4 Percentage difference (y-axis) of the increasing surface floor temperature for each thermal conductivity case (x-axis), in relation to the previous

300% increase from $0.71 \text{ W m}^{-1} \text{ K}^{-1}$ to $2.84 \text{ W m}^{-1} \text{ K}^{-1}$ in the thermal conductivity of the mortar domain, after the value of $1.85 \text{ W m}^{-1} \text{ K}^{-1}$, enhancing the thermal conductivity loses expression and translates into an increase of less than 1.5% of the RFS surface temperature, which is neither substantial nor proportional to the 20% increase in thermal conductivity. After the case with thermal conductivity of $2.13 \text{ W m}^{-1} \text{ K}^{-1}$, the corresponding increase in surface floor temperature is about 1%. This behaviour is in line with the literature [15].

The results of the relationship between the thermal conductivity of the mortar domain and the average heat flux of the floor surface is presented in Fig. 5, and in Fig. 6 are presented the percentage differences in increasing total heat flux, corresponding to each thermal conductivity case, in relation to the previous value.

Similar relationship is observed between the thermal conductivity of the mortar domain and the average heat flux, measured on the surface of the RFS. Again, enhancing thermal conductivity improves the heat flux until the value of

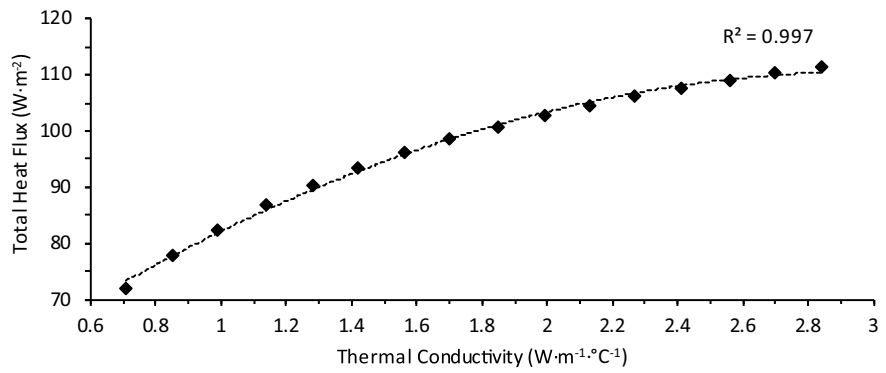


Fig. 5 Impact of the thermal conductivity of the mortar medium (x-axis) on the total surface heat flux (y-axis)

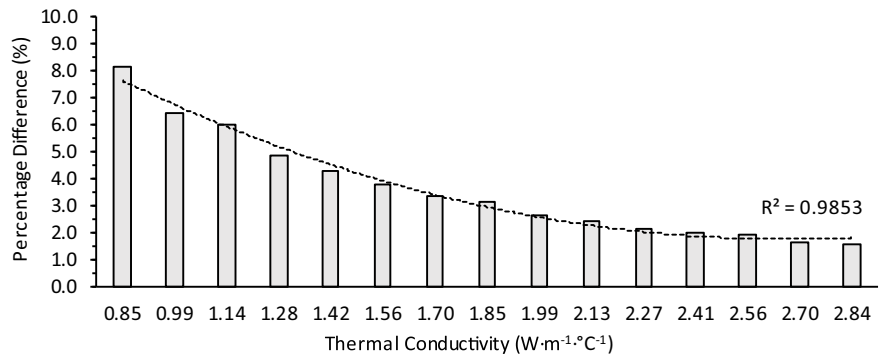


Fig. 6 Percentage difference (y-axis) of the increasing heat flux for each thermal conductivity case (x-axis), in relation to the previous

1.85 W m⁻¹ K⁻¹, beyond which the heat flux increases by less than 3% for each case. From the parametric study, a total increase in heat flux of 39.39 W m⁻² was observed. For the maximum thermal conductivity value, the corresponding heat flux of 111.35 W m⁻² was reached.

4 Conclusions

The thermophysical properties of the heat transfer medium surrounding the heating pipes, which in conventional systems is typically a mortar, strongly influence the thermal performance of hydronic RFS. To what extent enhancing the thermal conductivity of this domain actually benefits the surface temperature and the heat flux of RFS is still unclear. To investigate the impact of different thermal conductivities of

the mortar medium on the thermal performance of hydronic RFS, a 3D steady-state numerical simulation model was established in Ansys Fluent® 2024 R2.

The results from the parametric numerical study reveal that enhancing the thermal conductivity of the mortar domain increases both the average temperature of the floor surface and the heat flux. However, a linear increase in the thermal conductivity of the mortar did not result in a corresponding linear behaviour of floor surface temperature and heat flux. For the studied conditions, results indicate that after thermal conductivity reaches $1.85 \text{ W m}^{-1} \text{ K}^{-1}$, enhancing this property loses expression and translates into an increase of less than 1.5% of the RFS surface temperature. Surface heat flux shares a similar relationship with thermal conductivity. After the same threshold value, heat flux increases by less than 3% for each 20% increase of thermal conductivity.

Recognizing the effort involved in enhancing the thermal conductivity of mortars, the results obtained in this study may provide theoretical support and guidance to achieve a balance between improving the thermophysical properties of the heat transfer medium and the expected thermal performance of the RFS, during the design phase.

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Disclosure of Interests The authors have no competing interests to declare that are relevant to the content of this article.

References

1. González-Torres M, Pérez-Lombard L, Coronel JF, Maestre IR, Yan D (2022) A review on buildings energy information: trends, end-uses, fuels and drivers. *Energy Rep* 8:626–637. <https://doi.org/10.1016/J.EGYR.2021.11.280>
2. Kurniawan TB, Dewi DA, Usman F, Fadly F (2023) Towards energy analysis and efficiency for sustainable buildings. *Emerging Sci J* 7:2226–2238. <https://doi.org/10.28991/ESJ-2023-07-06-022>
3. Fu S, Pan Y, Wan X, Wang J, Jia X, Luo X, Ma H (2024) Numerical simulation of heat transfer characteristics of capillary radiant heating floor. *KSCE J Civ Eng* 28:546–556. <https://doi.org/10.1007/s12205-024-1518-1>
4. Du H, Lian Z, Lai D, Duanmu L, Zhai Y, Cao B, Zhang Y, Zhou X, Wang Z, Zhang X, Hou Z (2022) Comparison of thermal comfort between radiant and convective systems using field test data from the Chinese thermal comfort database. *Build Environ* 209:108685. <https://doi.org/10.1016/j.buildenv.2021.108685>
5. Rebelo F, Figueiredo A, Vicente R, Almeida RMSF, Paiva H, Ferreira VM (2024) Development of innovative mortars incorporating phase change materials and by-products for high performance radiant floor systems. *Constr Build Mater* 420:135488. <https://doi.org/10.1016/j.conbuildmat.2024.135488>
6. Ding P, Li Y, Long E, Zhang Y, Liu Q (2020) Study on heating capacity and heat loss of capillary radiant floor heating systems. *Appl Therm Eng* 165:114618. <https://doi.org/10.1016/J.APPLTHERMALENG.2019.114618>
7. Zhang B, Wang Y, Liu M, Zhang Z (2024) Experimental and numerical study of newly assembled lightweight radiant floor heating system. *Buildings* 14:2096. <https://doi.org/10.3390/buildings14072096>
8. Kang Z, Tan R, Yao Q, Zhang J, Zhang S, Wei Y (2025) Numerical simulation of energy storage radiant floor heating systems with phase change materials having different thermo-physical properties. *Constr Build Mater* 463:140010. <https://doi.org/10.1016/j.conbuildmat.2025.140010>
9. Wang Z, Gao W, Gao Y (2024) Influence of hot water pipe position on the performance of radiant floor heating systems integrated with PCM. *Case Stud Thermal Eng* 61:105030. <https://doi.org/10.1016/j.csite.2024.105030>
10. Wang Z, Gao W, Gao Y (2025) Effect of the integration mode of phase change materials on thermal performance of radiant floor heating systems. *J Energy Storage* 110:115275. <https://doi.org/10.1016/j.est.2024.115275>
11. Wang M, Wang J, Xu J (2025) Advancements in design of radiant floor heating systems with an innovative simplified calculation method. *Sci Technol Built Environ* 31:112–125. <https://doi.org/10.1080/23744731.2024.2351312>
12. Almeida RMSF, da Silva Vicente R, Ventura-Gouveia A, Figueiredo A, Rebelo F, Roque E, Ferreira VM (2022) Experimental and numerical simulation of a radiant floor system: the impact of different screed mortars and floor finishings. *Materials* 15:1015. <https://doi.org/10.3390/ma15031015>
13. Larwa B, Cesari S, Bottarelli M (2021) Study on thermal performance of a PCM enhanced hydronic radiant floor heating system. *Energy* 225:120245. <https://doi.org/10.1016/J.ENERGY.2021.120245>
14. (CEN), E.C. for S.: EN 1264-1:2021 (2021) Water based surface embedded heating and cooling systems—part 1: definitions and symbols
15. Cheng W, Xie B, Zhang R, Xu Z, Xia Y (2015) Effect of thermal conductivities of shape stabilized PCM on under-floor heating system. *Appl Energy* 144:10–18. <https://doi.org/10.1016/j.apenergy.2015.01.055>

Topological Optimization and Material Exploration for Improving the Thermal Performance of 3D Printed Prefabricated Wall Components



Valeria Villamil Cárdenas, Juan Diego Vargas, and Stefano Fantucci

Abstract Reducing the energy demand in buildings remains an urgent need, calling for innovative solutions. Additive Manufacturing (AM) is an evolving and rapidly advancing technology, which enables the manufacture of prefabricated and on-site components. 3D-printed (3DP) building components with optimized thermal performance present a promising approach for highly efficient envelope fabrication. However, while structural performance has been extensively studied, thermal behaviour requires further investigation. This study investigates how optimizing geometry and material composition can enhance the thermal properties of 3DP building envelope components. Algorithmic and parametric design was employed to generate and evaluate geometrical variations iteratively. Using Colibri for Rhinoceros, thermal transfer data for multiple design alternatives was analysed to identify the best-performing configurations based on heat path length and void fraction. Afterwards, the selected geometry was manufactured employing Liquid Deposition Modelling (LDM), using a clay mixture stabilized with Calcium Hydroxide ($\text{Ca}(\text{OH})_2$). Thermal conductivity of three different admixtures was measured employing a Heat Flux Meter (HFM) apparatus. Results indicate that adding $\text{Ca}(\text{OH})_2$ to the mixture can reduce thermal conductivity by up to 58%. Furthermore, optimizing the wall infill shape and void fraction, can lead to a thermal transmittance of $2.35 \text{ W/m}^2\text{K}$ (air cavities) and $1.33 \text{ W/m}^2\text{K}$ (aerogel filled cavities) for a 100 mm thick wall sample. The proposed methodology is replicable and scalable, facilitating the design and assessment of innovative 3DP building components. This work integrates computational design and AM, offering advantages such as improved thermal performance, use of locally available materials, and optimized resources efficiency, costs, and time in construction.

Keywords Topological Optimization · 3D-Printing (3DP) · Liquid Deposition Modelling (LDM) · Thermal Assessment · Material Exploration

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1 Introduction

Additive Manufacturing (AM) has grown exponentially in the past years, reaching more than fifteen thousand publications by 2022 [1]. The exploration done in the physics field represents less than 10% and in the Energy field, less than 2%, which opens an important window to move in depth. Clay is a widely used construction material, which has the possibility to be re-used indefinitely when not sintered, producing no waste. Additionally, it has important hygrothermal properties, high moisture buffering value (MBV) [2] and high thermal capacity.

Large scale additive manufacturing (LSAM) advancement has been studied, and some examples of prefabricated wall components can be found in literature [3, 4]. While less examples of 3DP with clay or earth-based materials are available [5, 6]. Although, literature lacks experimental-based analysis about the thermal performance of printable materials like clay and earthen mixtures, and components produced with AM.

Computational design allows a parametric approach, which offers multiple advantages as process optimization and a multi-criteria assessment. Its application to AM, specifically Liquid Deposition Modelling (LDM) using Grasshopper for Rhinoceros, is lucidly explained by Garcia and Pugliese [7].

This study proposes the use of computational design to optimize the topology of a 3DP prefabricated wall component, to improve its thermal properties. This project aims, as well, to understand clay as a material to be used by LDM (Liquid Deposition Modelling) as a technique of 3D printing technology, assessing its thermal conductivity, pure and mixed with Calcium Hydroxide $\text{Ca}(\text{OH})_2$.

2 Materials and Methods

2.1 Parametric Design and Optimization

Geometrical parameters were first set to achieve a self-standing component able to be manufactured and tested in laboratory with optimal thermal properties. The maximum possible size to be manufactured with the 3D printer, a cylinder of 400 mm in diameter and 1000 mm in height; the minimum face area of a component to be tested on the Heat Flux Meter (HFM) apparatus is length (l) 254, width (w) 254 mm and the maximum size of the element to be introduced on the machine is l600, w 600 mm face area, and thickness (t) 250 mm. The final component had a size of l300, w 300, t 100 mm.

The design consisted of a 2D pattern generated from the array of a single unit cell through a bidimensional grid with variable number of columns and rows, as seen in Fig. 1. In [6] it is highlighted the importance of having continuous non-straight angled vertices. Moreover, according to [3, 8], a 1:2.5 infill to void ratio is used and proved to be self-standing, see Fig. 2a. Additionally, the heat path length defined as

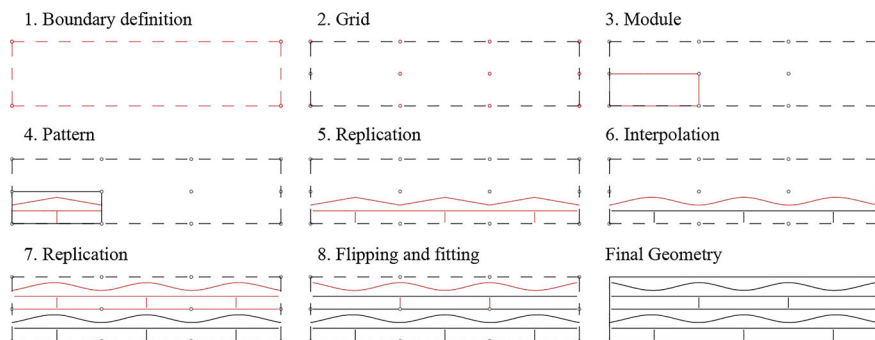


Fig. 1 Parametric design process

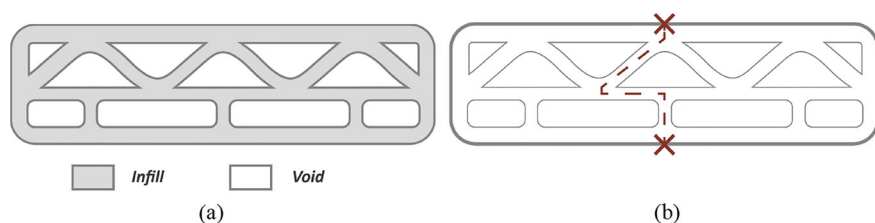


Fig. 2 **a** Void fraction. **b** Heat path length

the minimum distance the heat has to follow to go from one side to the opposite of the component, following the heat flow direction, see Fig. 2b.

2.2 Thermal Conductivity Measurement

To characterize the material, a Heat Flow Meter (HFM) apparatus LaserComp FOX600 was employed to perform a thermal conductivity test, according to the EN 12667 which aligns with ISO 8301 [9, 10]. Three different mixtures were made, using pyrophyllite clay and Calcium Hydroxide ($\text{Ca}(\text{OH})_2$). The first sample contained 100% clay, the second 90%clay and 10% $\text{Ca}(\text{OH})_2$, and the third 80%clay and 20% $\text{Ca}(\text{OH})_2$ (ratio are referred to humid mass).

The samples of 1320, w 320, t 40 mm were casted with an EPS (Expanded Polystyrene) frame. Considering that the mixture shrinks, the samples end up being 1290, w 290, t 36 mm approximately, see Fig. 3a. Drying process lasted about three weeks and occurred on a closed space with ambient conditions, about 23 °C and 50% RH to prevent cracks and deformations caused by a fast water lost.

Before thermal testing, each sample was covered with a plastic layer to avoid moisture content changes during the test. To avoid lateral heat losses, the sample was surrounded with mineral wool. As shown in Fig. 3b, rubber mats were placed

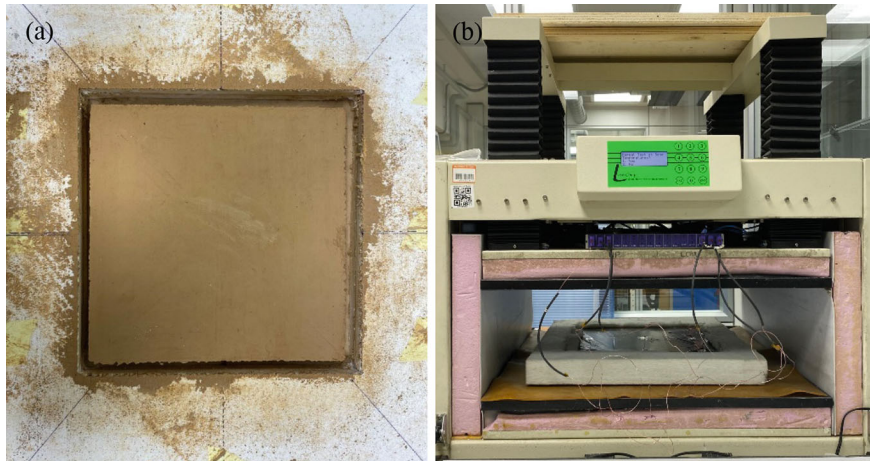


Fig. 3 **a** Preparation of the sample. **b** Set-up of the thermal conductivity test performed with the heat flux meter apparatus

both in the upper and lower sides of the sample to level the faces, and thermocouples were used to measure the temperature between the sample and the rubber mats. The temperature used to perform the test was 13 °C for the upper plate, 33 °C for the lower plate; with a temperature difference of 20 °C then and an average temperature of 23 °C.

2.3 Fabrication Process

A WASP 40100 3D printer was employed to produce the samples that were later tested to measure their thermal transmittance. The machine allows LDM with clay, and printability of admixtures with different concentrations of $\text{Ca}(\text{OH})_2$ was also tasted, using an 8 mm nozzle. The parametric design process explained before was made within the Grasshopper environment and the instructions given to the machine (G-code) [7], used to optimize the printing process, was included in the workflow.

2.4 Thermal Transmittance Assessment

A HFM test was performed to measure the thermal resistance and calculate the thermal transmittance (U) according to the standard ISO 6946 [11], following the formula (1). The test was performed in steady state conditions and with a single set point as presented in the previous section. To simulate the thermal resistance of the air layer on both surfaces of the component, some layers of 1.69 mm cross-linked

polyethylene (PEX) were placed above and below the component. One layer of PEX in the upper side with a resistance equivalent to $0.041 \text{ m}^2\text{K}$, and three layers on the lower side, representing $0.123 \text{ m}^2\text{K/W}$, as shown in Fig. 5. The resistance of the surface air layer values used in the experiment, $0.04 \text{ m}^2\text{K/W}$ for the exterior (R_{se}) and $0.13 \text{ m}^2\text{K/W}$ for the interior (R_{si}) are consistent with those specified in the standard [11].

$$U = \frac{1}{R_{si} + R_1 + R_2 + \dots + R_n + R_{se}} \quad (1)$$

To be tested, both open sides of the block were covered with a non-conductive fabric tape as would be for a confined wall component condition, see Fig. 4, a. A sample with air-cavities and silica-aerogel infill was tested. The component was wrapped with stone wool to avoid side thermal dispersions. The component was placed centred inside the HFM by the side to be tested, considering the direction to the flux due to the asymmetric nature of the geometry, see Fig. 4c.

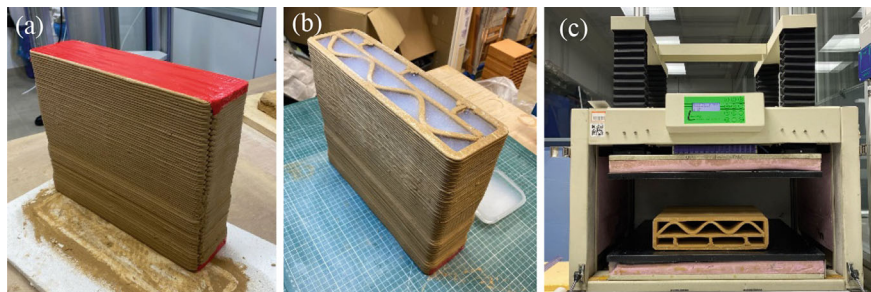


Fig. 4 a Component with air-cavities closed with fabric tape. b Silica-aerogel infill. c Test performed with a Heat Flow Meter (HFM) apparatus, to calculate thermal transmittance

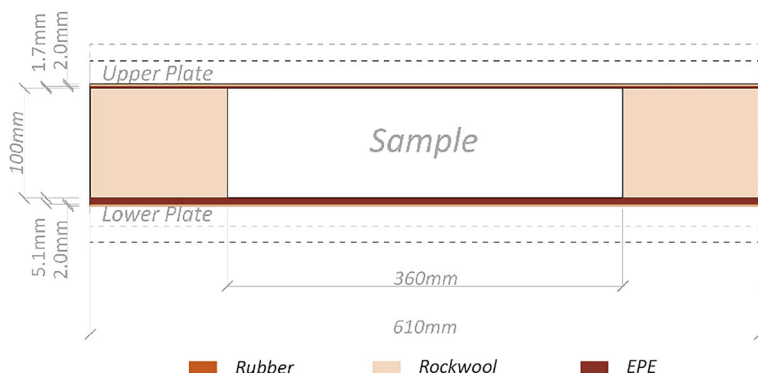


Fig. 5 Section of the HFM test configuration to calculate the thermal transmittance of the components. Stratigraphy: component and elements needed to perform the test

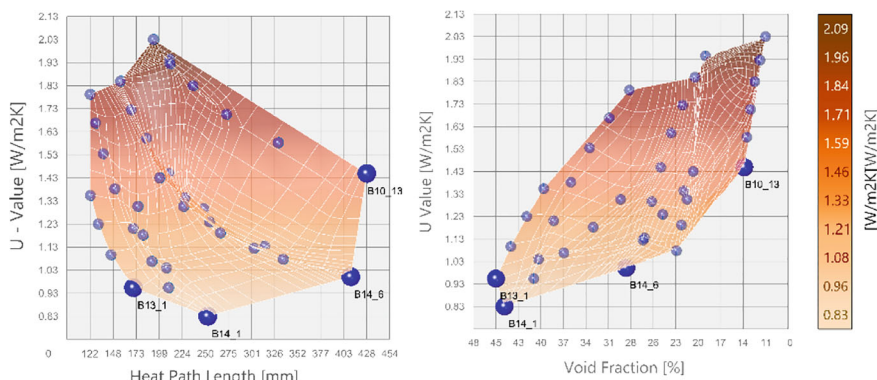


Fig. 6 Pareto front analysis for all the configurations with silica-aerogel infill

3 Results and Discussion

3.1 Topological Optimization

After a Pareto Front evaluation of all possible configuration for three different geometries, the selected geometry to be printed was block B13_1. It was the one with the lowest U-value achieved while having the highest void fraction and the shortest heat path length from all the pareto front individuals. It is valid to clarify that the selection of the component to print and test was made before the optimization process, to first validate the simulation results by experimental means.

A given geometry has a different performance depending on the infill, either air or aerogel. Figure 6 highlights the Pareto Front blocks for the geometries having aerogel as infill. Since the thermal conductivity of air changes depending on the size and geometry of the cavities, the optimal configurations for air-infill to achieve the lowest possible U-value would vary. Therefore, i.e. block B13_1 behaves best than any other with air infill while is not the case whit aerogel infill.

3.2 Thermal Conductivity of Clay Mixtures

As can be noticed in Fig. 7, thermal conductivity can be significantly reduced by adding $\text{Ca}(\text{OH})_2$ to the mixture. While for the 100% clay mixture the average thermal conductivity was 0.765 W/mK, for the mixture with 90% clay and 10% $\text{Ca}(\text{OH})_2$ was 0.431 W/mK (a reduction of about 44%) while for the mixture with 80% of clay and 20% of $\text{Ca}(\text{OH})_2$ it was reduced by more than half with respect to the 100%clay, 0.315 (a reduction of about 59%). This demonstrates that the addition of $\text{Ca}(\text{OH})_2$, generally used for clay stabilization and proved to be used for 3DP, clearly reduces the thermal conductivity.

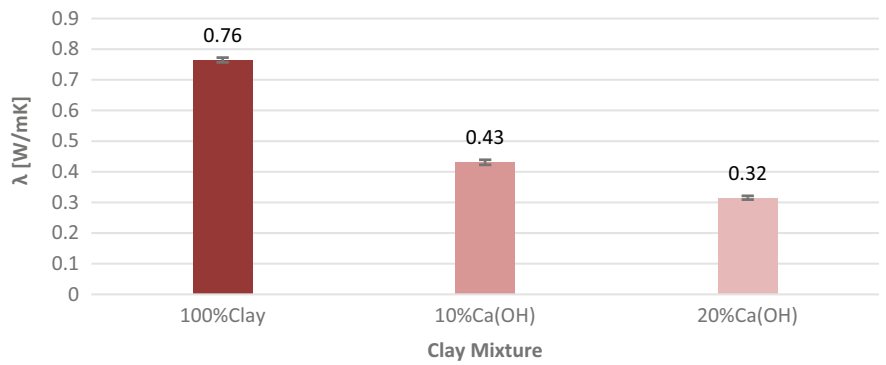


Fig. 7 Thermal conductivity [W/mK] comparison between the three mixtures

Table 1 U-values obtained from the HFM test for the component B13_1 with air-cavities and aerogel infill

Block Code	Air		Aerogel	
	R (m ² K/W)	U (W/m ² K)	R (m ² K/W)	U (W/m ² K)
B13_1T 100%Clay	0.43	2.35	0.68	1.33

3.3 Thermal Transmittance of the Component

As shown in Table 1, U-value measured for the block B13_1 with a 100%Clay mixture and air cavities, was 2.35 W/m²K. Results demonstrates that filling the cavities with granular aerogel allow the U-value to decrease to 1.33W/m²K.

4 Conclusions

Using computational design and from a parametrical approach, through an iterative process it is possible to extract the properties of several configurations of one geometry, finding an optimal individual. This workflow was applied to a laboratory-scale prefabricated wall component, and it could be eventually scaled up.

By adding up 20% of Calcium Hydroxide to a printable clay-based mixture, it is possible to reduce up to a 59% the thermal conductivity of the material. From the thermal transmittance results for the component B13_1, it is valid to say that computational design approach can be used to optimize the geometry. The U-value obtained with air cavities was 2.35 W/m²K and with aerogel-infill was reduced to 1.33W/m²K.

The results obtained with the admixtures of $\text{Ca}(\text{OH})_2$ are promising and future analysis will be held using this material with AM technology to perform the U-value of 3DP prefabricated wall components.

References

1. Kanishka K, Acherjee B (2023) Revolutionizing manufacturing: a comprehensive overview of additive manufacturing processes, materials, developments, and challenges. *J Manuf Process* 107:574–619. <https://doi.org/10.1016/j.jmapro.2023.10.024>
2. Gentile V, Vargas Velasquez JD, Fantucci S, Autretto G, Gabrieli R, Gianchandani PK, Armandi M, Bairo F (2024) 3D-printed clay components with high surface area for passive indoor moisture buffering. *J Build Eng* 91:109631. <https://doi.org/10.1016/j.job.2024.109631>
3. Lim S, Buswell RA, Le TT, Austin SA, Gibb AGF, Thorpe T (2012) Developments in construction-scale additive manufacturing processes. *Autom Constr* 21:262–268. <https://doi.org/10.1016/j.autcon.2011.06.010>
4. Ghaffar SH, Corker J, Fan M (2018) Additive manufacturing technology and its implementation in construction as an eco-innovative solution. *Autom Constr* 93:1–11. <https://doi.org/10.1016/j.autcon.2018.05.005>
5. Leschok M, Cheibas I, Piccioni V, Seshadri B, Schlüter A, Gramazio F, Kohler M, Dillenburger B (2023) 3D printing facades: design, fabrication, and assessment methods. *Autom Constr* 152:104918. <https://doi.org/10.1016/j.autcon.2023.104918>
6. Dubor A, Cabay E, Chronis A (2018) Energy efficient design for 3D printed earth architecture. In: De Rycke K, Gengnagel C, Baverel O, Burry J, Mueller C, Nguyen MM, Rahm P, Thomsen MR (eds) *Humanizing digital reality*. Springer Singapore, pp 383–393. https://doi.org/10.1007/978-981-10-6611-5_33
7. García Cuevas D, Pugliese G (2020) Advanced 3D printing with grasshopper: clay and FDM. Independently published. Printed by amazon
8. Alkhalidi A, Hataqay D (2020) Energy efficient 3D printed buildings: material and techniques selection worldwide study. *J Build Eng* 30:101286. <https://doi.org/10.1016/j.job.2020.101286>
9. BS EN 12667:2001. Thermal performance of building materials and products—determination of thermal resistance by means of guarded hot plate and heat flow meter methods—products of high and medium thermal resistance. <https://doi.org/10.3403/02109602U>
10. ISO 8301:1991. Thermal insulation—determination of steady-state thermal resistance and related properties—heat flow meter apparatus
11. BS EN ISO 6946-2017 (2017) Building components and building elements—thermal resistance and thermal transmittance—calculation methods. BSI British Standards. <https://doi.org/10.3403/30313347>

Development and Characterization of Architectural Integrated Solar Air Heating Façade Components



K. Friji, V. Villamil, V. Serra, A. Bouabidi, and S. Fantucci

Abstract Solar Air Heating Façades (SAHF) represent a promising solution to improve the energy efficiency of building envelopes by harnessing solar energy for heating. However, during cold seasons, these systems often face challenges with heat loss, which limits their efficiency. Moreover, their architectural integration still represents a relevant limitation for a large diffusion of these systems to residential buildings. This research examines the effect of different SAHF architectural/visual integration strategies and their impact on thermal performance. The experimental approach includes the assessment of i) the thermal resistance of different transparent/translucent elements constituted by multi-wall polycarbonate (PC) filled with granular Silica-Aerogel and, ii) the solar transmission of PC coupled with external timber lamella to enhance architectural integration and to provide summer shading. Uncoated timber and reflective aluminum top-coatings were evaluated. These configurations were tested under artificial sunlight. Results revealed that the integration of silica aerogel enhances thermal insulation of about 33% but moderately compromises the solar transmission (about 20%). Lamella configuration has also been observed to have a significant influence on solar transmission. It was demonstrated that the reflective top-coated lamella reaches up to 43% of solar transmission compared to the reference PC16 (53%). These findings highlight the potential of combining this strategy with Silica-Aerogel filled PC to balance solar energy harvesting, thermal insulation, and architectural integration.

Keywords SAHF · Solar transmission · Thermal insulation · Silica-Aerogel · Lamella

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1 Introduction

Energy demand reduction has driven the development of sustainable technologies across various practical applications. The building sector, responsible for approximately 40% of global energy consumption, represents a critical area for improvement [1]. Among the most promising approaches is the integration of solar energy systems into buildings, which help reduce energy demand [2]. A solution that has existed for many years and continues to be investigated is the Trombe wall, a passive solar system which is traditionally composed of a dark-colored layer covered with glazing, creating an air gap that allows natural air circulation between the wall and the glazing. Vents positioned at the top and bottom of the wall enable air to flow into the indoor space [3].

Achieving effective architectural integration in SAHF systems while maintaining thermal and solar performance can be accomplished through two key strategies. The first strategy focuses on enhancing the insulating properties of the glazed element by increasing its thermal resistance [4]. This can be achieved by filling the air gap with a translucent material like silica aerogel, which has low thermal conductivity and high porosity. It effectively prevents heat loss while allowing high solar transmission, as it is transparent to sunlight but opaque to infrared radiation [5, 6]. The second strategy involves using wooden lamella with improved solar reflectance to enhance architectural integration. Lamellas are lightweight, easy to install, and add depth to facades, making them a visually appealing alternative to traditional Trombe walls.

To optimize their performance, lamella requires advanced surface modifications, such as coatings or treatments to improve solar reflectance. These enhancements contribute to greater energy efficiency, sustainability, and improved thermal comfort while supporting urban microclimate management.

Moretti et al. [7] explore integrating granular silica aerogel into polycarbonate (PC) multiwall panels of varying thicknesses (16, 25, and 40 mm). The results show a significant reduction in U-values of 46%-68% for aerogel-filled panels compared to air-filled systems. Lv et al. [8] tested 12 aerogel-filled glass samples with different particle sizes (0.41–2.54 mm) and gaps (6–12 mm), finding that larger particles increased light transmittance, while thicker fillings reduced it.

This study enhances the architectural integration of the SAHF system by focusing on improving thermal resistance through Silica-Aerogel-filled polycarbonate and analyzing solar transmission with and without aerogel and lamella. The architectural aspect specifically evaluates the role of lamella in both aesthetics and solar performance. Architectural aesthetics were assessed through a qualitative design analysis based on material appearance, integration with facade elements, and visual impact. Key criteria included surface finish (the reflective quality of aluminum coatings), visual rhythm created by lamella spacing, and the degree of transparency offered by different configurations. Experimental testing evaluates thermal performance and integration into building design (Fig. 1).



Fig. 1 Picture of polycarbonate Trombe walls developed by the authors and integrated in a real building under monitoring. (Left) Trombe walls without lamella; (right) Trombe wall with wooden lamella

2 Methodology

The objective of this study is to assess the energy efficiency of a SAHF, focusing on achieving an optimal balance between energy savings and architectural aesthetics. The research focuses on an experimental methodology to analyze both thermal transmittance (U-value) and solar transmission characteristics of the transparent components. The lamella configuration tested was designed for integration into large-scale Trombe SAHF wall systems. The thermal resistance measurements were conducted using a Heat Flux Meter (HFM) apparatus LaserComp FOX 600; composed of two plates (upper and lower), which can work with temperatures from 0 to 60 °C. For HFM tests a minimum sample size of $[300 \times 300 \times 1 \text{ mm}]$ is required, due to the measuring sensors area $[254 \times 254 \text{ mm}]$. As far as the solar transmission assessment is concerned, measurements were carried out in a climatic chamber (BET-CELL) simulating the solar exposure through an artificial sun. The artificial sun system used complies with DIN 75220:1992 and CEI EN IEC 60904-3:2020 standards, featuring a 6500 K correlated color temperature (CCT) and parabolic symmetric reflectors to ensure a high proportion of parallel beam irradiation. It provides a uniform irradiation area of $1200 \times 1600 \text{ mm}$, with an intensity ranging from 1000 to 1200 W/m^2 at peak performance, ensuring short-term instability (STI) of $\pm 0.5\%$ and long-term instability (LTI) of $\pm 2\%$.

2.1 Material and Configuration

To investigate the performance of the SAHF, different configurations were tested to evaluate the individual and combined effects of Silica-Aerogel insulation of the polycarbonate panel on thermal resistance and aluminum-coated lamella (B2 configuration) on solar transmission. The baseline material in all configurations for the solar

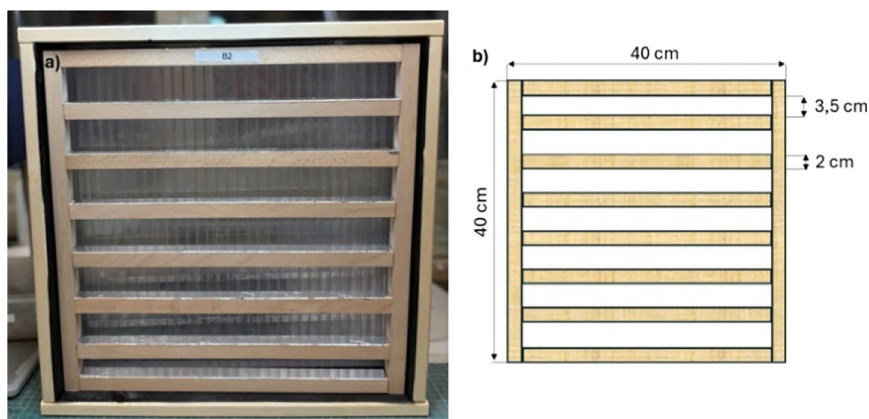


Fig. 2 **a** Aluminum-coated Lamella sample and **b** sample's dimensions

transmission was PC16, a 16 mm thick polycarbonate sheet. The prototype used for solar transmission analysis consists of a well-structured lamella box with a wooden frame. The box measures 40×40 cm and includes uniform horizontal lamella. The lamellas were coated, on the top surface, with aluminum (B2 configuration) as presented in Fig. 2a, 2 cm width and 40 cm length as in Fig. 2b.

2.2 Experimental Setup for Thermal Transmittance Assessment

Thermal transmittance (U-value) was measured according with ASTM C518 standard [9]. A granular LUMIRA translucent aerogel LA1000 declared thermal conductivity of 0.012 W/mK was used. The tested PC16 (thickness of 16 mm) sample, shown in Fig. 3, had a face area of $[40 \times 40 \text{ cm}]$ and was subsequently used to construct a small-scale prototype. The boundary conditions are reported in Table 1.

HFM test provided the thermal resistance of the sample $[\text{m}^2\text{K/W}]$, used to calculate the U-value, considering also the internal (R_{si}) and external (R_{se}) surface resistance $[\text{m}^2\text{K/W}]$, with values equivalent to 0.13 and 0.04 respectively, according to the Standard EN ISO 6946:2017 [10].

2.3 Experimental Setup for Solar Transmission Test

The solar transmission analysis was conducted using an artificial sun, shown in Fig. 4a, evaluating a PC sheet combined with an aluminum-coated lamella system. The prototype was positioned in front of the simulated solar radiation, with a fixed

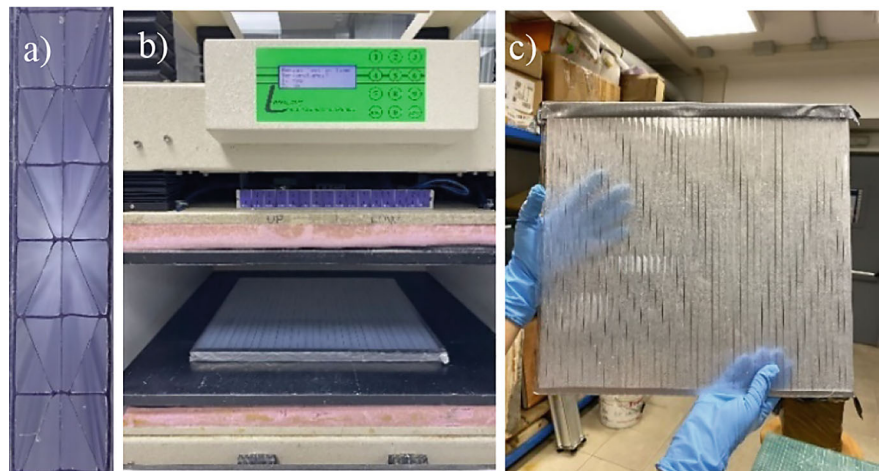


Fig. 3 **a** Detail of the tested panel of 16 mm with four cavities (five “walls”); **b** heat flux meter test configuration; **c** hollow polycarbonate panel filled with Silica-Aerogel

Table 1 Set points used to perform the tests of PC16 (with and without Silica-aerogel)

Flux direction	T _{up} (°C)	T _{low} (°C)	mT (°C)	ΔT (°C)
Upward	13.0	33.0	23.0	20.0
Downward	33.0	13.0	23.0	20.0

1-m distance from the light source to ensure uniform irradiance as illustrated in Fig. 3b. The setup uses four high-intensity projectors providing an irradiance of approximately 1000 W/m². Two second-class pyranometers (Hukseflux LP02) were placed behind the PC layer to measure the average irradiance. Data were recorded every 10 s over a 15-min test period, with analysis focusing on the final 5 min after thermal stabilization.

The performance evaluation metrics of the SAHF system was assessed using three key metrics: thermal transmittance (U-value), solar transmission (τ) calculated with Eq. (1), and solar reduction factor (RF) in Eq. (2).

$$\tau = \left(\frac{I_{sample}}{I_{baseline}} \right) \cdot 100 \tag{1}$$

$$RF = 1 - \left(\frac{\tau_{analyzed\ component}}{\tau_{baseline}} \right) \cdot 100 \tag{2}$$

where I_{sample} and I_{baseline} are the solar irradiance measured with the sample and without the sample respectively. τ_{analysed\ component} represents the solar transmission of the analyzed component, and τ_{baseline} represents the solar transmission of the baseline component (PC16).

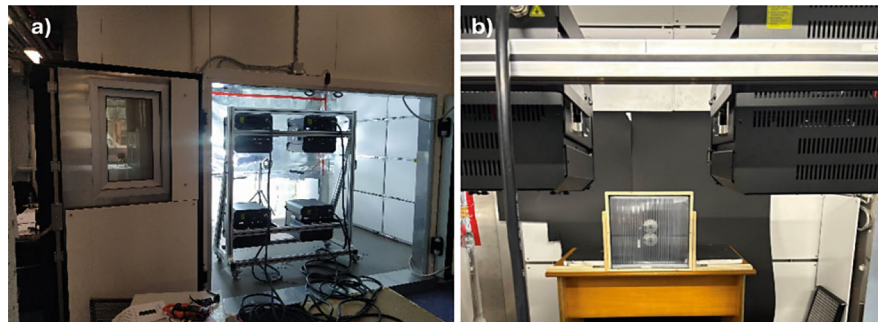
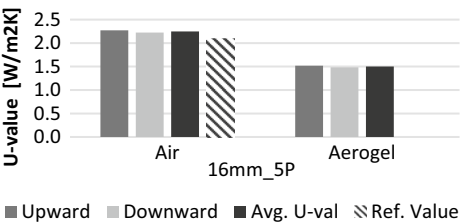


Fig. 4 **a** The artificial sun and the BET test-cell; **b** testing sample: polycarbonate panel PC16 (Reference)

Fig. 5 Thermal transmittance (U-value) of the polycarbonate panel with air and aerogel infill



3 Results and Discussions

3.1 Thermal Transmittance

U-value results are reported in Fig. 5. The results are comparable with the value provided by the manufacturer [11]. The average value for the PC16 with air-cavities was $2.2 \text{ W/m}^2\text{K}$, while the one achieved with the Silica-aerogel was about $1.5 \text{ W/m}^2\text{K}$. Therefore, the U-value $[\text{W/m}^2\text{K}]$ is reduced by around 33% with Silica-aerogel as infill.

3.2 Solar Transmission

The performance of different configurations PC16, PC16 + B2, and PC16 + Silica-Aerogels analyzed in terms of solar transmission (τ) and Reduction Factor (RF), as shown in Fig. 6. The PC16 configuration serves as the reference, exhibiting the highest solar transmission ratio (53.4%), allowing the highest solar radiation to pass through. When the B2 lamella is introduced (PC16 + B2), the transmission ratio decreases to 42.8%, indicating a 19.8% reduction in the transmission compared to PC16.

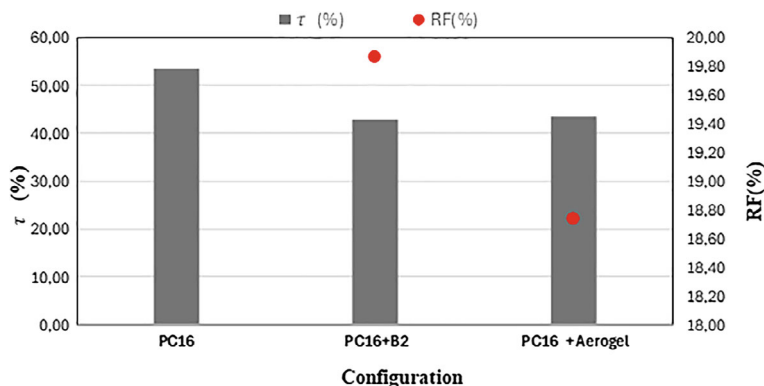


Fig. 6 Effect of lamella and Silica-Aerogel on solar transmission and reduction factor

Table 2 Measured global irradiance for different configurations

Configuration	I_{average} (W/m ²)	I_{baseline} (W/m ²)
PC16	525.2	983.0
PC16 + B2	417.6	975.2
PC16 + Aerogel	426.8	983.0

Similarly, the integration of Silica-Aerogel (PC16 + Aerogel) results in a transmission ratio of 43.4%, with a slightly lower RF of 18.80% compared to PC16 + B2. This suggests that aerogel slightly reduces solar transmission while simultaneously enhancing the system's insulation by minimizing conductive heat losses.

Table 2 presents the measured average irradiance (I_{average}) for different configurations (PC16, PC16 + B2, and PC16 + Aerogel).

4 Conclusion

This study experimentally investigated strategies to improve both the thermal resistance and solar transmission of Solar Air Heating Façade (SAHF) systems by evaluating a polycarbonate (PC16) filled with granular Silica-Aerogel, and external timber lamella configuration with uncoated and reflective aluminum top-coatings. The results demonstrated that integrating Silica-Aerogel into PC panels significantly improves thermal insulation by approximately 33%, though it leads to an 18.8% reduction in solar transmission.

Additionally, the influence of lamella configurations on solar transmission was evident, with reflective aluminum top-coated lamella proving to be the most effective in optimizing solar transmission. The experimental findings revealed that the PC16 configuration exhibited the highest solar transmission (53.4%), serving as a reference. The addition of B2 lamella (PC16 + B2) reduced transmission to 42.8%,

corresponding to a 19.8% reduction, while the integration of Silica-Aerogel (PC16 + Aerogel) led to a transmission ratio of 43.4%, with a lower reduction factor of 18.8%.

These findings emphasize the potential of combining Silica-Aerogel with reflective lamella to achieve a well-balanced façade system that enhances thermal insulation while maintaining solar energy harvesting capabilities. The combined strategy provides an optimized solution for integrating SAHF systems into building designs, improving both energy efficiency and architectural appeal. The solutions presented have been implemented in a SAHF applied to a real building under monitoring.

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References

1. Kwatra S, Kumar A, Sharma P (2020) A critical review of studies related to construction and computation of Sustainable Development Indices. *Ecol Ind* 112:106061. <https://doi.org/10.1016/j.ecolind.2019.106061>
2. Omara AAM, Abuelnuor AAA (2020) Trombe walls with phase change materials: a review. *Energy Storage* 2(6):e123. <https://doi.org/10.1002/est.123>
3. Trombe Wall - an overview | ScienceDirect Topics. Accessed 24 Feb 2025 [Online]. Available: <https://www.sciencedirect.com/topics/engineering/trombe-wall>
4. Cuce E (2018) Accurate and reliable *U*-value assessment of argon-filled double-glazed windows: A numerical and experimental investigation. *Energy Build* 171:100–106. <https://doi.org/10.1016/j.enbuild.2018.04.036>
5. Berardi U (2015) The development of a monolithic aerogel glazed window for an energy retrofitting project. *Appl Energy* 154:603–615. <https://doi.org/10.1016/j.apenergy.2015.05.059>
6. Cuce E, Cuce PM, Wood CJ, Riffat SB (2014) Toward aerogel based thermal superinsulation in buildings: a comprehensive review. *Renew Sustain Energy Rev* 34:273–299. <https://doi.org/10.1016/j.rser.2014.03.017>
7. Moretti E, Zinzi M, Belloni E (2014) Polycarbonate panels for buildings: experimental investigation of thermal and optical performance. *Energy Build* 70:23–35. <https://doi.org/10.1016/j.enbuild.2013.11.045>
8. Lv Y et al (2018) Quantitative research on the influence of particle size and filling thickness on aerogel glazing performance. *Energy Build* 174:190–198. <https://doi.org/10.1016/j.enbuild.2018.06.026>
9. ASTM C518 requirements. Standard test method for steady-state heat flux measurement and thermal transmission properties by means of the heat flux meter apparatus
10. BS EN ISO 6946:2017. Building components and building elements—thermal resistance and thermal transmittance—calculation methods

11. Catalogue of the Alveolar Polycarbonate Panels offered by the company. “Dott. Gallina – Polycarbonate Systems and Sheets”: CATALOGO dott Gallina ed_ita_07_2016def.pdf. Last time consulted: 28 of January 2025

A Framework for Achieving Smart Grid-Interactive Efficient Buildings: Defining the Grid-Building Interaction Levels and Comparing with Smart Readiness Indicator



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Abstract The increasing urgency of the energy transition drives the interest in demand-side flexibility to alleviate grid congestion and facilitate greener electrification. This work introduces the Smart Grid-Interactive Efficient Building (SGEB) assessment to evaluate demand-side flexibility in buildings, adapted from the grid-interactive efficient buildings (GEB) concept. The framework is built upon ten flexibility-related requirements from the Smart by Powerhouse, a Norwegian framework to measure commercial buildings' smartness. The SGEB assessment employs a multi-level scoring system that categorizes assets into three tiers: "grid-stressor," "grid-capable," and "Smart Grid-Interactive Efficient." Assets evaluated include heating, cooling, ventilation, indoor spaces, domestic hot water, internal loads, and on-site generation, with the final SGEB score ranging from 0 to 100%, with each tier contributing equally to the overall score. Ten pilot buildings in Norway were assessed to validate the SGEB, while potential enhancements like indoor temperature modelling and load forecasting were explored to project future outcomes. A comparative analysis with the smart readiness indicator (SRI) reveals that SGEB better represents flexibility assets and grid-building interaction. In contrast, the current SRI implementation does not adequately differentiate between flexible assets and generation technologies.

Keywords Demand-side flexibility · Grid-interactive efficient buildings (GEB) · Smart readiness indicator (SRI) · Smart by Powerhouse · Energy flexibility

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1 Introduction

In 2020, the European Union (EU) targeted the electrification of the demand side as one of the key elements towards a clean energy transition [1]. From the supply side, the continent faced a boost in the installation of renewable generation, which is empowering the process of the grid's decarbonization. However, their seasonality and forecasting complexity becomes a challenge for balancing and congestion management of the grid [2]. To address these challenges, one of the potential solutions is demand-side flexibility [3]. Only in Europe, the building sector accounts for 40% of the energy usage [4], which represents a large potential for energy flexibility if the loads are well controlled. In that context, a building that can provide flexibility to the grid while being energy efficient and aware of the users' needs is cataloged a "Grid-interactive Efficient Building (GEB)" [5].

1.1 Research Gaps

The assessment of building capacities, especially concerning energy use, differs among countries due to varying research and policies. A prime example is the Energy Performance Certificate (EPC) [6], which focuses mainly on energy efficiency. Recently, under the European Union, the Smart Readiness Indicator (SRI) [7] was introduced to evaluate the smart readiness of buildings. In Norway, the Smart by Powerhouse [8] was developed to measure new commercial buildings' smartness. In the grid-building interaction topic, the SRI includes it in its calculation core, while Smart by Powerhouse also considers this connection to some degree.

A comparative framework proposed by Campodonico Avendano et al. [9] integrates both the SRI and Smart by Powerhouse. This framework aids stakeholders in better understanding the smartness and smart readiness of a portfolio of buildings, with modifications made to accurately capture the importance of demand-side flexibility within the Norwegian context. Märzinger and Österreicher [10] expanded the application of the SRI to provide a quantitative assessment of load-shifting potential. Other studies have identified multiple key performance indicators (KPIs) that can be used for flexibility-based quantitative assessments [11]. However, quantitative methods require a high level of modeling and detailed data to estimate demand-side flexibility potential accurately. To the current author's knowledge, no other studies on the SRI or EPCs focused explicitly on applying demand-side flexibility as a qualitative assessment.

To address this gap, the Smart Grid-Interactive Efficient Building (SGEB) Score is proposed. Next, the current status of ten pilot buildings is assessed using the SGEB Score, and the results are compared with the established SRI indicator. Additionally, a hypothetical scenario is created in which data-driven techniques are employed to improve the buildings, leading to a final assessment comparison.

2 Methodology

2.1 Case Study

Building Pilots. The base of this work is developed as an extension of the Smart by Powerhouse assessment [8]. Therefore, the same ten pilots, of which seven are part of COLLECTiEF project [12], are used as study cases. The pilots are located in Ålesund, Norway, and they fall under four distinct building categories: School, Health center, Care facility, and Sport building. More detailed information for the pilots can be found in [9].

Data-driven technologies for demand-side flexibility. This study presents an “expected” scenario that uses data-driven technologies to enhance building data control, gathering, storage, and utilization. It focuses on physics-inspired machine learning, particularly for time series prediction and online learning [13], to model energy consumption and indoor temperatures. This serves as an additional control layer to existing building management systems (BMS), emphasizing thermal systems and indoor environment modulation. However, the study does not discuss how metered values, sensor data, or forecasts are visualized for users.

2.2 The SGEB Assessment

This work focusses on proving and implementing a replicable and general assessment for measuring the smartness level of interaction between the building and the grid in buildings (flexibility), but in a comparative manner, analogous of what an “energy labeling” can do. Therefore, the “Smart Grid-Interactive Efficient Building” or SGEB assessment is proposed. Before, a definition of a GEB was provided. Moreover, this definition is implemented as the basis of the proposed SGEB Assessment, and it further extended to three different levels that aim to cover all the possible levels of interaction between buildings and the grid (interaction levels):

- **Grid-stressor (GS):** a building in which there exists a lack of overall smartness, hardware (e.g., sensors) and BMS to allow interaction between the building and the grid. A building classified as “grid-stressor” can only respond, in the best of the cases, to user- and energy efficiency-related signals, and not to external signal that can enable grid interaction.
- **Grid-capable (GC):** a grid-capable building presents the necessary hardware and BMS to provide flexibility. However, it is not aware of external signals and lacks the smartness and digitalization tools to exploit its full flexibility potential.
- **Smart-grid interactive efficient (SGE):** an SGE building possesses the hardware, software, and communication protocols to provide demand-side flexibility while optimizing the resource utilization of its inner systems without losing focus on the end users. SGEB can provide an automatized response to grid signals by

coordinating the different assets, forecasting demand and inner states, as well as providing predictive and auto-diagnosing tools for maximizing the operation of the systems.

The SGEB score calculation. The base of the SGEB assessment is the Smart by Powerhouse assessment. The “functional requirements” used in Smart by Powerhouse are filtered to identify those relevant to the interaction to the grid. These functional requirements were originally designed for assessment at the building level, but they can also be applied, with minor modifications, to various flexibility assets within a building. These assets include heating systems, cooling systems, ventilation, indoor spaces, domestic hot water (DHW), lighting and internal gains (IG), electric vehicle charging (EVC), and on-site generation and storage.

In Table 1, the functionality levels (i) and corresponding score points are outlined, featuring the current Smart by Powerhouse score (refer to [9]) and the assigned points from the SGEB score assessment (denoted by $x_{i,j}^k$, where k represents the interaction levels and j the target asset). These functional requirements do not necessarily apply to all the flexibility during the calculations.

To calculate the SGEB score, each interaction level k of the assessment, GS, GC, and SGE, is estimated to have an equal value in the final score (through normalization). Next, the final SGEB score corresponds to the weighted sum of the interaction scores with flexibility weights (w_j), as indicated in Eq. (1), and it ranges from 0 to 100%. In the current weight configuration, the three interaction levels are evenly distributed. A score of 0% to 33.3% indicates that the building is classified as a GS. A score ranging from 33.3% to 66.6% categorizes the building as GC, while a score between 66.6% and 100% signifies that the building is SGE.

$$SGEB\ Score(\%) = 100\% \cdot \sum_j^J w_j \sum_k^K \sum_i^I \frac{x_{i,j}^k}{x_{i,j}^{k,\max}} \quad (1)$$

The selected weights are chosen to differentiate the interaction level between the different assets and the grid, as well as between different buildings and the grid. The methodology for their estimation is based on a power balance defined previously for the SRI assessment [9]. A summary of the non-normalized weights for the four categories of buildings is shown in Table 2. It is important to note that the total weight assigned to heating, cooling, and ventilation will correspond to the weights designated for the thermal environments. Additionally, if the HVAC system is non-electric, only 20% of the weight will be considered due to the presence of electric auxiliary systems that may still be exploited. The final weight estimation considers normalization based on the total sum of all applicable weights.

Table 1 Functional requirements of Smart by Powerhouse utilized for calculating SGEB assessment. The “Points in Smart by Powerhouse” column indicates the selected smartness levels per functionality requirements, ranging from 1 to 7. The SGEB score $\left(x_{i,j}^k\right)$ is the total count of the selected smartness levels for each functionality requirement shown in the point range column

ID	Functional requirements (<i>i</i>)	Points in Smart by Powerhouse			Score in SGEB $\left(x_{i,j}^k\right)$		
		Interaction levels (<i>k</i>)					
		GS	GC	SGE	GS	GC	SGE
1.2	Integration of control systems	3	4,5	6,7	1	2	2
1.3	Data availability, e.g. through use of sensors	2,3	4,5	6,7	2	2	2
1.4	Structural data collection and analysis	2,3	4–6	7	2	3	1
1.5	Maturity level of digital twins	2,3	4–6	7	2	3	1
2.1	Thermal environment	1–3	4,5	6,7	3	2	2
2.2	Atmospheric environment	1–3	4,5	6,7	3	2	2
3.2	Use of electricity and unit control	1–3	4	5–7	3	1	3
3.3	Refrigeration, air conditioning and thermal systems	2,3	4	5–7	2	1	3
3.4	Integration with grid, energy production and storage	3	4	5–7	1	1	3
4.6	Condition-based operation and maintenance	2,3	4	5–7	2	1	3

Table 2 Reference power values for the flexibility assets in (Wh/m²/year)

Building	Heating	Cooling	Ventilation	Indoor	DHW	IG	EVC	Gen
School	32.7	0.0	4.3	37.0	2.0	8.6	49.1	10.7
Health center	17.0	7.1	4.6	28.6	4.3	8.1	17.5	11.3
Care facility	18.4	0.1	4.2	22.8	3.5	3.7	10.5	6.2
Sport building	22.6	6.1	8.5	37.2	6.4	9.3	27.6	11.5

2.3 Assessing the Effectiveness of Data-Driven Modeling

While the SGEB assessment can label the grid-building interaction and compare it among a portfolio of buildings, the SRI can complement this information by showing

how the interaction is achieved based on the individual buildings' limits. Therefore, to include the SRI in the discussion, two cases need to be compared:

- **Current status:** the baseline or current scores of the group of buildings
- **Expected status:** improvement case that corresponds to the application of data-driven modeling for energy and indoor space forecasting.

The scores obtained by Campodonico Avendano et al. [9] are used as baseline results for the SRI assessments. Hence, the first step in this work is to calculate the baseline results for the SGEB assessment. The second step is to identify the functional requirements of the sample of buildings that can be improved with the "Data-driven modeling" approach as a study case. Finally, the SRI and SGEB can assess the "current" and "expected" cases.

3 Results

This section discusses the results of the work on the SGEB assessment. The SGEB assessment is calculated for ten buildings based on current conditions and available flexibility assets. Additionally, a new SGEB assessment is conducted for an updated BMS that utilizes data-driven modeling for forecasting indoor conditions and load demands. Finally, the implications of the updated assessment on grid-building interaction are compared with the expected increase in SRI score.

Figure 1 depicts the results obtained when the SGEB assessment is deployed in the ten building pilots, with the "current" and "expected" status. The current case shows a steady score between 41 and 47% in all the pilots; thus, they fall in the classification of GC buildings. This definition is adequate since all the BMS' are from the same provider. The system allows real-time data visualization and control of various systems through API-enabled setpoint and schedule adjustments. However, this potential can be exploited to enhance the interaction between the buildings' assets and the electrical grid. In short, the buildings have the tools but lack the smart software layer for this improvement. As highlighted in the accumulated bars, due to the normalization of the weights, the more flexible asset does not necessarily indicate a larger flexibility score. Indeed, the overall impact of each flexible asset is decreased. In B01, a maximum of eight assets are considered, while in buildings B06 and B10, which are district heating-based, only 4 assets are considered, and around the same SGEB score is obtained. Due to the reduced electricity consumption in these two buildings, IG takes a more significant fraction of the overall score than other buildings, where the indoor climate is considerably larger. Next, passing from the current to expected status, the buildings face an increase in score ranging from 25% in B10 to 39% in B03, B07, and B09, labeling all as SGE buildings. The lowest increases are faced in the same buildings with district heating technologies, B06 and B10, due to the natural limitation of improving the flexibility services due to the lack of smart measures in the IG assets. Due to the implementation of measures mainly

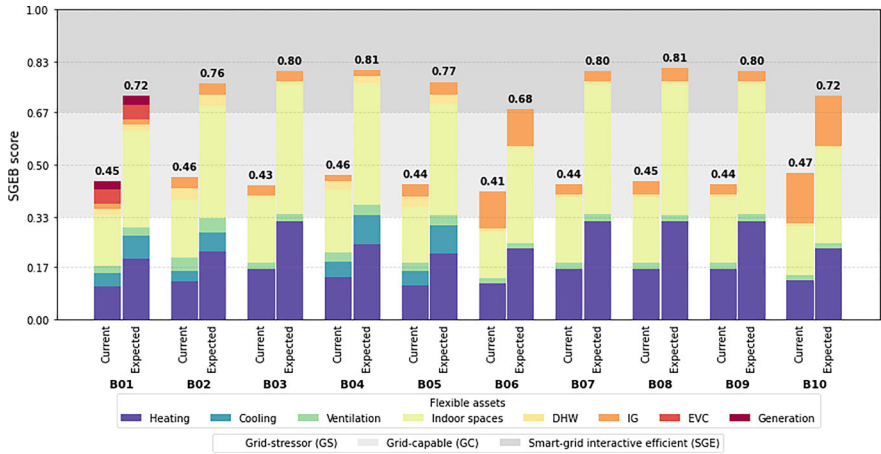


Fig. 1 Bar chart comparing current and expected SGEB scores for buildings B01 to B10. Each bar is segmented by categories: heating, cooling, ventilation, indoor spaces, DHW, IG, EVC, and generation. The chart highlights differences in scores, with values ranging from 0.41 to 0.81. A legend at the bottom identifies the color-coded categories

in data collection and smart controls for HVAC systems, the increases that drive the change in score are mainly heating and indoor spaces.

In Fig. 2, a comparative chart of the SGEB score with the SRI score and the grid aggregated score are displayed, respectively. In both figures are observable two clusters, a lower-left and upper-right, that represent the current and expected cases, respectively. For the “current” status, the SRI score is ranging from 20 to 35%. With the implementation of the data-driven tools for smartening up the buildings, the new overall score positions all pilots in the range of 65–80%, the third-highest smart readiness level. A point to consider is samples B06 and B10, which are penalized in the SGEB assessment. However, in the overall SRI, they reach two of the largest scores in the “expected case”. A similar behavior for these and all sample is observable in the grid aggregated score, where these samples reach almost the maximum achievable score even when other flexible assets, such as Ventilation, DHW and IG, are not targeted in the “expected assessment.” Moreover, a larger gap in the scores is found in the aggregated grid scores compared to the overall SRI. The “current” status cluster ranges from 0 to 20%, while the expected status primarily falls within the upper end of the scale. This suggests two main points: first, the overall SRI score heavily depends on the other aggregated scores from the assessment. Second, there is an indication of a shortfall in the grid-building interaction assessment within the SRI, as the SGEB scores do not reach the upper score threshold. This is likely because the SRI does not account for improvements in all flexibility assets and does not distinguish between generation technologies, as the SGEB does. A positive point of the SRI is vase B01, which includes EVC and on-site generation. It is emphasized that failing to modernize the controls for these assets will negatively impact the grid’s aggregated score.

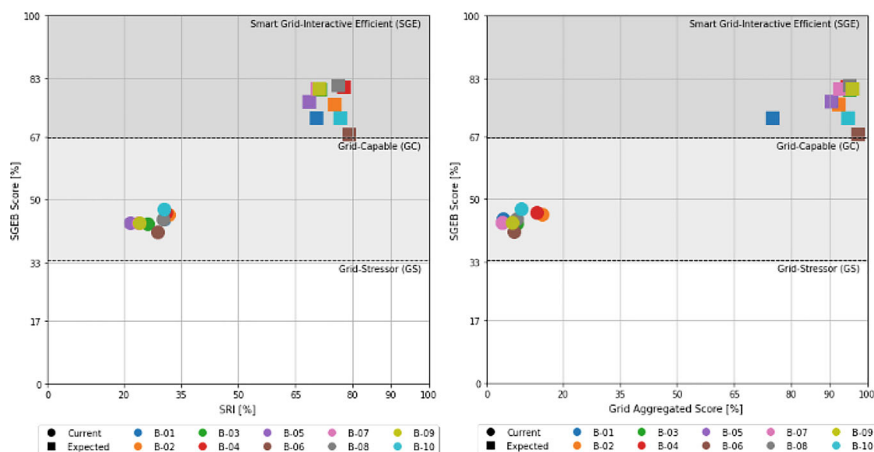


Fig. 2 Two X-Y charts comparing building assessment scores. data points across different categories. The left chart plots “SRI” versus “SGEB” scores with data points clustered in the lower left and upper right quadrants. The right chart shows “Grid Aggregated Score” versus “SGEB” with a similar distribution. Different building samples are color-colored, while the interaction levels are defined with the horizontal grid lines

4 Conclusion

This research work proposed a qualitative assessment, the SGEB assessment, for labeling the potential interaction between buildings, their flexible assets, and the grid. Moreover, ten building pilots were assessed with the SGEB and SRI under the current conditions and with a hypothetical case in which the thermal systems and indoor spaces are improved with data-driven and machine learning techniques. The results found that SGEB provides a better differentiation between the technologies for grid interaction. It also allows for score comparison among various buildings, paving the way for future “Energy Flexibility Performance Certificates.” For future research, a more refined functionality level for each assessment needs to be explored, and the weighting system should encompass a broader classification of buildings and consider different geographic locations.

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References

1. Communication From the Commission to The European Parliament, The European Council, The Council, The European Economic and Social Committee and the Committee of the Regions: The European Green Deal (2019)
2. Sinsel SR, Riemke RL, Hoffmann VH (2020) Challenges and solution technologies for the integration of variable renewable energy sources—a review. *Renew Energy* 145:2271–2285. <https://doi.org/10.1016/j.renene.2019.06.147>
3. Lund PD, Lindgren J, Mikkola J, Salpakari J (2015) Review of energy system flexibility measures to enable high levels of variable renewable electricity. *Renew Sustain Energy Rev* 45:785–807. <https://doi.org/10.1016/j.rser.2015.01.057>
4. In focus: Energy efficiency in buildings—European Commission. https://commission.europa.eu/news/focus-energy-efficiency-buildings-2020-02-17_en. Last accessed 29 Mar 2025
5. Neukomm M, Nubbe V, Fares R (2019) Grid-interactive efficient buildings. U.S. Dept. of Energy (USDOE), Washington DC (United States); Navigant Consulting, Inc., Chicago, IL (United States). <https://doi.org/10.2172/1508212>
6. Sesana MM, Salvalai G, Della Valle N, Melica G, Bertoldi P (2024) Towards harmonising energy performance certificate indicators in Europe. *J Build Eng* 95:110323. <https://doi.org/10.1016/j.jobe.2024.110323>
7. Ma Y, Verbeke S, Protopapadaki C, Dourlens-Quaranta S (2023) Smart readiness indicator (SRI): assessment package: Practical Guide SRI Calculation Framework v 4.5
8. Powerhouse: Smart by Powerhouse. Powerhouse (2019)
9. Campodonico Avendano IA, Heimar Andersen K, Erba S, Moazami A, Aghaei M, Najafi B (2024) A novel framework for assessing the smartness and the smart readiness level in highly electrified non-residential buildings: a Norwegian case study. *Energy Build* 314:114234. <https://doi.org/10.1016/j.enbuild.2024.114234>
10. Märzinger T, Österreicher D (2020) Extending the application of the smart readiness indicator—a methodology for the quantitative assessment of the load shifting potential of smart districts. *Energies* 13:3507. <https://doi.org/10.3390/en13133507>
11. Johra H, Heiselberg P, Dréau JL (2019) Influence of envelope, structural thermal mass and indoor content on the building heating energy flexibility. *Energy Build* 183:325–339. <https://doi.org/10.1016/j.enbuild.2018.11.012>
12. Aghaei M, Moazami A, Erba S, Hosseini M, Avendano IAC, Shahid M-S, Torrens-Galdiz I, Mastandrea G, Solli R, Riederer P, Bevilacqua G, Javanroodi K, Papadopoulos P, Carlucci S, Nik VM (2023) Collective intelligence for energy flexibility—Collectief: an EU H2020 project for enhancing energy efficiency and flexibility in existing buildings. In: 2023 international conference on future energy solutions (FES), pp 1–6. <https://doi.org/10.1109/FES57669.2023.10182779>
13. Campodonico Avendano IA, Dadras Javan F, Najafi B, Moazami A, Rinaldi F (2023) Assessing the impact of employing machine learning-based baseline load prediction pipelines with sliding-window training scheme on offered flexibility estimation for different building categories. *Energy Build* 294:113217. <https://doi.org/10.1016/j.enbuild.2023.113217>

Impact of Structural Anchors and Metallic Frame on the Thermal Performance of Opaque Ventilated Facades Through a CFD Analysis



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Abstract The development of bioclimatic technologies for energy retrofitting of building envelopes is crucial for achieving energy efficiency and sustainability in the built environment. Beyond addressing these challenges, opaque ventilated façades (OVFs) can contribute to reduce cooling energy demand, being a solution toward decarbonized buildings. The system operates by absorbing solar radiation on the external coating, which heats up and warms the air, creating a stack effect in the cavity. This natural convection phenomenon expels heat from the cavity, lowering the temperature of internal walls and subsequently reducing the building's cooling loads. The studies on OVFs have overlooked the presence of obstructions within the cavity, which are essential. Indeed, structural connections are necessary for the mechanical anchor of the coating to the massive wall, while horizontal metallic frame serves as a support for the external cladding façade, guaranteeing stability. These obstructions introduce additional pressure drops, reducing the mass flow rate within the cavity, weakening the stack effect, so diminishing the heat expelled. Consequently, this affects the heat flux entering the building wall. This study aims to evaluate the impact of these obstructions on the thermal performance of ventilated façades using three-dimensional computational fluid dynamics (CFD) analyses. The necessity of multi-dimensional analyses arises from the need for a representation of the stack effect, for an accurate assessment of the outgoing heat flow from the cavity. Specifically, a comparison between configurations with and without obstructions in terms of cooling load and energy expelled from the cavity is presented.

Keywords Opaque ventilated façade · Building energy efficiency · CFD analysis · Obstructions · Cooling load

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1 Introduction

Indoor overheating has become an increasingly prevalent issue in modern buildings. Several studies have assessed the associated risks, demonstrating that the number of overheating hours during warm months exceeds acceptable thresholds [1, 2]. Moreover, climate change is expected to exacerbate this phenomenon. Escandón et al. [3] analyzed a dataset of over 42,000 social housing units in southern Spain, revealing that 38% of the dwellings are already at risk of overheating. To mitigate the adverse effects of heatwaves, various strategies have been proposed. For instance, exterior roller blinds, night ventilation, and cool roofs have been investigated as solutions for a school constructed in 1958 in Canada [4]. Additionally, bioclimatic architectural strategies, such as green roofs [5], green walls [6], dynamic shading systems [7], and opaque ventilated façades (OVFs) [8], have been increasingly implemented for enhancing indoor comfort in an energy-efficient and sustainable manner.

In particular, an opaque ventilated façade consists of an external opaque cladding layer installed externally at a defined distance from the building envelope, thereby creating an air cavity. The system operates based on buoyancy-induced natural convection, whereby air gains heat from the external façade exposed to solar radiation, and carries heat away from the building. OVFs present the benefits of insulated walls for winter period, avoiding heat dispersion from inside to outside, and minimize solar heat gains during summer, thus improving indoor thermal comfort with less energy required for cooling. In addition, they provide protection of the insulating from rain and wind, the prevention from vapor stagnation and condensed moisture, and the elimination of structural discontinuities and thermal bridges.

To achieve a reliable simulation of OVF performance, computational fluid dynamics (CFD) analyses should be employed. Several CFD-based investigations have been conducted to evaluate OVF behavior under different conditions. For instance, Astorqui et al. [9] examined an OVF incorporating a mechanically controlled airflow system with a double-chamber configuration through a CFD analysis. Additionally, experimental validation of CFD simulations, incorporating various turbulence and radiation models, has been explored in [10]. Currently, opaque ventilated façade simulations typically neglect the influence of the metal structures necessary for the mechanical anchor and support, both the structural anchors between the façade cladding and the masonry wall, and the horizontal metallic frames, that provide structural elements to ensure the stability of the external cladding façade. These elements obstruct the airflow within the cavity, causing additional pressure losses and consequently reducing the mass flow rate in the cavity. A lower mass flow rate diminishes the amount of heat that the ventilated façade can dissipate, with a higher wall heat rate that enters inside the building.

The aim of this study is the investigation of the impact of including these structural components in ventilated façade simulations to achieve a more accurate assessment of their thermal performance. To this end, three-dimensional CFD simulations are conducted to model the influence of metallic frames in the cavity. The analyses focus on a typical summer day in August, in Messina, southern Italy, to evaluate the

performance of the system in a warm climate. The comparison assesses differences in terms of the average internal surface temperature $\bar{T}_{w,i}$ (i.e., the internal wall of the building), cooling energy demand, Q_c , and energy expelled from the cavity Q_{exp} .

2 Materials and Methods

Accurately modeling an opaque ventilated façade requires a detailed characterization of the airflow within the cavity. The stack effect is represented by solving the coupled mass, momentum, and energy conservation equations in a CFD implementation through COMSOL Multiphysics software. To enhance computational velocity, the Boussinesq approximation is applied. The energy conservation equation is coupled with a radiation model based on the gray body assumption, applied to the external façade. The incoming heat flux from solar radiation G_{sun} has been partitioned according to the spectral band of a black body considered at the Sun's surface temperature, equal to 5780 K. Specifically, the solar radiation G_{sun} is multiplied by the fraction of spectral intensity within the considered wavelength range, computed using Planck's law, relative to the total intensity obtained from the Stefan-Boltzmann law. The radiative heat flux G_{sun} is imposed as a boundary condition on the outer surface of the façade. To account for different façade's spectral properties, two emissivity bands are introduced as functions of the wavelength λ for solar radiation ε_{sol} ($\lambda \in [0.1; 3.0 \mu m]$), and for infrared radiation ε_{ir} ($\lambda \in [3.0 \mu m; +\infty]$).

The computational domain consists of four main components: the external façade, the ventilated cavity (with and without the presence of obstructions), the multilayered wall, and an external air control volume. The latter is essential for correctly capturing the natural convection phenomena, as directly imposing boundary conditions at the cavity outlet would not allow an accurate representation of the air flow. To ensure a realistic flow development, the height of the external air control volume, H_a , is set to twice the height of the façade, H_f , while its width, W_a , is defined as 80% of H_f .

To account for temporal variations in the external air temperature within this control volume, a dummy heat generation $\dot{Q}_{air}$ is introduced:

$$\dot{Q}_{air} = \frac{\rho c_p (T_e(t) - T_e(t-1))}{\Delta t} \quad (1)$$

where ρ is the density, c_p is the heat capacity at constant pressure, T_e is the external air temperature, derived from the imposed boundary condition applied to the air control volume, and t is the time. For computational efficiency, the indoor environment is not explicitly modeled. Instead, heat transfer between the interior space and the ventilated façade is represented through a convective boundary condition, assuming a convective heat transfer coefficient $h_i = 7.7 \text{ W/m}^2\text{K}$, which is characteristic of natural convection in enclosed indoor spaces. The indoor air temperature is set to $T_i = 26 \text{ }^\circ\text{C}$, consistent with typical summer set-point values for buildings in Mediterranean climates.

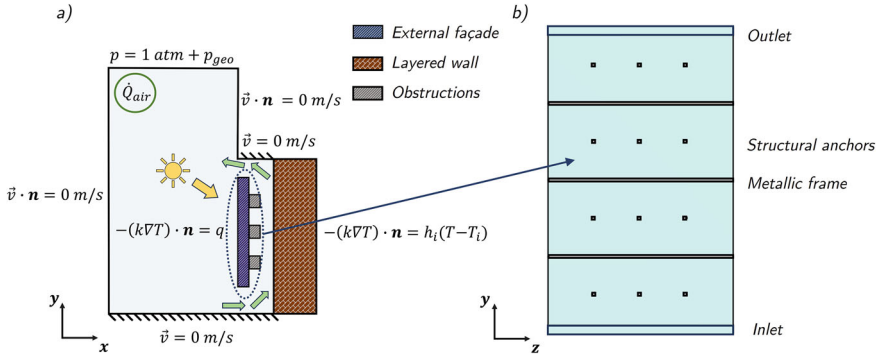


Fig. 1 Boundary conditions (a) and representation of structural anchors and metallic frames (b)

In Fig. 1a the boundary conditions applied in the numerical model in a 2D representation are illustrated. Here the obstructions are not presented, because these are not relevant for the boundary conditions schematization. At the upper boundary of the external air control volume, a pressure condition p is applied, corresponding to the sum of atmospheric pressure p_{atm} and the geodetic pressure contribution, given by $p_{geo} = \rho g y$. This arises from the need to simulate an undisturbed flow condition. In natural convection, this is the only known boundary condition, making it necessary to extend the computational domain beyond the building dimensions. In addition, temperature continuity is ensured across material interfaces.

For simulating a three-dimensional model, an additional depth d of 4.0 m along the z-axis is included, with the velocity component w representing the flow in that direction. and in the x-y boundary surfaces, the air control volume enforces $\vec{v} \cdot \mathbf{n} = 0$, while in the cavity is $\vec{v} = 0$. Figure 1b shows a schematic representation of the metallic frames and structural anchors in the y-z plane. The metallic frames consist of steel bars extending along the entire cavity length z , with a cross-sectional area of $5 \times 5 \text{ mm}$. Similarly, the structural anchors, also made of steel, connect the cavity to the layered wall, matching the cavity length and featuring the same cross-sectional dimensions. In this model, metallic frame vertical obstructions are not considered, as they are assumed to have a negligible impact on airflow. Since the primary air movement occurs along their length, they are not expected to significantly disrupt the ventilation dynamics within the cavity.

The initial conditions assume a zero-velocity field $\vec{v}$ for air, a pressure p equal to the sum of atmospheric p_{atm} and geodetic pressure p_{geo} on each point of the air domain. The air temperature is initially prescribed at $T = T_e(0)$, while a linear gradient is imposed between the initial temperature of air $T_e(0)$, and ambient temperature T_i in the layered wall. This assumption is made due to the lack of precise knowledge of the initial temperature distribution T within the wall. The analyzed wall, and the inlet/outlet of the cavity, have a height of 6.6 m and 20 cm, respectively; the façade emissivity is $\varepsilon_{sol} = 0.5$, $\varepsilon_{ir} = 0.9$. In our model and simulations, the external coating remains unchanged; therefore, both the solar spectrum emissivity and the

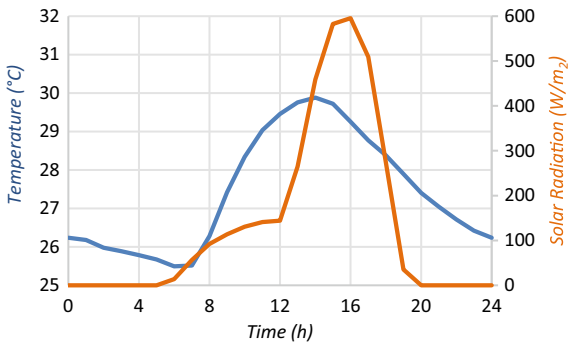
long-wavelength (infrared) emissivity are assumed constant. Naturally, when material properties vary, their radiative characteristics also change. Typically, traditional and stone-based materials exhibit high infrared emissivity, whereas metallic materials tend to show significantly lower values. Consequently, especially when metallic panels are used as the external cladding in ventilated façades, it is crucial to accurately model the radiative and spectral properties, taking into account the relevant wavelength ranges (e.g., solar, visible, and infrared spectra). The mesh utilized is about 40,000 elements for the 2D model, and 700,000 elements for the 3D model. Grid consistency and timestep are verified for each model, using two different meshes and timestep that are, respectively, two times and half of the employed ones. Finally, in Table 1 are showed the thicknesses and the thermal properties of the external façade cladding and of the layered wall, and in Fig. 2 are represented the solar radiation G_{sun} and the external air temperature T_e on a typical day in Messina during summer.

In Sect. 3, the results are analyzed based on three key parameters: the average internal surface temperature of the wall $\bar{T}_{w,i}$, the cooling load Q_c (Eq. 2) required to sustain the indoor set-point temperature T_i , and the energy expelled from the cavity Q_{exp} (Eq. 3) which reduce the building’s thermal load. The internal surface temperature of the wall $\bar{T}_{w,i}$ and the cooling load Q_c are directly related, as an increase in $\bar{T}_{w,i}$ results in higher Q_c .

Table 1 Thicknesses and thermal properties of the external façade and of the wall components

Component	Thickness d (cm)	Thermal conductivity k (W/mK)	Density ρ (kg/m ³)	Specific heat c_p (J/kgK)
External façade	1.5	1.30	2000	880
External plaster	2.5	1.40	1400	840
Insulation layer	10	0.04	75	1030
Brick	30	0.30	800	880
Internal plaster	1.5	0.70	1200	840

Fig. 2 Solar radiation G_{sun} and the external air temperature T_e on a typical day in Messina



$$Q_c = h_i(\bar{T}_{w,i} - T_i)\Delta t \quad (2)$$

$$Q_{\text{exp}} = \dot{m}c_p(\bar{T}_{c,o} - \bar{T}_{c,i})\Delta t \quad (3)$$

where $\dot{m}$ is the mass flowrate inside the cavity, and $\bar{T}_{c,i}$ and $\bar{T}_{c,o}$ are the average cavity inlet and outlet temperatures, respectively. These parameters are important for the energy difference percentage $\Delta E(\%)_{Q_i}$ evaluation, assessed for both the cooling load $\Delta E(\%)_{Q_c}$ and the energy expelled from the cavity $\Delta E(\%)_{Q_{\text{exp}}}$.

$$\Delta E(\%)_{Q_i} = \pm \frac{Q_{i,1} - Q_{i,2}}{Q_{i,1}} \cdot 100 \quad i = c, \text{exp} \quad (4)$$

A positive sign is used for the cooling load, indicating reduced energy consumption, while a negative sign is applied to the expelled energy, as it corresponds to heat removed from the building's thermal load.

3 Results

The initial results, presented in Fig. 3a, illustrate the time-dependent evolution of the average temperature on the internal wall $\bar{T}_{w,i}$ for the three configurations analyzed: without obstructions, with a metallic frame (MF), and with both a metallic frame and structural anchors (MF + SA). The velocity w profile at 15:00 is depicted in Fig. 3b, for a cross-section of the cavity in the configuration containing all the obstructions: it can be noted a zero-velocity near the presence of obstructions, impeding the air flow.

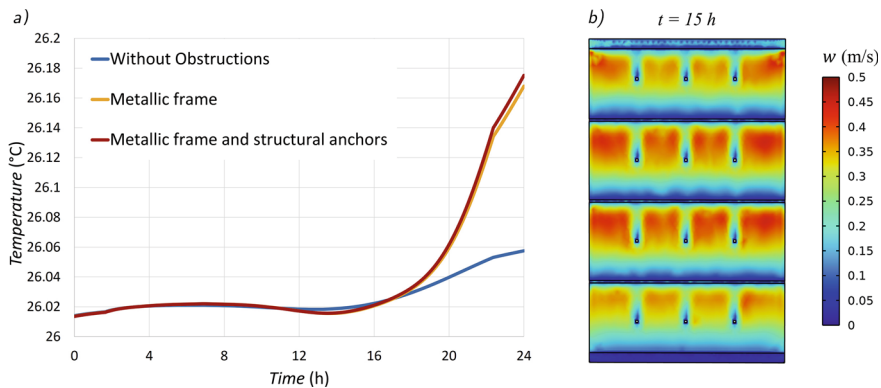


Fig. 3 Average temperature on the internal wall $\bar{T}_{w,i}$ as a function of time t for the three configurations (a), and velocity w for a cross-section of the cavity for the MF + SA configuration (b)

The presence of obstructions leads to a higher average wall temperature $\overline{T}_{w,i}$ compared to the unobstructed case (Fig. 3a).

This effect arises from a reduction in the air flow within the cavity $\dot{m}$ (Fig. 4), which consequently decreases the amount of energy expelled Q_{exp} and increases the thermal load on the wall. A clear distinction can be observed between the unobstructed case and those with obstructions, whereas the difference between the MF-only and MF + SA configurations is minimal. This trend is further reflected in Table 2, which presents the energy difference percentages $\Delta E(\%)_{Q_c}$ in both cooling load Q_c and energy expelled from the cavity Q_{exp} . For the table interpretation, values in each row indicate the difference in percentage terms relative to the corresponding column values for the cooling load, while the opposite applies to the expelled energy from the cavity Q_{exp} . Additionally, it is observed that the mass flowrate $\dot{m}$ remains relatively similar during periods without solar radiation G_{sun} but diverges significantly under solar exposure. This behavior reinforces the reliability of the CFD model, demonstrating its accurate response to thermal variations. In quantitative terms, the cooling load E_{cool} for the unobstructed wall is 0.13 kWh, while the expelled energy E_{exp} is 0.49 kWh. In contrast, for the configuration with all obstructions, these values shift to 0.20 kWh and 0.07 kWh, respectively (Table 2).

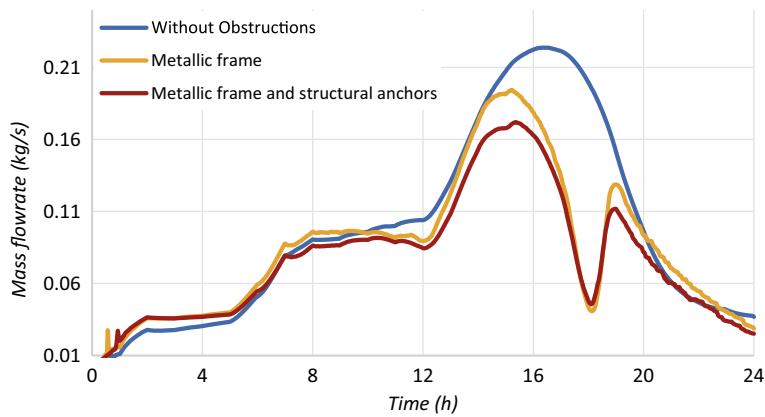


Fig. 4 Mass flowrate $\dot{m}$ as a function of time t for the three configurations

Table 2 Cooling load and energy expelled from the cavity difference percentages $\Delta E(\%)_{Q_c}$, $\Delta E(\%)_{\text{exp}}$

	$\Delta E(\%)_{Q_{\text{exp}}}(\%)$			
$\Delta E(\%)_{Q_c}(\%)$		MF + SA	MF	No obstructions
	MF + SA	–	11.24	86.42
	MF	2.71	–	84.70
	No. obstructions	50.11	46.15	–

These findings highlight that those horizontal obstructions, such as metallic frames, induce a significantly higher pressure drop compared to structural anchors. As a result, any modeling of a ventilated façade should account for these elements, and during the design phase, minimizing horizontal protrusions would be beneficial, as they notably disrupt airflow.

4 Conclusions

In this study, it is investigated the thermal performance of a ventilated façade by analyzing the effects of obstructions on airflow dynamics and heat transfer. The results reveal that horizontal elements, such as metallic frames (MF), significantly hinder the airflow within the cavity, leading to an increase in the internal wall temperature $\bar{T}_{w,i}$. A comparison of three configurations—unobstructed, MF, and MF with structural anchors (MF + SA)—demonstrates that obstructions reduce the expelled energy Q_{exp} , but the difference between the MF-only and MF + SA cases remains marginal. Quantitatively, the cooling load Q_c for the unobstructed façade is 0.13 kWh, while the expelled energy Q_{exp} reaches 0.49 kWh. In contrast, for the fully obstructed configuration, these values shift to 0.20 kWh and 0.07 kWh, respectively, highlighting the adverse impact of obstructions on energy dissipation. Additionally, mass flow rate $\dot{m}$ analysis shows that airflow patterns remain similar during non-radiative periods, but diverge significantly under solar exposure. These findings emphasize the need to horizontal protrusions in ventilated façade models, and to minimize them in designs to enhance natural convection and thermal efficiency.

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References

1. Tink V, Porritt S, Allinson D, Loveday D (2018) Measuring and mitigating overheating risk in solid wall dwellings retrofitted with internal wall insulation. *Build Environ* 141:247–261
2. Laouadi A, Bartko M, Lacasse MA (2020) A new methodology of evaluation of overheating in buildings. *Energy Build* 226:110360
3. Escandón R, Suárez R, Alonso A, Mauro GM (2022) Is indoor overheating an upcoming risk in southern Spain social housing stocks? Predictive assessment under a climate change scenario. *Build Environ* 207:108482
4. Baba FM, Ge H, Wang L, Zmeureanu R (2023) Assessing and mitigating overheating risk in existing Canadian school buildings under extreme current and future climates. *Energy Build* 279:112710

5. Bevilacqua P, Bruno R, Arcuri N (2020) Green roofs in a Mediterranean climate: energy performances based on in-situ experimental data. *Renew Energy* 152:1414–1430
6. Cuce E (2017) Thermal regulation impact of green walls: an experimental and numerical investigation. *Appl Energy* 194:247–254
7. Pinto MC, Crespi G, Dell'Anna F, Becchio C (2023) Combining energy dynamic simulation and multi-criteria analysis for supporting investment decisions on smart shading devices in office buildings. *Appl Energy* 332:120470
8. Fantucci S, Serra V, Carbonaro C (2020) An experimental sensitivity analysis on the summer thermal performance of an Opaque Ventilated Façade. *Energy Build* 225:110354
9. Santa Cruz Astorqui J, Porras-Amores C (2017) Ventilated Façade with double chamber and flow control device. *Energy Build* 149:471–482
10. Buratti C, Palladino D, Moretti E, Di Palma R (2018) Development and optimization of a new ventilated brick wall: CFD analysis and experimental validation. *Energy Build* 168:284–297

Investigation on Plate-Finned Tube Evaporator Performance with the Hybrid Method by Varying Geometrical Specifications



Silvia Macchitella, Gianpiero Colangelo, and Giuseppe Starace

Abstract Starting from the local scale thermo-fluid dynamic analytical calculations, the “hybrid method” combines data of both sides of heat transfer cells of fin and tube evaporators resulting in low processing costs and high accuracy performance outcomes at the overall scale. The hybrid method is based on selectable regression equations generated from known data (analytical, experimental, or numerical) to compute temperature fields, pressure drop data, and heat transfer rates for both sides of the heat exchanger to be combined over the effective geometry of the evaporator. In the present work, the hybrid method was used to carry out simulations on a plate-finned tube evaporator with the aim of testing its robustness and investigating the evaporator performance with the variation of some geometric parameters such as the tubes’ diameter, the fin pitch and the materials. The simulations show that the hybrid method algorithm is capable to address evaporator performance variations caused by the geometric ones. Thus, this method can be used to optimize the design of a plate-finned tube evaporator both in terms of heat transfer rate and refrigerant pressure drops by increasing the tubes’ diameter and using higher-conductivity materials such as copper, or by decreasing the fin pitch.

Keywords Hybrid method · Evaporator · Plate-finned tube

1 Introduction

The design process of a plate-finned tube heat exchanger (PFTHX) can be exceedingly challenging due to the high number of design variables involved. One of the most important decisions the designer has to take is which model to employ to determine the heat exchanger’s performance. By using a specific scale approach, models

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can be categorized as small, large, or multi-scale [1]. When small-scale interaction phenomena are thoroughly analysed by computational fluid dynamics (CFD) techniques, their conclusions are frequently highly accurate. However, they are time and computationally challenging. Fin profiles and tube geometries are the subject of detailed small-scale analyses in [2–8].

Conversely, manufacturing organizations may find large-scale approach models advantageous due to their simplicity and quickness in implementation. These are usually analytical models that are frequently generated by experimental investigations with the limitation of possibly returning results that are inaccurate. The great number of research studies present in the literature shows that it is the most often used method for determining heat exchanger performance [9–14].

Multi-scale models, instead, combine the advantages of analytical methods with more accurate numerical approaches; they are very adaptable and appropriate for a variety of HX geometries and operating conditions.

The hybrid method, which was originally developed by Starace et al. [15, 16], is an alternative design multi-scale method that uses an algorithm that employs a multi-scale strategy based on data from experimental, analytical, or numerical studies. The hybrid approach was first used on compact cross-flow HXs and then on counter-current evaporative condensers [17]. Starace et al. [18–22] then used the control volume approach to apply the hybrid method to plate-finned evaporator with very simple circuit arrangement for the refrigerant at first and then with more complex layouts to assess how circuitry arrangement impacts overall performance.

In this paper the hybrid method is used to investigate the influence of some geometrical specifications as the tube diameter and the fin pitch as well as the construction materials on the performance of plate-finned tube evaporators in terms of heat transfer rate and refrigerant pressure drops. In addition, the simulations show that the hybrid method is capable of addressing evaporator performance variations caused by the geometric ones.

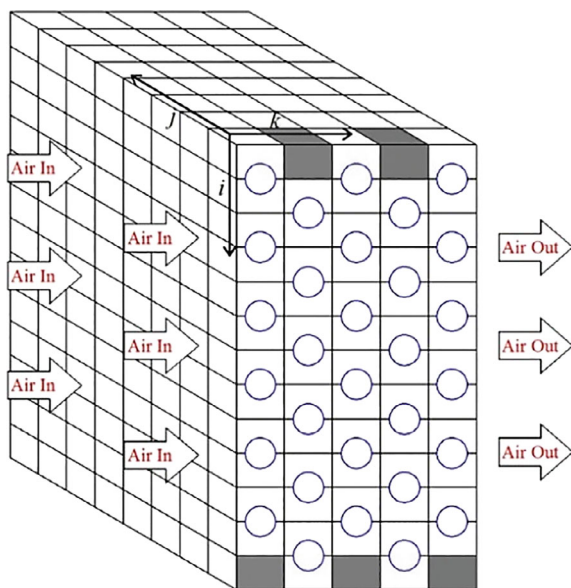
2 The Hybrid Method

The general architecture of the HX at the base of the model is represented by a three-dimensional matrix organized into tube-centred elementary cells (Fig. 1).

The heat exchanger used in the case study is a staggered finned tube evaporator. The working fluid, refrigerant, evaporates as a result of the heat exchange with air moving perpendicular to the tubes between the fins. The refrigerant runs through two or more complex circuits that make up the evaporator, each of which has an equal number of tubes. The assumptions that underlie the mathematical model are listed as follows.

- frost growth is not modelled. In any case, there is never frost formation in any of the simulation scenarios that were run;
- the refrigerant fluid never reaches the state of superheated vapor;

Fig. 1 Schematic representation of an evaporator through a three-dimensional matrix



- calculations are done in steady-state;
- all parameters are taken into account as constant within each elementary cell that the evaporator is divided into;
- the tube junction bends are not included in the heat transfer process.

A local study is performed in each of the elementary cells of the evaporator to calculate the heat transfer parameters. Using information obtained from experimental correlations reported in the literature [23–31], a regression analysis is used to develop prediction functions for the air side and refrigerant thermodynamic properties. The adaptability of the hybrid approach algorithm is one of its benefits. Actually, it is feasible to utilize different correlations or experimental data than those taken into account in the simulations described in this study, while keeping the same setup and algorithm. So, by building prediction functions using data from any experimental, analytical, or even numerical study, the algorithm merely “learns” from the data used each time and determines the exchangers’ real performance. The algorithm iteratively calculates the tube wall temperature for each cell, taking into account the conductive contribution of the piping as well as the convective contribution of the air and refrigerant, provided that the convergence condition between the air side and the refrigerant side heat transfer rate is verified. Following the computation of each cell, the algorithm then verifies pressure drops on both the air-side and refrigerant-side. If the requirements are not satisfied, the algorithm redistributes the mass flow rates into each cell again, changing the flow rate according to the deviation from the mean value and starting the calculation again until the convergence conditions on the air-side and refrigerant-side are both verified.

3 Results and Discussion

This study employs the hybrid method to examine how certain geometrical parameters, as well as construction materials, affect plate-finned tube evaporators' efficiency in terms of heat transfer rate and refrigerant pressure drops. Three different sets of simulation were run changing the inner tube diameter (Simulation A), the tube and fin materials (Simulation B) and the fin pitch (Simulation C), respectively, while leaving all other geometric specifications unchanged (see Table 1) and with the same operating conditions, as reported in Table 2. The evaporator chosen for all simulations is a 5-row staggered finned tube evaporator with 4 refrigerant circuits, as shown in Fig. 2.

The results of Simulation A and Simulation B are illustrated in Figs. 3 and 4. As can be seen from Fig. 3a, the heat transfer rate increases with a parabolic trend as the tube inner diameter increases (with the same thickness) as there is an increase in the heat exchange surface, with the same geometry and operating conditions. In detail, a designer who wants to maximize the thermal power, by increasing the tube inner diameter of 76.2% can obtain a heat transfer rate greater than 19.1%, calculated as an average between the 4 materials taken into consideration. The same trend occurs for all materials: the best performing material is definitely copper which corresponds to a higher conductivity. Stainless steels AISI 304 and AISI 416 are the least performing with a much lower conductivity than copper.

Aluminum and copper have similar performance with an increase in heat transfer rate of 18.4% compared to an increase of 76.2% of the tube inner diameter. Furthermore, as can be observed, with the same diameter of 0.00738 m and geometry, a

Fig. 2 Schematic representation of 4-circuit evaporator used for Simulation A, B and C

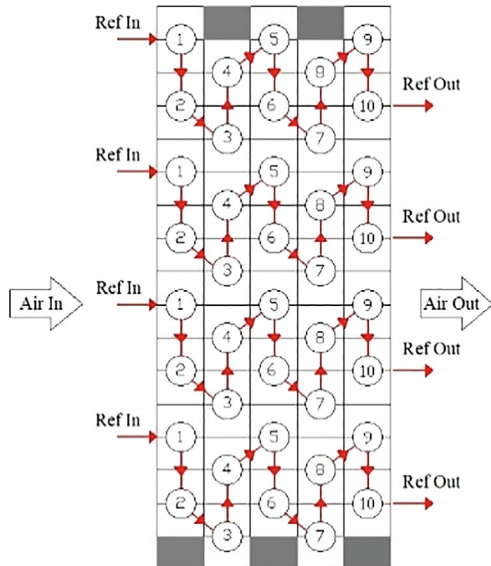


Table 1 Geometrical specification of the evaporator for Simulation A, B and C

Specification	Unit	Simulation A	Simulation B	Simulation C
Tube material	–	Copper	Copper/aluminum/ steel AISI 430/steel AISI 304	Copper
Tube inner diameter	m	0.00738/0.009/ 0.011/0.013	0.00738	0.00738
Tube thickness	m	0.00056	0.00056	0.00056
Longitudinal pitch	m	0.02165	0.02165	0.02165
Transversal pitch	m	0.025	0.025	0.025
Fin pitch	m	0.002	0.002	0.002/0.0025/0.005/ 0.01
Fin thickness	m	0.0001	0.0001	0.0001
Evaporator height	m	0.2125	0.2125	0.2125
Evaporator width	m	0.11	0.11	0.11
Evaporator length	m	0.5	0.5	0.5

Table 2 Operating conditions for Simulation A, B and C

Specification	Unit	Value
Refrigerant fluid	–	R134a
Refrigerant mass flow rate	kg/s	0.0058
Air mass flow rate	kg/s	0.657
Evaporation temperature	K	271.5
Air inlet temperature	K	288
Air inlet relative humidity	–	0.65
Inlet vapor quality	–	0.2
Air inlet velocity	m/s	5.1

designer can obtain an increase in thermal power of 1.9% by using copper instead of AISI 304/416 steels. The advantage of using high conductivity materials becomes less and less evident as the diameter of the tubes increases: for diameters of 0.013 m, in fact, the difference in heat transfer rate between the two evaporators simulated with copper and AISI 304/416 steel is only 0.4%.

The advantages of using larger diameters are also evident in terms of refrigerant pressure drops, as shown in Fig. 3b. In detail, by increasing the diameter by 76.2% (passing from 0.00738 m to 0.013 m), a strong reduction in refrigerant pressure drops of 91.6% can be achieved, for all simulated materials.

Simulation C was conducted in order to evaluate the evaporator performance as the fin pitch varies. As shown in Fig. 4a, as the fin pitch increases, the heat transfer rate decreases almost linearly due to the decrease in the finned surface, and therefore of the heat exchange, for the same evaporator overall dimensions. In particular, by quadrupling the fin pitch, the performance reduced by 30.8% in terms of thermal

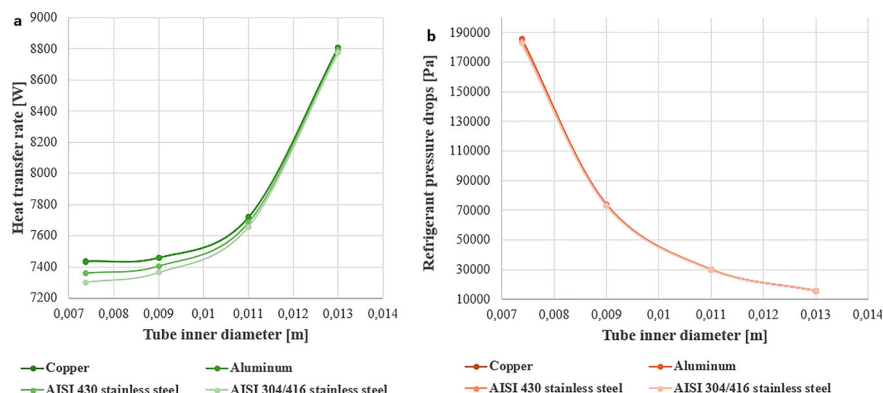


Fig. 3 Two-panel figure showing X-Y charts as a result of Simulation A and Simulation B at operating condition of Table 2 and with unchanged geometrical specification of Table 1. Panel (a) displays a green line graph of heat transfer rate (W) versus tube inner diameter (m) for different materials: copper, aluminum, AISI 430 stainless steel, and AISI 304/416 stainless steel. The heat transfer rate increases with diameter. Panel (b) shows an orange line graph of refrigerant pressure drops (Pa) versus tube inner diameter (m) for the same materials, with pressure drops decreasing as diameter increases

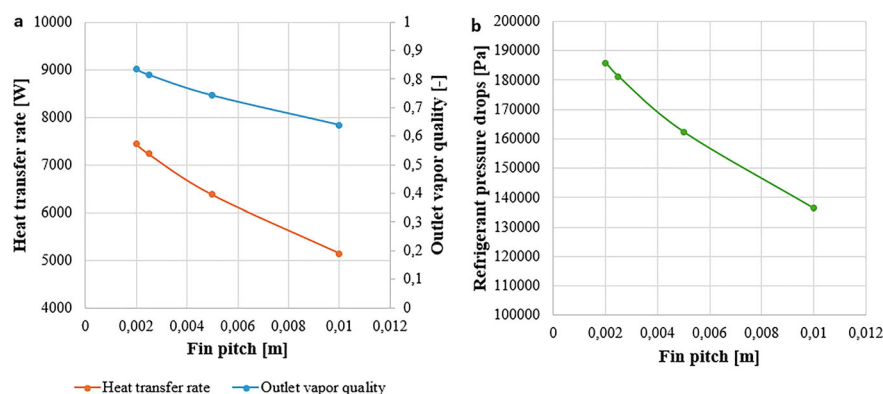


Fig. 4 Two-panel figure showing X-Y charts related to fin pitch as a result of Simulation C at operating condition of Table 2 and with unchanged geometrical specifications of Table 1. Panel (a) displays two lines: an orange line for heat transfer rate and a blue line for outlet vapor quality, both decreasing as fin pitch increases. Panel (b) shows a green line representing refrigerant pressure drops, also decreasing with increasing fin pitch

power. For the same reason, the refrigerant vapor quality at the outlet also decreases by 23.5%. As can be seen in Fig. 4b, the disadvantage of using a higher fin pitch can be compensated by a decrease in refrigerant pressure drops. Therefore, by quadrupling the fin pitch, with the same evaporator overall dimensions, the refrigerant pressure drops decrease by 26.6% as a consequence of a lower heat exchange and therefore of the decrease in vapor quality at the evaporator outlet.

4 Conclusions

To test the robustness of the method and provide designers with useful information for the design process of plate-finned tube heat exchangers, a multi-scale model, already known as the hybrid method, was employed. This method uses a local analysis to obtain the heat transfer characteristics on each elementary volume. Here, the regression technique was applied to data from experimental correlations found in the literature in order to identify the prediction functions.

The thermodynamic parameters of the air and refrigerant sides were then computed using these prediction functions. This method's high degree of versatility comes from its ability to use data from both analytical and numerical analyses, producing somewhat accurate findings at a reasonable cost. Three different simulations were run to investigate the performance of a 5-row plate-finned tube evaporator with four refrigerant circuits in terms of heat transfer rate and refrigerant pressure drops, varying the inner tube diameter (Simulation A), the tube and fin materials (Simulation B) and the fin pitch (Simulation C) while leaving all other geometric specifications and operating conditions unchanged. Simulations showed that a designer aiming to optimize the thermal power can achieve a heat transfer rate of more than + 9.1% (average value among the materials considered) by increasing the tube inner diameter by 76.2% (from 0.00738 m to 0.013 m), with the overall dimensions unchanged. Furthermore, with the same increase in diameter a significant decrease in refrigerant pressure drops (−91.6%) can be obtained. This pattern remains true for all the tested materials: copper, which has the highest conductivity, is unquestionably the best-performing one. The least effective stainless steels are AISI 304 and AISI 416, which have substantially poorer conductivity than copper. Moreover, the difference between the materials becomes less and less significant as the tube diameter increases. Simulations showed also that the heat transfer rate decreased by 30.8% when the fin pitch was quadrupled, passing from 0.002 m to 0.01 m, together with a drop of 23.5% in the outlet's refrigerant vapor quality. On the other hand, the refrigerant pressure reduces by 26.6% only quadrupling the fin pitch while maintaining the same overall evaporator dimensions.

In conclusion, simulations showed that the hybrid method is suitable and capable of predicting the performance of a finned tube evaporator considering variations in geometry and materials. Nevertheless, in order to make the hybrid method model more representative of a coil's actual operation, in the future the same authors plan to test more configurations under real-world conditions. It is crucial to give designers these tools in order to prevent oversizing or undersizing and the resulting waste of resources during construction and operation.

Abbreviations

Nomenclature

G	Mass flux ($\text{kg m}^{-2} \text{s}^{-1}$)
i	Enthalpy (J kg^{-1})
Δp	Pressure drop (Pa)
$\dot{Q}$	Heat transfer rate (W)
RH	Relative humidity
T	Temperature (K)
V	Velocity (m s^{-1})
x	Vapor quality

Greek Symbols

β	Regression coefficient
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Subscripts

A,R	Air, refrigerant
in	Inlet
m	Mean value
o	Outer
out	Outlet
w	Wall

Abbreviations

HX	Heat exchanger
PFTHX	Plate-finned tube heat exchanger

References

1. Macchitella S, Colangelo G, Starace G (2023) Performance prediction of plate-finned tube heat exchangers for refrigeration: a review on modeling and optimization methods. *Energies* 16:1948

2. Bhuiyan AA, Islam AS (2011) CFD analysis of different fin-and-tube heat exchangers. *J Mech Eng* 62:237–249
3. Lee YT, Chien LH, He J, Wen C-Y, Yang AS (2022) Air side performance characterization of wavy Fin-and-tube heat exchangers having elliptic tubes with large waffle heights. *Appl Therm Eng* 217:119220
4. Rauber WK, Silva UF, Vaz M, Alves MVC, Zdanski PSB (2022) Investigation of the effects of fin perforations on the thermal-hydraulic performance of Plate-Finned heat exchangers. *Int J Heat Mass Transf* 187:122561
5. Li Y, Qian Z, Wang Q (2022) Numerical investigation of thermohydraulic performance on wake region in finned tube heat exchanger with section-streamlined tube. *Case Stud Therm Eng* 33:101898
6. Lindqvist K, Skaugen G, Meyer OHH (2021) Plate fin-and-tube heat exchanger computational fluid dynamics model. *Appl Therm Eng* 189:116669
7. Taler D, Taler J, Trojan M (2020) Thermal calculations of plate–fin–and-tube heat exchangers with different heat transfer coefficients on each tube row. *Energy* 203:117806
8. Taler D, Taler J, Wrona K (2020) Transient response of a plate-fin-and-tube heat exchanger considering different heat transfer coefficients in individual tube rows. *Energy* 195:117023
9. Kays WM, London AL (1984) Compact heat exchangers, 3rd edn. McGraw-Hill, New York, NY, USA
10. Corberan JM, Garcia M (1998) Modelling of plate finned tube evaporators and condensers working with R134a. *Int J Refrig* 21:273–284
11. Jiang H, Aute V, Radermacher R (2006) CoilDesigner: a general-purpose simulation and design tool for air-to-refrigerant heat exchangers. *Int J Refrig* 29:601–610
12. Tarrad AH, Al-Nadawi AK (2015) Modelling of finned-tube using pure and zeotropic blend refrigerants. In: Proceedings of the ATINER'S conference, Athens, Greece
13. Tong L, Li H, Wang L, Sun X, Xie Y (2011) The effect of evaporator operating parameters on the flow patterns inside horizontal pipes. *J Therm Sci* 20:324–331
14. Domanski PA (1999) Finned-tube evaporator model with a visual interface. In: Proceedings of the international congress of refrigeration 20th. IIR/IIF, Sydney, Australia
15. Starace G, Fiorentino M, Longo MP, Carluccio E (2017) A hybrid method for the cross flow compact heat exchangers design. *Appl Therm Eng* 111:1129–1142
16. Carluccio E, Starace G, Ficarella A, Laforgia D (2005) Numerical analysis of a cross-flow compact heat exchanger for vehicle applications. *Appl Therm Eng* 25:1995–2013
17. Fiorentino M, Starace G (2018) The design of countercurrent evaporative condensers with the hybrid method. *Appl Therm Eng* 130:889–898
18. Starace G, Fiorentino M, Meleleo B, Risolo C (2018) The hybrid method applied to the plate-finned tube evaporator geometry. *Int J Refrig* 88:67–77
19. Starace G, Macchitella S, Fiorentino M, Colangelo G (2021) Influence of circuit arrangement on evaporator performance using the hybrid method. In Proceedings of the 6th IIR conference on thermophysical properties and transfer processes of refrigerants, Vicenza, Italy
20. Starace G, Macchitella S, Colangelo G (2021) The hybrid method for the plate-finned tube evaporator design process. In Proceedings of the 76° ATI Conference, Rome, Italy
21. Starace G, Macchitella S, Colangelo G (2022) Improvements to the hybrid method applied to the design of plate-finned tube evaporators. In: Proceedings of the 77° ATI conference, Bari, Italy
22. Macchitella S, Colangelo G, Starace G (2024) On the influence of the refrigerant inlet position and circuitry layout on plate-finned tube evaporator performance through the hybrid method. *J Phys Conf Ser* 2893:012091
23. Bourabaa A, Saighi M, Belal I (2011) The influence of the inlet conditions on the air side heat transfer performance of plain finned evaporator. *Int J Math Comput Phys Elect Comput Eng* 5(11):1667–1670
24. Wang CC, Lin YT, Lee CJ (2000) An airside correlation for plain fin-and-tube heat exchangers in wet conditions. *Int J Heat Mass Transf* 43(10):1869–1872
25. Thulukkanam K (2013) Heat exchanger design handbook. CRC Press

26. Kays WM, London AL (1984) Compact heat exchanger. 3rd ed. McGraw-Hill, New York
27. Ma X, Dinga G, Zhanga Y, Wang K (2007) Airside heat transfer and friction characteristics for enhanced fin-and-tube heat exchanger with hydrophilic coating under wet conditions. *Int J Refrigeration* 30(7):1153–1167
28. Liang SY, Wong TN (2010) Experimental validation of model predictions on evaporator coils with an emphasis on fin efficiency. *Int J Therm Sci* 49:187–195
29. Choi TY, Kim YJ, Kim MS, Ro ST (2000) Evaporation heat transfer of R-32, R-134a, R-32/134a and R-32/125/134a inside a horizontal smooth tube. *Int J Heat Mass Transf* 43(19):3651–3660
30. Stephan K, Abdelsalam M (1980) Heat transfer correlations for natural convection boiling. *Int J Heat Mass Transf* 23(1):73–87
31. Pierre B (1964) Flow resistance with boiling refrigerants—Part 1. *ASHRAE J* 6(9):58–65

Simulating Tree Cooling Effects on Building Energy Performance: An Integrated Microclimate-Driven Approach



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and Jonathan Natanian 

Abstract Nature-based solutions (NbS) regulate the microclimate and influence building energy consumption. Trees, in particular, reduce cooling demand through both shading and ambient air-cooling effects. However, conventional Building Energy Modeling (BEM) tools—typically reliant on Typical Meteorological Year (TMY) data—fail to capture the spatial variability of these cooling effects at the building scale. This study presents an integrated BEM approach that incorporates building face-specific, near-surface microclimate data from ENVI-met. A case study in Tel Aviv evaluates two urban block typologies—courtyard (CY) and high-rise (HR)—under tree-covered and tree-free conditions for representative summer days. Results show that conventional BEM underestimates tree-induced cooling loads by up to 8%, particularly in compact urban settings. The integrated approach captures both urban heat amplification in tree-free environments and the spatial tree-induced cooling effects, providing improved accuracy in energy performance predictions. This zone-level evaluation framework supports informed decisions about tree placement and building design in relation to vegetation and can be extended to assess other NbS, such as green roofs and facades. Future work will address computational limitations and enable annual performance assessments.

Keywords Building energy performance · Nature-based solutions · Vegetation cooling effects · Urban microclimate

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1 Introduction

1.1 Context and Motivation

Buildings currently account for more than 40% of global energy consumption, a figure expected to rise further due to climate change and rapid urbanization [1]. Rising global temperatures increase the demand for air conditioning, while urbanization intensifies this effect by creating urban heat islands (UHIs) [2, 3]. The increased use of cooling systems can, in turn, exacerbate UHI effects, creating a negative feedback loop [4].

Geometry-based, material-based, and nature-based solutions offer strategies to mitigate the combined impacts of climate change and UHI on building energy performance. Material-based solutions, such as thermochromic coatings, help reduce solar heat gains and mitigate longwave radiation contributing to the UHI effect [5]. However, their effectiveness tends to decline with prolonged environmental exposure [6]. Geometry-based measures can impact microclimatic conditions and, in turn, energy performance, both during early massing phases of design [7] and at later stages, through envelope detailing—such as window shades—that remain effective in reducing solar heat gains in existing buildings [8].

While geometry- and material-based strategies target the built environment itself, nature-based solutions (NbS) operate by modifying the surrounding microclimate, offering complementary and potentially synergistic benefits. Nature-based solutions, such as trees, enhance cooling performance through both shading and air-cooling effects [9]. In addition to blocking solar radiation, tree canopies reduce radiative heat exchange between buildings and surrounding surfaces. Through evapotranspiration, trees lower ambient air temperatures, while their canopies slow wind speeds, reducing convective heat transfer. However, these same effects may lead to increased energy demand in winter, as tree coverage can obstruct beneficial solar heat gains [10].

1.2 Challenges in Simulating Tree Cooling Effects

Current building energy modeling (BEM) tools cannot inherently simulate the air-cooling effects of trees on energy performance. While these tools can account for tree shading, they do not fully capture the influence of trees on ambient air temperature [11, 12]. Some studies have attempted to model these effects by modifying weather file data and adjusting convective heat transfer coefficients (CHTCs) [9]. Updating CHTCs using near-surface wind speed data allows BEM tools to reflect changes in heat transfer rates caused by tree canopies. However, modifying air temperature, relative humidity, and other climate variables in weather files only enables BEM tools to estimate cumulative cooling effects, but fails to capture the localized impacts of trees on specific building surfaces [13].

1.3 Overall Aim of This Study

This study presents an integrated BEM approach that holistically simulates the effects of trees using building face-specific, near-surface data derived from ENVI-met, an urban microclimate modeling (UMM) tool. By incorporating high-resolution microclimate data, this method enables BEM tools to simulate the spatially varying air-cooling effects of trees. A case study is conducted to demonstrate the effectiveness of the proposed integrated approach.

2 Methodology

As shown in Fig. 1, this study adopts a five-phase methodology to implement the integrated BEM approach and compare it against a conventional workflow. Each phase is elaborated below.

2.1 Phase-I: Recognition of Representative Climate Days

Since computational fluid dynamics (CFD)-based urban microclimate modeling (UMM) tools are highly resource-intensive—particularly for annual high-resolution simulations—this study adopts a representative-day approach. These representative days are identified using unsupervised machine learning (ML) models applied to the

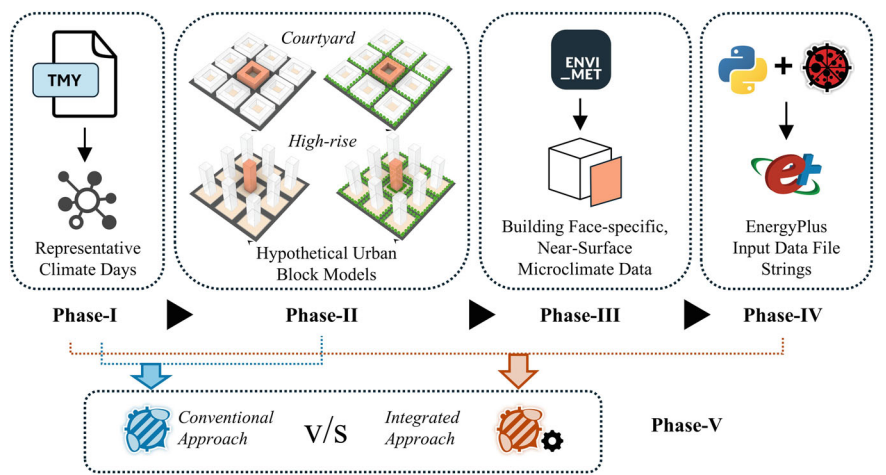


Fig. 1 Overview of the five-phase methodology

Table 1 Urban and building design parameters

Parameters	Values
Floor area ratio	6
Window to wall ratio	0.45
Road width	24 m
Tree type	American sweet gum
Tree to tree distance	4.5 m (Maximum tree canopy radius)
Tree to building distance in site	Courtyard N/A/High-rise: 6.75 m

Typical Meteorological Year (TMY) dataset for Tel Aviv [14]. Building on the clustering method originally introduced by Acero et al. [15], daily profiles are grouped according to hourly air temperature patterns and other climate variables.

The selected days include:

- **Summer Days:** April 22nd (representing 4.4% of total climate conditions) and July 5th (50%).
- **Winter Days:** December 5th (18.3%) and December 9th (20.2%).
- **Extreme Climate Days:** the remaining 26 days of the year, which do not clearly align with either the summer or winter clusters.

A preliminary energy performance analysis revealed that the presence of trees did not result in heating penalties on the two representative winter days. Therefore, the scope of this study is limited to the identified representative summer days, where the impact of vegetation on cooling demand is more pronounced.

2.2 Phase-II: Hypothetical Block Models Specification

Four hypothetical urban block models—representing courtyard (CY) and high-rise (HR) typologies—are used to demonstrate the integrated BEM approach (see Fig. 1). The CY model characterizes compact, dense urban form, while the HR model represents an open configuration. Key urban and building parameters used in the model setup are summarized in Table 1.

2.3 Phase-III: Simulation and Extraction of Building Near-Surface Microclimate Data

Microclimate simulations for representative summer days are conducted using ENVI-met. For each model, building face-specific data—air temperature, wet-bulb temperature, wind speed, and direction—is extracted and compiled into CSV files. To ensure

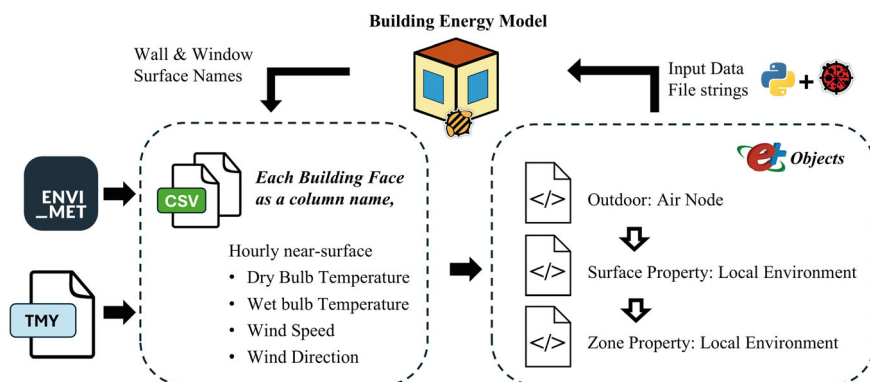


Fig. 2 Workflow for transforming ENVI-met data into usable EnergyPlus inputs using Grasshopper

continuity in EnergyPlus, which requires full annual hourly input, non-simulated hours are filled with standard TMY data.

2.4 Phase-IV: Generation of EnergyPlus Input Data File Strings

To incorporate the extracted microclimate data into EnergyPlus, a set of input strings is generated to activate specific simulation objects—*Outdoor Air: Node*, *Surface Property: Local Environment*, and *Zone Property: Local Environment*. These enable EnergyPlus to process localized environmental inputs and compute the convective and radiative heat exchanges between building surfaces and their immediate surroundings. The integration process is illustrated in Fig. 2.

To automate this process, custom visual programming components were developed in Rhinoceros-Grasshopper (Rhino-GH). The Ladybug Tools API was used to create scripts that parse surface and zone-level details of the building models, generate the required input strings, and reinsert them into the simulation workflow.

2.5 Phase-V: Demonstration of the Integrated Approach's Potential

In this phase, the four urban block models are converted into two sets of energy models using both the conventional and integrated BEM approaches. Each building floor is divided into core and perimeter zones with a 6-meter offset, allowing for an assessment of the directional impact of tree-induced cooling.

Energy simulation parameters, including envelope properties and occupancy-related inputs, follow the recommendations of the Israeli Residential Energy Code (SI 5282) and previous studies [16]. Only the central buildings in the CY and HR block models (highlighted in Fig. 1) are transformed into energy models, while neighboring buildings and trees are modeled as shading objects. Simulations for representative climate days are conducted to analyze changes in energy cooling loads due to trees in both the conventional and integrated BEM approaches.

3 Results and Discussion

Simulations were conducted for the two identified representative summer days. Among these, July 5th—characterizing 94% of Tel Aviv’s summer climate conditions—exhibited the most pronounced differences in cooling performance between the conventional and integrated modeling approaches. Accordingly, the discussion below focuses on this date as a representative example (Fig. 3).

In the courtyard (CY) model, the conventional modeling approach yielded a 12% reduction in cooling loads, while the integrated approach achieved a more substantial 20% reduction. In contrast, the high-rise (HR) model showed similar reductions in cooling loads under both approaches, with only marginal differences observed.

Two primary factors explain the more pronounced tree-induced cooling effect in the CY model:

- (1) **Spatial variation in near-surface air temperature without trees:** On July 5th, TMY data indicated a peak air temperature of 29 °C (12:00–15:00), while the integrated simulation showed over 30.5 °C in the CY model without trees. In contrast, the HR model recorded cooler near-surface temperatures—below 28 °C. This difference led to a 5% increase in cooling loads in the CY model and a 15% decrease in the HR model without vegetation (Fig. 3).

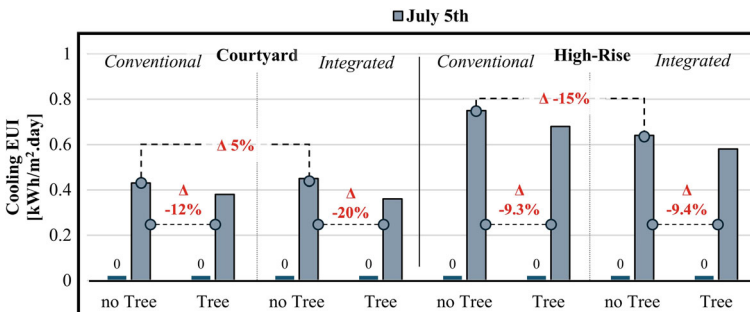


Fig. 3 Cooling loads in courtyard (CY) and high-rise (HR) models using conventional and integrated approaches on representative summer days

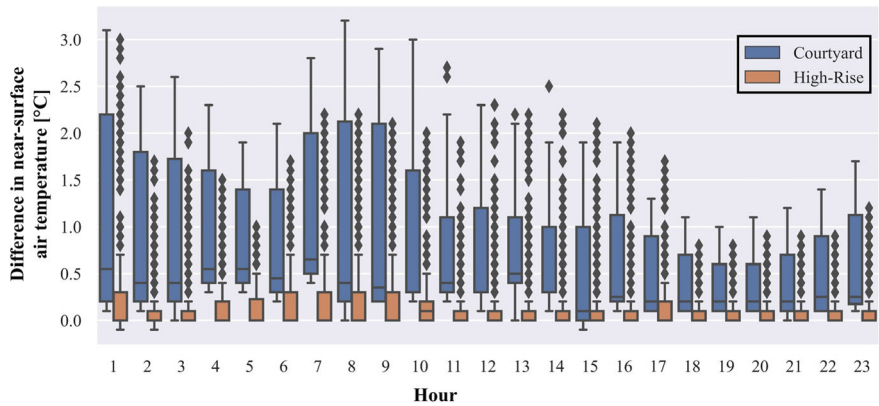


Fig. 4 Near-surface air temperature reduction due to trees in CY and HR models on July 5th, based on integrated simulations

(2) **Limited Exposure to Tree-induced Cooling Effects:** In the CY model, most facades experienced near-surface air temperature reductions of up to 2.25 °C due to the air-cooling effects of trees. In the HR model, only facades adjacent to or beneath the tree canopies showed noticeable temperature drops, as reflected in the outliers in Fig. 4.

Further analysis reveals that only a small proportion of the HR model’s thermal zones benefited from tree proximity. While near-ground perimeter zones achieved up to 70% savings, these zones constitute a minor share of the total floor area. In contrast, the CY model displayed cooling savings across a broader range of orientations and elevations, with west-facing zones achieving up to 70% and others showing up to 25% savings (Fig. 5).

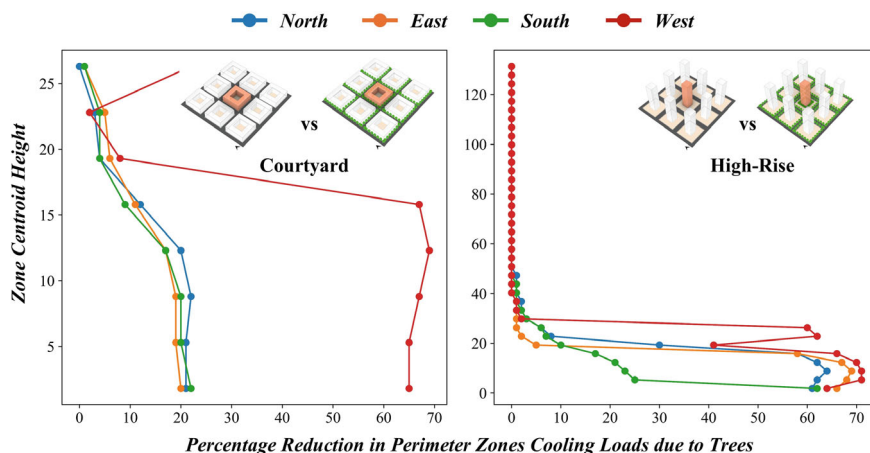


Fig. 5 Tree-induced reduction in cooling loads for courtyard (CY) and high-rise (HR) models using the integrated near-surface microclimate approach

4 Conclusion

This study introduces an integrated building energy modeling (BEM) approach that leverages building face-specific, near-surface microclimate data to account for both the shading and spatial air-cooling effects of trees. A case study using hypothetical courtyard (CY) and high-rise (HR) models demonstrated the performance differences between conventional and microclimate-integrated approaches under scenarios with and without trees.

Results indicate that the conventional method underestimates tree-induced cooling by up to 8%, especially in compact urban configurations. The integrated approach better captures urban heat amplification in tree-free environments and localized tree-induced cooling effects. By enabling zone-level resolution, it informs more precise tree placement strategies and promotes responsive building design based on surrounding vegetation. Furthermore, the methodology is broadly applicable to other nature-based solutions, including green roofs, facades, and walls.

While the present study is limited to representative summer days and single-zone analysis due to computational constraints, future work will aim to scale the approach using machine learning-based urban microclimate metamodels to enable scalable, annual simulations of vegetation effects on building energy performance. Future work will also examine the effects of diverse tree species, canopy densities, and seasonal dynamics to enable year-round performance assessments.

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References

1. Cao X, Dai X, Liu J (2016) Building energy-consumption status worldwide and the state-of-the-art technologies for zero-energy buildings during the past decade. *Energy Build* 128:198–213. <https://doi.org/10.1016/j.enbuild.2016.06.089>
2. Isaac M, van Vuuren DP (2009) Modeling global residential sector energy demand for heating and air conditioning in the context of climate change. *Energy Policy* 37:507–521. <https://doi.org/10.1016/j.enpol.2008.09.051>
3. Yang X, Peng LLH, Jiang Z, Chen Y, Yao L, He Y, Xu T (2020) Impact of urban heat island on energy demand in buildings: local climate zones in Nanjing. *Appl Energy* 260:114279. <https://doi.org/10.1016/j.apenergy.2019.114279>
4. Afshari A, Salvati A (2023) Assessing the impact of climate change and urban heat island on the city-wide building cooling demand in Barcelona using the SUECM model. In: IBPSA, pp 2833–2839. <https://doi.org/10.26868/25222708.2023.1577>
5. Manapragada NVSK, Pignatta G (2021) Climate-adaptive building skins for building energy conservation and UHI mitigation: transient building energy simulation with thermochromic coatings. In: International conference on construction, energy, environment and sustainability 2021, Portugal
6. Nagare SM, Hakami A, Biswas PK, Stefanakos EK, Srinivasan SS (2025) A review of thermochromic materials for coating applications: production, protection, and degradation of organic thermochromic materials. *J Coat Technol Res* 22:91–115. <https://doi.org/10.1007/s11998-024-00982-9>
7. Natanian J, Kastner P, Dogan T, Auer T (2020) From energy performative to livable Mediterranean cities: an annual outdoor thermal comfort and energy balance cross-climatic typological study. *Energy Build* 224:110283. <https://doi.org/10.1016/j.enbuild.2020.110283>
8. Hoffmann S, Lee ES, McNeil A, Fernandes L, Vidanovic D, Thanachareonkit A (2016) Balancing daylight, glare, and energy-efficiency goals: an evaluation of exterior coplanar shading systems using complex fenestration modeling tools. *Energy Build* 112:279–298. <https://doi.org/10.1016/j.enbuild.2015.12.009>
9. Hsieh C-M, Li J-J, Zhang L, Schwegler B (2018) Effects of tree shading and transpiration on building cooling energy use. *Energy Build* 159:382–397. <https://doi.org/10.1016/j.enbuild.2017.10.045>
10. Simpson JR, McPherson EG (1998) Simulation of tree shade impacts on residential energy use for space conditioning in Sacramento. *Atmos Environ* 32:69–74. [https://doi.org/10.1016/S1352-2310\(97\)00181-7](https://doi.org/10.1016/S1352-2310(97)00181-7)
11. Palme M, Privitera R, La Rosa D (2020) The shading effects of green infrastructure in private residential areas: building performance simulation to support urban planning. *Energy Build* 229:110531. <https://doi.org/10.1016/j.enbuild.2020.110531>
12. Calcerano F, Martinelli L (2016) Numerical optimisation through dynamic simulation of the position of trees around a stand-alone building to reduce cooling energy consumption. *Energy Build* 112:234–243. <https://doi.org/10.1016/j.enbuild.2015.12.023>
13. Manapragada NVSK, Natanian J (2025) Urban microclimate and energy modeling: a review of integration approaches. *Sustainability* 17:3025. <https://doi.org/10.3390/su17073025>
14. Manapragada NVSK, Natanian J (2025) A hybrid machine learning framework for identifying representative climate days in bimodal weather distributions. In: 12th International conference on urban climate, Rotterdam, The Netherlands, 7–11 Jul 2025, ICUC12-169. <https://doi.org/10.5194/icuc12-169>
15. Acero J, Pignatta G, Norford L (2018) Use of clustered meteorological data for microclimate and thermal comfort analysis in a tropical area
16. Natanian J, Aleksandrowicz O, Auer T (2019) A parametric approach to optimizing urban form, energy balance and environmental quality: the case of Mediterranean districts. *Appl Energy* 254:113637. <https://doi.org/10.1016/j.apenergy.2019.113637>

Dynamic Hygrothermal Assessment of a Stone Wall for the Installation of a Novel Bio-Based Multi-purpose Insulation Material



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Abstract A new era of sustainable construction products centered on human comfort improvement and energy and environmental impact reduction is under development. In this context, biomaterials have an important role as they can reduce energy consumption and resource depletion from the perspective of a circular economy. In this work, an external stone wall was analysed through WUFI Pro software in different configurations to assess its hygrothermal properties and evaluate the possibility of integrating a newly developed bio-based lignin-polyurethane foam panel from ligno-cellulosic sources. First, the stone wall was modelled varying the thickness, and the less performing thickness was studied by adding to the traditional stratigraphy two types of thermal insulation material with different water vapor resistance factors. The case study external wall typology was selected based on the review of representative typologies of Italian historic buildings. The component-scale performance was evaluated via WUFI Pro, which allows realistic calculation of the transient one-dimensional heat and moisture transport in building components. In this study, the analyses were carried out in the Italian climate zone D (Florence). Results pertain to the modelling of all the mentioned stone wall configurations and highlight the influence of the use of thermal insulation materials in historic building refurbishment for the improvement of the hygrothermal performance of building opaque envelope components.

Keywords Dynamic hygrothermal simulation · Building refurbishment · Historic stone wall

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1 Introduction

The efforts of current governments aim at the development of eco-sustainable cities [1] intervening in various sectors. In particular, the construction sector has high environmental impacts during all the life cycle phases, from production to operation and end-of-life [2]. One of the solutions to reduce these impacts is acting on energy consumption for building heating and cooling by improving the thermal insulation of the building envelope with materials that are also able to reduce the environmental impact. However, to evaluate the benefits produced by the application of insulation materials in building components, it is necessary to define first the hygrothermal performance of the original scenario.

The thermal properties of an envelope opaque component are connected to two specific boundary conditions [3]: stationary conditions, where the thermal behavior is completely characterized by the thermal transmittance U ($\text{Wm}^{-2} \text{K}^{-1}$) according to EN ISO 6946:2018, and dynamic conditions, where the characteristic quantities are periodic thermal transmittance Y_{ie} ($\text{Wm}^{-2} \text{K}^{-1}$), attenuation factor or factor decrease f_a (—), and time lag or delay of the thermal wave ϕ (h) according to UNI EN ISO 13786:2018. Regarding the hygrometric properties, the analysis of the vapor migration phenomena that pass through the opaque component allows the evaluation of the risk of humidity entering the wall, with the consequent possible formation of vapor condensation. There are two approaches for this type of analysis: the “Glaser model”, based on the UNI EN ISO 13788:2013, and the dynamic approach, based on the UNI EN 15026:2023. The first proposes a stationary calculation that is easy to perform but precautionary: it analyzes only the effect of vapor diffusion and could signal condensation risks even where they do not exist. Instead, dynamic models evaluate the hygrothermal behavior more realistically. Consequently, in addition to having good thermo-physical properties (i.e., thermal conductivity λ ($\text{Wm}^{-1} \text{K}^{-1}$), specific heat c_p ($\text{Jkg}^{-1} \text{K}^{-1}$), density ρ (kgm^{-3}), and porosity ϕ ($\text{m}^3 \text{m}^{-3}$)), the materials to be developed to improve the hygrothermal performance of the building envelope need to satisfy the requirements of adequate hygrometric properties (i.e., in terms of water vapor permeability δ ($\text{kgm}^{-1} \text{s}^{-1} \text{Pa}^{-1}$) and water vapor resistance factor μ (—)) [4]. Furthermore, to support environmentally sustainable construction, they should comply with the requirements of circular economy.

When the stratigraphy is defined, the hygrothermal performance, closely connected to the comfort of the indoor environment and the risk of condensation (especially non-visible interstitial condensation), can be studied with different software. Among them, WUFI is the most used [5]. Furthermore, it is necessary to define climate boundary conditions to verify the hygrothermal performance in a realistic scenario.

In the last decades, researchers have focused on the development and implementation of new thermal insulation materials, recently focusing on biomaterials. The use of biomaterials or recycled materials in buildings pursues both the objectives of good thermo-hygrometric properties and the reduction of environmental impacts, achieving a circular economy [6]. Korjenic et al. [7] used jute, flax, and

hemp to develop a new insulation material from renewable resources with physical and mechanical properties comparable to those of the most commonly used insulation materials. However, traditional materials continue to dominate the construction sector, and there is a lack of knowledge among policymakers and developers regarding biomaterials. The review by Chen et al. [8] attempted to define construction biomaterials, their policies, and life cycle assessment through case studies. Among the most common materials for thermal insulation are polyurethanes derived from the reuse of plastic materials. Hysek et al. [9] provided a solution for the use of two waste materials, namely soft polyurethane foam residues from mattress production and winter wheat husks.

In this framework, this research study aims to evaluate the hygrothermal performance of the application of different insulation materials to opaque building envelope components and, specifically, external walls using WUFI Pro software. First, bibliographic research was carried out on the most common typologies of external walls for Italian residential buildings in different construction periods. As for historic buildings (built before 1945) stone walls were identified as representative. The traditional stratigraphy was analyzed varying the stone thickness and, then, thermal insulation materials applied. Finally, a comparison was made between the parameters obtained for the traditional stratigraphy and the insulated ones. Results show that the use of insulation materials allows improving the regulation of thermal and humidity flows inside the stone wall, paving the way for further analyses aimed at introducing new bio-based eco-sustainable panels for building envelope thermal insulation.

2 Materials and Methods

This study was developed in the framework of the LIGNOCAP PRIN project. The project aims to develop a bio-based insulation panel for energy efficiency in buildings with advanced thermo-acoustic insulation performance, low environmental impact, and long-term stability. To achieve this aim, the study of the energy performance associated with the integration of the new material into the building envelope was divided into various phases:

- definition of the calculation codes for hygrothermal analysis and building dynamic simulation, considering their inputs/outputs;
- definition of components to which the new material could be applied to implement its performance and installation methods;
- identification of the most common Italian typologies of external walls of three historical periods (historic buildings, post-World War II buildings, and new buildings) and choice of different Italian climatic zones for the simulation;
- heat and mass transfer simulation of the new material when applied to the selected external wall typologies;
- building dynamic simulation when applied to prototype buildings.

In this framework, this research aims to evaluate the hygrothermal performance of a stone wall (without or with the application of two different thermal insulation materials) using WUFI Pro to assess the effect of the insulation application. The work carried out serves as a basis for identifying the necessary parameters for the software simulation and its functionalities. Next steps will analyze the new bio-based polyurethane insulation material performance for different building external wall stratigraphies.

2.1 Heat and Mass Transfer Simulation

The choice for the numerical simulation software was made among those capable of simulating in detail the hygrothermal performance in terms of heat and mass transfer at the component scale. Among the existing tools, in this research work, WUFI Pro was considered because it is specific for 1D heat and moisture transfer analysis of building components. It refers to different standards for simulating external boundary conditions. In particular, it is possible to compare results derived from EN 15026:2023, EN 13788:2013, and ASHRAE 160:2016. First, all the inputs needed for the characterization of the component stratigraphy in the software were identified. The definition of the geometry of the stratigraphy (position and thickness of the individual layers, and the associated materials) was carried out using the software database of building materials.

2.2 Opaque Components Description and Properties

The definition and choice of building types to be analyzed was carried out considering the most recent ENEA study [10], which reports Italian statistical data relating to properties, divided by climate zones and construction periods. The data relating to buildings highlight that about 85% of the buildings are registered as residential. Therefore, it was decided to use this typology due to its greater diffusion in Italy compared to other types. Regarding the climate zone, in this work, the Italian zone D was considered for the high number of residential buildings present (24.10%), and Florence was selected as the example case study climate context. Climate zone D, according to the Italian Legislation (DPR 412/93) is characterized by Heating Degree Days (HDD) between 1411 and 2100. HDD are used to estimate the energy needed for heating; the higher the value of HDD, the colder is the location. Florence is characterized by 1821 HDD.

Among the different sources of data that classify the building envelope components typically used in Italy, distinguished per climate context and/or construction period, this research analyzed the three main ones: the IEE projects TABULA and

EPISCOPE database, the UNI/TR 11552:2014 standard, and ENEA reports. In particular, this study focuses on external wall applications that, among the main components of the building envelope (walls, floors, and roofs), are those that occupy a predominant fraction. Also, the study focuses on historical buildings applications. About the historical buildings, the most representative technology used to build external walls before 1945 in Italy was the stone wall according to the literature analysis. Therefore, the effectiveness and feasibility of implementing insulation materials was studied for this selected representative construction typology. Indeed, the new bio-based insulation material can be used to develop panels for the refurbishment of the building envelope.

2.3 Input and Output Parameters

First, the climate data were retrieved from the Meteororm software and uploaded to WUFI Pro. Then, the external wall typology (stone wall) was modeled. The software has a database of materials with their thermophysical characteristics (density ρ , porosity ϕ , specific heat c_p , thermal conductivity λ , and water vapor resistance factor μ). To choose the closest materials to those in the analyzed stratigraphy, the parameters obtained from the UNI/TR 11552:2014 standard were compared with those in WUFI Pro. The analyses were divided into two parts:

- Part I: analysis of the traditional stone wall with varying thicknesses of the stone layer (0.4, 0.6, and 0.8 m);
- Part II: analysis of the less-performing stone wall varying the type of applied thermal insulation material based on the water vapor resistance factor.

The other input data were selected considering the North orientation (worst conditions in terms of temperature and incident solar radiation), interior surface resistance equal to $0.125 \text{ m}^2\text{KW}^{-1}$ and exterior surface resistance of the wall equal to $0.0588 \text{ m}^2\text{KW}^{-1}$. The initial humidity and temperature conditions were 80% for relative humidity (RH) and 20°C for air temperature (T). The high humidity is due to the possibility of verifying how the component studied behaves in unfavorable initial hygrothermal conditions. The outputs obtained were calculated using the weather file from Meteororm for the external climate conditions and the UNI 15026:2003 to set the required indoor environmental conditions, which allows the hygrothermal variables to be analyzed more precisely. The duration of the analysis was set to 5 years, which corresponds to a standard duration that allows for the verification of the stabilization of the hygrothermal behavior of the components of the analyzed stratigraphy.

3 Results and Discussion

3.1 Thermo-Hygrometric Analysis of the Traditional Stone Wall

The main properties of the materials in the assessed stratigraphy are reported in Table 1.

The results relating to the trend of the total water content within the stone wall stratigraphy (Fig. 1a) when varying the wall thickness (0.4, 0.6, and 0.8 m) are reported in Fig. 1b for the five years of simulation. An increasing water content over the years, without reaching equilibrium, is an indication of a potential problem as it highlights that the technical solution accumulates water without the capacity to dispose of it towards the outside, with consequent problems of condensation, mold, or corrosion. The graphs show that all the configurations reach equilibrium after about 2 years and then continue to have small oscillations due to normal seasonal variations. Moreover, the initial and final water content difference has a very limited variation among the analyzed thicknesses.

To evaluate the stratigraphy with the worst performance, the isopleth graph was analyzed. In this graph, the relative humidity on the internal surface is represented as a function of the temperature. Initially, the points are clearer, and progressively darken, allowing also to have temporal information. In the graphs (Fig. 1c), also the limit isopleths (LIM B I, dashed line in the graph, and LIM B II, solid line) are reported, which define the limit combination of RH and T above which microbiological growth is possible on the wall internal surface (if the points go beyond the dashed line there is only the possibility of micro-biological formation while if they go beyond the solid line there is a certainty). For 0.60 and 0.80 m thick stone walls, the values are always below the curve representing the LIM B I limit, meaning that the formation of mold is not physically possible. Among the configurations, the one with the greatest potential risk of mold formation is the 0.40 m thick stone wall. For this reason, the 0.4 m thick stone wall was used for the following analyses.

The results of the second analysis concern the hygrothermal performance obtained by applying two different types of thermal insulation materials on the internal side of the stone wall—since the intervention was hypothesized on a historic building with preservation requirements. Furthermore, a thickness of 5 cm was chosen for the thermal insulation layer as it is an average thickness for an insulation material applied

Table 1 Main properties of stratigraphy components (from the internal to the external side)

Material	ρ (kgm ⁻³)	c_p (Jkg ⁻¹ K ⁻¹)	λ (Wm ⁻² K ⁻¹)	μ (—)
Plaster	2000	850	1.2	9.61
Stone	2300	850	2.3	70
*Render	1571	850	0.8	25

*Lime and cement mortar that has worse hygrothermal conditions

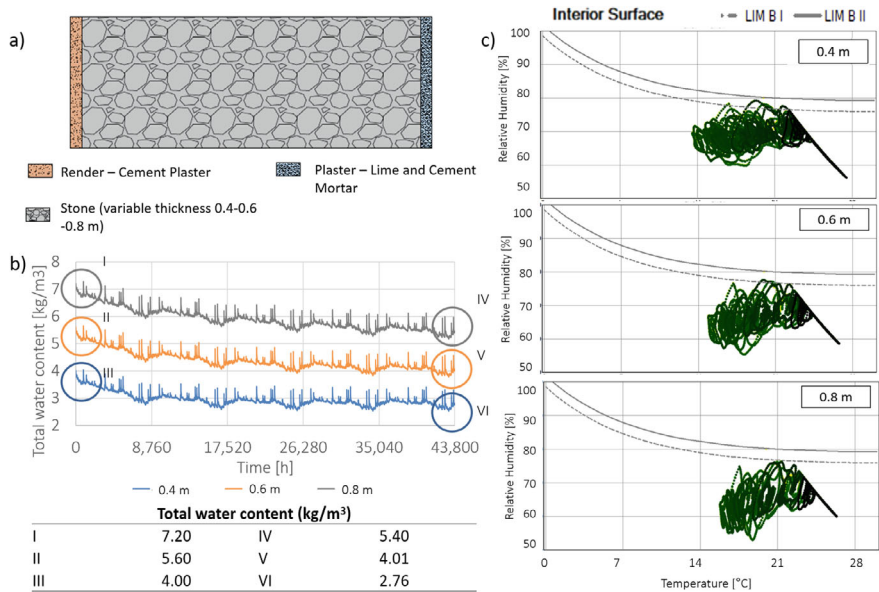


Fig. 1 a Stone wall stratigraphy, b total water content trend in relation to the variation in wall thickness and, c isopleth graphs. Thermo-hygrometric analysis of the stone wall with thermal insulation

on walls. The stratigraphy analyzed is shown in Fig. 2a while the data relating to the most important properties of the chosen insulation materials are reported in Table 2. These materials were selected to evaluate the influence of the variation in the value of water vapor diffusion resistance factor μ (—), which is equal to 8 and 69 for the two materials, respectively. This characteristic does not substantially affect the trend of the water content after five years within the stratigraphy (Fig. 2b).

Thereafter, temperature and humidity profiles over time were analyzed on the cold side of the insulation material layer (Fig. 3). This test allows identifying the possibility of ice formation if there is simultaneously a relative humidity between 95–100% and temperatures near 0 °C. In the case of more permeable insulation material the possibility of interstitial condensation forming is higher because, despite a RH trend similar to the less permeable insulation material, the T values are much lower.

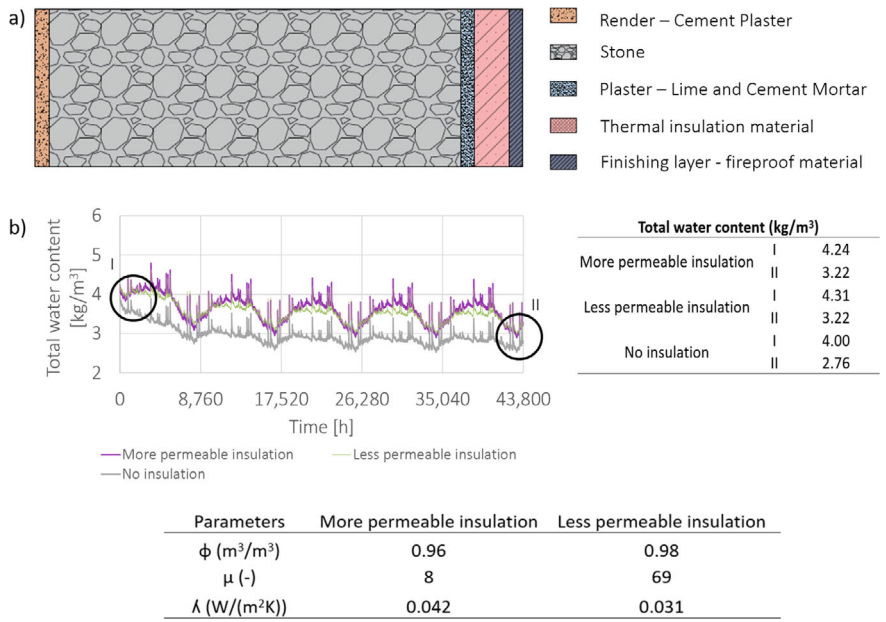


Fig. 2 **a** Insulated stone wall stratigraphy and insulating materials main parameters and, **b** initial and final water content trend

Table 2 Main parameters for thermal insulation materials chosen

Parameters	More permeable material	Less permeable material
ϕ (m³m ⁻³)	0.96	0.98
μ (-)	8	69
λ (Wm ⁻² K ⁻¹)	0.042	0.031

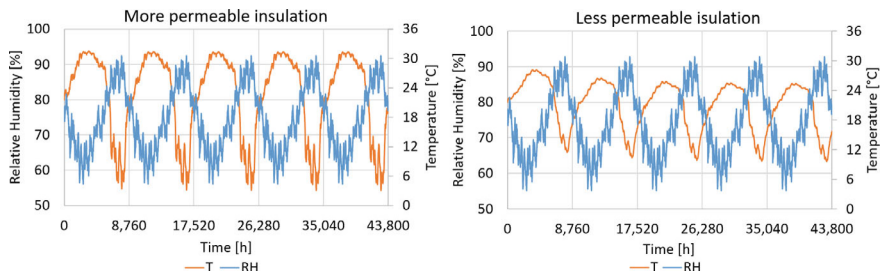


Fig. 3 Temperature and relative humidity trend on the insulation material surface (cold side)

4 Conclusion

The analyses of hygrothermal performance carried out using WUFI Pro on different stone wall configurations confirmed that a lower wall thickness (0.4 m) leads to a greater risk of mold formation on the internal surface. By adding internal insulation with different water vapor diffusion resistance factors to this stratigraphy, it was found that an insulation less permeable to water vapor is suitable to avoid the risk of interstitial condensation and, simultaneously, improve the thermal performance of the envelope. These considerations are fundamental for the production and subsequent analysis of a novel bio-based multi-purpose thermal insulation material.

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References

1. Cucca R (2012) The unexpected consequences of sustainability. Green cities between innovation and ecogentrification. *Il Mulino* 2(6):1–21
2. Khasreen MM, Banfill PFG, Menzies GF (2009) Life-cycle assessment and the environmental impact of buildings: a review. *Sustainability* 1(3):674–701
3. Salani C (2010) Regime stazionario e regime dinamico. *Neo-Eubios* 33:54–57
4. Asdrubali F, D'Alessandro F, Schiavoni S (2015) A review of unconventional sustainable building insulation materials. *Sustain Mater Technol* 4:1–17
5. Ramos NM, Delgado JQ, Barreira E, De Freitas VP (2009) Hygrothermal properties applied in numerical simulation: interstitial condensation analysis. *J Build Apprais* 5(2):161–170
6. Majumder A, Canale L, Mastino CC, Pacitto A, Frattolillo A, Dell'isola M (2021) Thermal characterization of recycled materials for building insulation. *Energies* 14(12):3564
7. Chen L, Zhang Y, Chen Z, Dong Y, Jiang Y, Hua J et al (2024) Biomaterials technology and policies in the building sector: a review. *Environ Chem Lett* 22:715–750
8. Torres-Rivas A, Pozo C, Palumbo M, Ewertowska A, Jiménez L, Boer D (2021) Systematic combination of insulation biomaterials to enhance energy and environmental efficiency in buildings. *Constr Build Mater* 267:120973
9. Marra E (2016) Le simulazioni igrotermiche dinamiche. Possibili applicazioni nella pratica edilizia. *Neo-Eubios* 55:13–23
10. ENEA (2024) La consistenza del parco immobiliare nazionale

Optimizing 3D-Printed Concrete Panels' Thermal Performance with Materials, Metrics, and Generative Design



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Abstract Additive manufacturing has introduced new possibilities for the construction sector, especially regarding the rapid and precise production of customised 3D-printed concrete panels. This customisation offers the possibility of adapting the formal volumetry to the performance requisites, such as thermal behaviour, guaranteeing that these panels achieve the required energy and thermal performance specified by the standards. This paper highlights recent advancements in materials – such as phase change materials (PCMs), lightweight aggregates, and innovative mortar mixes – while examining how generative design methods integrate these developments to enhance thermal characteristics. A bibliometric analysis to identify prevailing research themes was outlined, showcasing how key studies have approached thermal optimisation from both experimental and computational perspectives. Our findings indicate that combining concrete mixtures with parametric modelling can produce lightweight, high-insulation walls that maintain acceptable structural integrity. However, most existing studies are constrained to laboratory-scale experiments, underscoring the need for large-scale testing and real-world validation. While integrated approaches that address thermal, structural, and sustainability objectives are emerging, further research is needed to align these aspects within comprehensive multi-objective frameworks. Future directions incorporate full-scale demonstrators, advanced simulation tools, and synergistic material design processes to address these challenges. By validating performance under real-life environmental conditions and bridging the gap between theory and practice, the construction sector can fully exploit the benefits of 3D-printed building envelopes. Ultimately, an integrated approach – combining innovative materials, generative

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design, and experimental validation – can establish thermally efficient, sustainable, and structurally sound solutions for the next generation of construction.

Keywords Three-dimensional printing for construction (3DPC) · Thermal performance · Generative design · Energy efficiency · Additive manufacturing (AM) · Parametric modelling

1 Introduction and Methodology

3D-printed concrete panels could redefine building envelope thermal performance through production methods and advanced material selection innovations, such as Expanded Thermoplastic Microspheres (ETM¹), Phase Change Materials (PCMs²), and optimised cavity geometries. These advancements reduce thermal conductivity (λ) by up to 40% and U-values by 60%, addressing global energy efficiency targets [1–4]. Generative design workflows further enhance gains, enabling topology-optimised façades and adaptive systems that reduce annual energy consumption by 9–11% [5–7]. Despite progress, gaps persist in scalability, hygrothermal behaviour, durability, and regulatory alignment [8–10]. To address these challenges, this work synthesises findings from a systematic review of Scopus/Web of Science (2010–2024), prioritising peer-reviewed studies with quantitative thermal data (λ , U-value). Non-empirical works were excluded, and data extraction focused on three themes:

1. **Material innovations:** Lightweight aggregates such as ETM [1] and PCMs [3], moisture-resistant strategies [8], and recycled insulation [11].
2. **Geometric optimisation:** Cavity configurations [4], modular prefabrication [12], and generative design [5, 13].
3. **Interdisciplinary integration:** Resolving thermal-structural trade-offs [1, 3, 14]. Thematic analysis consolidates insights into actionable pathways for energy-efficient, code-compliant systems.

2 Thermal Performance Metrics

Thermal performance in 3D-printed walls can be effectively characterised by parameters such as the U-value (heat transmittance), which directly relates to thermal resistance (R-value) and material-specific thermal conductivity (λ). These indicators primarily determine thermal performance, while hygrothermal considerations (e.g., moisture absorption and vapour permeability) may also influence heat transmission by affecting material conductivity. Efforts to reduce building energy demand

¹ ETM = Expanded Thermoplastic Microspheres.

² PCMs = Phase Change Materials.

include lightweight aggregates, phase change materials (PCMs), and advanced cavity geometries, among other potential solutions.

2.1 Thermal Behavior of 3D-Printed Cementitious Mortar

The U-value can effectively represent thermal performance in 3D-printed construction, a relevant parameter for characterising assembly-level heat transmittance. Key findings include:

U-Value Optimization

- **Cavity infill:** Polyurethane foam reduces U-values by ~ 60% (0.4 vs. 1.0 W/m² K) compared to unfilled designs [2, 14].
- **Material substitution:** ETM-modified concrete with foam achieves $U = 0.199 \text{ W/m}^2\cdot\text{K}$ [1].
- **Modular systems:** Recycled aggregate honeycomb blocks ($U = 0.78\text{--}1.57 \text{ W/m}^2\cdot\text{K}$) and ventilated panels ($U = 0.48 \text{ W/m}^2\cdot\text{K}$) demonstrate scalability [4, 11, 12]

Table 1 presents a comparative analysis highlighting the thermal performance range achievable through different 3D-printed wall configurations. Additionally, Pessoa et al. [8] provide a complementary reference, evaluating the thermal properties of a cementitious mortar (Weber 3D 145–2) specifically developed for 3D printing.

Including typical concrete wall panels [16] as a baseline highlights the thermal performance enhancements achievable through different 3D-printed configurations. Additionally, Pessoa et al. [8] provide a complementary reference, evaluating the thermal properties of a cementitious mortar (Weber 3D 145–2) specifically developed for 3D printing.

Material-Specific Thermal Conductivity (λ)

Material-specific thermal conductivity (λ) significantly influences insulation capacity, particularly for homogeneous materials.

- ETM/waste glass: Reduces λ from 0.74 to 0.45–0.47 W/m·K [1].
- Aerogels/foams: Achieve ultra-low λ (0.04–0.25 W/m·K) but require strength trade-offs [9, 18].
- Parametric optimisation: Balances void distribution and printability [18]. Figure 1 depicts the variants tested by Cuevas et al. [1], where Variant F attains the lowest U-value (0.199 W/m²·K) with polyurethane infill ($\lambda 0.03$).

Phase Change Materials (PCMs) store and release latent heat in specific temperature ranges, stabilising indoor temperatures by buffering peaks and valleys. Liu et al. [3] demonstrated that incorporating microencapsulated paraffin-based PCM particles (particle sizes compatible with a standard rectangular nozzle of approximately 20 mm

Table 1 Comparative analysis of thermal performance in 3D-printed walls

Study	Material/ configuration ³	U-Value ⁴ (W/ m ² .°C)	Material λ ⁵ (W/m.K)	Key findings
ASHRAE Handbook [16]	Conventional concrete wall panel	1.5–2.0	~1.4–1.75	Typical thermal performance baseline for conventional concrete walls
Pessoa et al. [8]	Weber 3D 145–2 cementitious mortar (used for 3D printing)	–	1.327 (dry conditions)	Thermal conductivity comparable to traditional mortars requires additional insulation for acceptable performance
Marais et al. [17] ⁶	LWFC (multi-cavity design)	–	0.37	Smaller cavities (20 mm width, > 50% void ratio) improve insulation vs. solid LWFC. Cavities worsen LWFC performance if too large
	HPC (multi-cavity design)	–	1.1	Cavities improve thermal performance (internal temperature reduced by ~ 1 °C in summer). Higher λ but benefits from cavity design
Hassan et al. [2]	Polyurethane foam-filled cavities	~ 0.4*	N/A	~ 60% reduction versus Tamimi et al.'s baseline (U = 1.0 W/m ² .K). Validated through in situ measurements
Tamimi et al. [14]	Unfilled cavity walls	1.0*	N/A	Baseline for thermal performance comparison (e.g., Hassan et al.'s 60% reduction)
He et al. [7] ⁷	3D-VtGW with XPS insulation soil	–	–	Annual energy consumption was reduced by 9.12% and AC load by 11.2% in summer

(continued)

³ LWFC = Lightweight foam concrete; HPC = High-performance concrete; 3D-VtGW = modular 3D-printed concrete vertical green wall; XPS = Extruded polystyrene; PS = Polystyrene; ETM = Expanded thermoplastic microspheres.

⁴ U-value: Overall thermal transmittance of the wall assembly.

⁵ λ (lambda): Material-specific thermal conductivity.

*Assumed Values: Derived from illustrative calculations or baseline references (e.g., Hassan et al.'s [3] 60% reduction assume Tamimi et al.'s [15] unfilled baseline).

⁶ Marais et al. [17] do not explicitly calculate U-values; thermal performance is inferred from temperature differences and resistance models.

⁷ He et al. [7] Focused on the energy efficiency of vertical green walls; insulation is not the primary metric.

Table 1 (continued)

Study	Material/ configuration	U-Value (W/ m ² .°C)	Material λ (W/m.K)	Key findings
Rubeis [11]	Hollow blocks filled with wool/ PS	0.78 (wool), 1.57 (PS)	–	Demonstrated feasibility of 3dp insulating blocks; wool outperformed polystyrene
Volpe et al. [12]	Recycled aggregate + insulation	Customizable	–	Interlocking honeycomb design allows tailored thermal performance
Cuevas et al. [1]	ETM-modified concrete + PU foam (Variant F)	0.199	0.45–0.46	Optimal U-value with polyurethane filler; ~ 40% improvement over conventional walls
	ETM-modified concrete + foam concrete	0.46–0.66		Foam concrete filler improves U-value vs. air-filled walls
	ETM-modified concrete + air voids	0.6–0.8		Air-filled cavities yield higher U-values (convective heat transfer)
Nemova et al. ⁸ [4]	Ventilated cavities + nozzle optimisation	0.48	0.7 (concrete)	The lowest U-value (0.48 W/ m ² .K) was achieved among 8 tested configurations, best performance with insulated cavities and optimised airflow
	Polyurethane foam infill	0.48–1.19		Insulated variants (e.g., Design 1, Option 1) reduced the U-value to 0.48 W/m ² .K. Requires mechanical stability checks for thicker insulation layers

× 15 mm dimensions) into a standard 3D-printable cementitious mix (cement, sand, fly ash, silica fume, and water) can enhance thermal performance. The PCM particles, typically microencapsulated to diameters compatible with standard printing nozzles, were successfully incorporated at 1% to 3% weight fractions, demonstrating good printability without nozzle blockage or leaking. The encapsulation of PCM within a polymer shell prevents melting leakage upon melting, allowing designers to utilise the latent heat capacity of PCMs without compromising structural integrity. In that way, microencapsulated paraffin PCMs enhance thermal inertia but require dosage optimisation according to Table 2.

Future research should focus on assessing the long-term durability of PCM-integrated 3D-printed materials under cyclic thermal and moisture exposure and developing cost-effective methods to achieve high-PCM formulations without compromising structural integrity [3].

⁸ Nemova et al. [14] U-values sourced directly from validated CFD simulations.

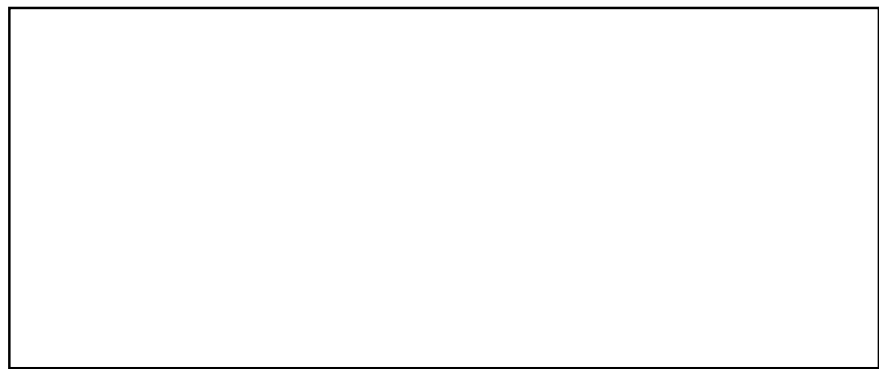


Fig. 1 Evaluated wall system topologies (Adapted from Cuevas et al. [3]). This image is distributed under a Creative Commons Attribution License (CC BY 4.0). For details, see <http://creativecommons.org/licenses/by/4.0/>

Table 2 PCM integration in 3D-printed cementitious materials

PCM dosage	Thermal benefits	Structural impacts	Printability
1–3 wt% ⁹	Delays peak heat flux by 1 h; reduces cooling loads by ~ 30% in tropical climates [3]	Compressive strength declines by 10–15% [3]	Good, no nozzle blockage [3]
> 5 wt%	Increased thermal buffering	Significant porosity increase weakens the interlayer bond	Potential issues [3]

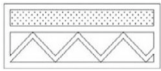
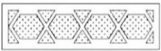
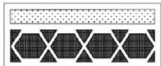
3 Geometric Innovations

3.1 Wall Configuration

Nemova et al. [4] explored several 3D-printed panel topologies, examining their thermal transmittance (U-value) through ANSYS Fluent simulations and corresponding thermal chamber experiments. Their study underscores how geometric configuration, cavity design (e.g., ventilated vs. solid), and insulation choices can significantly influence thermal outcomes:

⁹ “wt%” stands for weight per cent. It indicates the proportion or percentage of a particular component by weight relative to the total weight of the mixture.

Table 3 Thermal transmittance U-values of 3D-printed constructions with different configurations and types of insulation [4] (Adapted)

Characteristic	Construction cross-section view	U _e , ¹⁰ W/m ² .°C	U _c , ¹¹ W/m ² .°C
3		0.28	0.78
5		1.10	1.10
7		0.37	1.03
8		0.31	1.19

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- Panels 7 and 8 exhibited the best-simulated U-values in preliminary tests. However, due to practical limitations in manufacturability (e.g., complexities in nozzle path or wall geometry), Panel 3 was ultimately chosen for physical testing (Table 3).
- Ventilated cavities proved particularly effective at reducing heat transfer, mainly by introducing air gaps that limit conduction and enhance convective heat exchange within the cavities.
- Thicker wall sections generally improved insulation by increasing the travel distance for heat flow. However, thicker sections must be balanced against material use, structural demands, and print time.
- Strategic nozzle size and print settings were crucial for controlling layer adhesion and the consistency of internal cavities, ensuring minimal bridging defects that might otherwise compromise insulation.

Designs 1 to 8 of the original study tested varying cavity widths, insulation types, and airflow configurations. Their work further emphasises the synergy between geometric design and insulation selection in optimising U-values. Even minor adjustments, such as cavity width, ventilation channels, or additional insulation layers, can shift results substantially. Meanwhile, Volpe et al. [13] propose a prefabrication-oriented approach using 3D printing to assemble high-performance building envelopes. Their concept focuses on modular, dry-assembled blocks manufactured off-site in a controlled environment (Fig. 2). By leveraging magnesium-potassium-phosphate cement (MKPC) and carefully tailored mix designs, the authors demonstrate how 3D printing can yield elements with:

¹⁰ U_e: Experimental U-value.
¹¹ U_c: Simulated U-value.

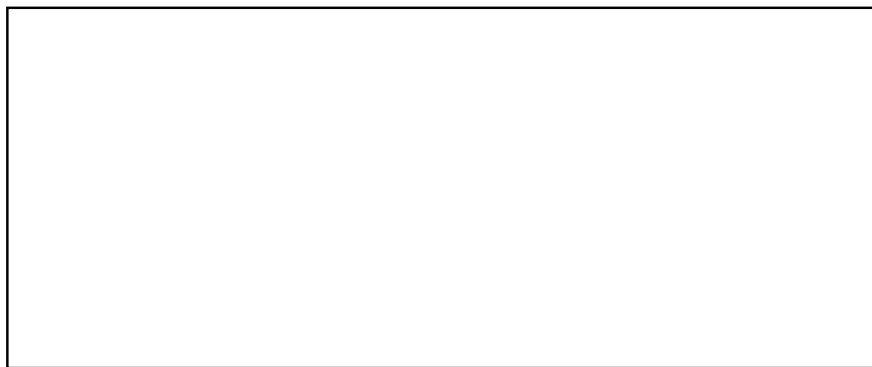


Fig. 2 Prefabricated 3D-printed building envelope concept by Volpe et al. [13]. This image is distributed under a Creative Commons Attribution License (CC BY 4.0). For details, see <http://creativecommons.org/licenses/by/4.0/>

- Enhanced thermal consistency, thanks to customised cavity shapes and integrally placed insulating materials.
- Reduced on-site variability, as the manufacturing process occurs in a factory-like setting, improving quality control and repeatability of each unit.
- Streamlined installation because each printed block arrives ready for rapid assembly, minimising formwork and labour.

Taken together, Nemova et al. [4] and Volpe et al. [13] underscore that wall configuration, encompassing ventilated compartments, insulation integration, and specialised mortar mixes, is central to achieving low U-values without compromising mechanical stability. Integrating generative design or topology optimisation into these prefabrication workflows may further optimise cavity layouts, nozzle paths, and material usage for consistent, high-performance 3D-printed building envelopes.

3.2 *Façade Design*

Complex 3D-printed geometries transcend basic cavity designs, addressing multifunctional building envelope requirements such as thermal insulation, ventilation, humidity control, and active temperature regulation. Design-for-additive manufacturing (DFAM) methodologies leverage topology optimisation, parametric toolpath planning, and spatial infill modelling to create site-specific geometries that adapt to environmental conditions. For example, Leschok et al. [5] developed a DFAM workflow (Fig. 3): involving four iterative stages: (1) geometric parameterisation of variable-thickness skins/internal channels in tools like Grasshopper; (2) performance evaluation via CFD/FEA simulations to optimise thermal resistance; (3) integration fabrication constraints (e.g., ≤ 2 mm layer heights, multi-axis kinematics); and (4)



Fig. 3 DFAM methodologies for 3D-printed facades focus on optimising topology, infill design, and planning toolpath [5]. This image is distributed under a Creative Commons Attribution License (CC BY 4.0). For details, see <http://creativecommons.org/licenses/by/4.0/>

refinement via Pareto optimisation to balance U-value targets ($\pm 0.1 \text{ W/m}^2\cdot\text{K}$) and structural stability.

Sarakinioti et al. [6] advanced this paradigm with adaptive façades featuring water circulation channels. Their prototypes demonstrated dual functionality: (1) thermal resistance enhancement through elongated internal cells ($\leq 15 \text{ mm}$ width) and (2) active thermal buffering via fluid channels acting as low-grade thermal batteries. However, such designs demand precision to prevent leakage (e.g., epoxy coatings for large panels) and address challenges like UV degradation in polymers or cracking in concrete.

New challenges include resolving structural-thermal trade-offs (e.g., thin-walled channels risking mechanical failure), scaling fabrication via modular dry-assembly with snap-fit joints, and ensuring long-term durability under hygrothermal cycles. Multi-objective optimisation algorithms (e.g., NSGA-II) and material innovations (e.g., nano-clay additives) mitigate these issues. Future efforts focus on multi-material printing (e.g., aerogel mortars with $\lambda = 0.04 \text{ W/m}\cdot\text{K}$), standardised robotic workflows, and real-world validation to align with net-zero energy codes. By merging computational design with additive manufacturing, 3D-printed façades evolve into adaptive, energy-efficient interfaces, transforming static envelopes into dynamic, climate-responsive systems [5, 6].

4 Generative Design and Synthesis

Generative design resolves competing thermal-structural demands in 3D-printed construction through parametric optimisation, leveraging tools like Grasshopper and Dynamo to iteratively adjust cavity geometry, wall thickness, and material distribution [1, 17]. Simulation platforms (e.g., ANSYS Thermal, COMSOL Multiphysics)

evaluate design variants for U-value reduction and structural stability, while multi-objective algorithms (e.g., genetic algorithms) identify Pareto-optimal solutions that balance heat transfer minimisation with strength thresholds [5]. For instance, Leschok et al. [5] integrated topology optimisation (Altair Inspire) with RoboDK toolpath planning, reducing façade U-values by 25% through iterative testing of 50+ infill patterns (hexagonal, gyroid) under ≤ 2 mm layer heights and ≤ 25 mm/s nozzle speeds.

Material innovations further enhance thermal performance: expanded thermoplastic microspheres (ETM) and waste glass reduce thermal conductivity by 40% ($\lambda = 0.45\text{--}0.47$ W/m·K vs. conventional 0.74 W/m·K) [1], while phase change materials (PCMs) delay peak heat flux by over an hour, cutting cooling demands by 30% in tropical climates [3]. However, PCM integration at 3% dosage reduces compressive strength by 10–15%, necessitating careful calibration [3]. Geometric optimisations, such as polyurethane foam-filled cavities (U-value reduction of 60% [2, 14]) and ventilated configurations ($U = 0.48$ W/m²·K [4]), demonstrate how cavity design and modular prefabrication (e.g., interlocking honeycomb blocks [12]) harmonise thermal and structural needs.

Challenges persist in hygrothermal dynamics, with 3D-printed mortar exhibiting a 14% λ increase at 80% RH [8], and scalability limitations, such as micro-voids in fluid channels [5, 13]. Computational workflows address these through dual-material extrusion [19], parametric cavity layouts [4, 5], and adaptive façades (e.g., water-circulating channels reducing annual energy use by 9–11% [6, 7]). For example, Cuevas et al. [1] prioritised structural efficiency over minimal U-values (0.199 W/m²·K), while Nemova et al. [4] achieved 0.48 W/m²·K through airflow optimisation, underscoring context-specific trade-offs.

Synthesis of these advancements reveals a complex interdependence between material properties (e.g., ETM-modified concrete), geometric configurations (e.g., 20 mm cavities), and fabrication constraints (e.g., print speed). Hybrid strategies, such as alternating structural and insulating layers [18], exemplify the need for interdisciplinary collaboration to advance scalable, code-compliant solutions. By bridging computational innovation (topology optimisation, parametric scripting) and additive manufacturing realities (overhang angles, robotic kinematics), generative design positions 3D printing as a transformative tool for energy-efficient, resilient building envelopes.

5 Conclusion

3D-printed concrete panels redefine thermal performance in building envelopes, achieving U-values as low as 0.199–0.48 W/m²·K through material innovation (e.g., ETM-modified concrete with 40% reduced λ [1]), geometric optimisation (e.g., foam-filled cavities [2]), and PCM integration (30% cooling load reduction [3]). These advancements surpass conventional concrete walls ($U = 1.5\text{--}2.0$ W/m²·K [16]), demonstrating additive manufacturing's capacity to harmonise insulation, structural

integrity, and sustainability. Generative design workflows further enhance gains, enabling adaptive façades (e.g., fluid-circulating systems [6]) that reduce annual energy use by 9–11% [7].

Challenges remain, notably hygrothermal vulnerabilities (14% λ increase at 80% RH [8]), mechanical trade-offs (e.g., 10–15% strength loss with PCMs [3]), and the need for real-world validation of lab-scale innovations. Future efforts must prioritise:

- Generative design: AI-driven multi-objective optimisation to resolve thermal-structural conflicts [5, 6].
- Scalability validation: Full-scale testing of aerogel-enhanced or modular prototypes [5, 13].
- Standardisation: Standardised protocols aligned with energy codes.
- Thermal plasters: Investigating 3D-printable finishing materials to enhance envelope performance.

Transitioning to industry adoption demands circular economy principles (e.g., recycled aggregates [11]) and collaboration across research, policy, and construction sectors. By bridging computational innovation with scalable fabrication, 3D printing can deliver resilient, energy-efficient envelopes that align with global net-zero targets, advancing sustainable construction practices through technical and operational feasibility.

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References

1. Cuevas K, Strzałkowski J, Kim J-S, Ehm C, Glotz T, Chougan M, Ghaffar SH, Stephan D, Sikora P (2023) Towards development of sustainable lightweight 3d printed wall building envelopes—experimental and numerical studies. *Case Stud Constr Mater* 18:e01945
2. Hassan H, Rodriguez-Ubinas E, Al Tamimi A, Trepici E, Mansouri A, Almehairbi K (2024) 3d printing in construction. *Autom Constr* 163:105417
3. Liu Z, Li M, Kandasamy R, Ho JY, Wong TN, Li HKH, Tan MJ (2022) Comprehensive investigations on printability and thermal performance of cementitious material incorporated with pcm under various conditions. *Energy Convers Manage* 261:115667
4. Nemova D, Kotov E, Andreeva D, Khorobrov S, Olshevskiy V, Vasileva I, Zaborova D, Musorina T (2022) Experimental study on the thermal performance of 3d-printed enclosing structures. *Energies* 15:4230
5. Leschok M, Cheibani I, Piccioni V, Seshadri B, Schlüter A, Gramazio F, Kohler M, Dillenburger B (2023) 3d printing facades: design, fabrication, and assessment methods. *Autom Constr* 152:104918
6. Sarakinioti MV, Turrin M, Konstantinou T, Tenpierik M, Knaack U (2018) Developing an integrated 3d-printed façade with complex geometries for active temperature control. *Mater Today Commun* 15:275–279
7. He Y, Zhang Y, Zhang C, Zhou H (2020) Energy-saving potential of 3D printed concrete building with integrated living wall. *Energ Build* 222. <https://doi.org/10.1016/j.enbuild.2020.110110>
8. Pessoa S, Jesus M, Guimarães AS, Lucas SS, Simões N (2023) Experimental characterisation of hygrothermal properties of a 3d printed cementitious mortar. *Case Stud Constr Mater* 19:e02355
9. Baghban MH (2019) Thermal insulating cementitious composite containing aerogel and phosphate-based binder. In: IOP conference series: materials science and engineering, vol 609. <https://doi.org/10.1088/1757-899X/609/6/062024>
10. Latorraca T, Guimarães AS, Rangel B (2024) Bibliometric analysis of personalized 3D-printed concrete-based modules for construction: leveraging the Ordination method. *Buildings* 14(3):802. <https://doi.org/10.3390/buildings14030802>
11. de Rubeis T (2022) 3D-printed blocks: thermal performance analysis and opportunities for insulating materials. *Sustainability (Switzerland)* 14. <https://doi.org/10.3390/su14031077>
12. Volpe S, Sangiorgio V, Petrella A, Notarnicola M, Varum H, Fiorito F (2023) 3D printed concrete blocks made with sustainable recycled material, VITRUVIO. *Int J Architect Technol Sustain* 8:70–83. <https://doi.org/10.4995/vitruvioijats.2023.18832>
13. Volpe S, Sangiorgio V, Petrella A, Coppola A, Notarnicola M, Fiorito F (2021) Building envelope prefabricated with 3d printing technology. *Sustainability* 13(16):8923
14. Al Tamimi A, Hassan H, Rodriguez-Ubinas E, Alhaidary H, Mansouri A (2023) Thermal performance of 3D concrete printed walls: calculated and in-situ measured U-values. *J Asian Architect Build Eng* 1–13. <https://doi.org/10.1080/13467581.2023.2278467>
15. Stewart K et al (2023) Thermal conductivity. *Britannica*. <https://www.britannica.com/science/temperature>
16. Heather EK (2021) 2021 ASHRAE Handbook—Fundamentals. *ASHRAE*. <https://www.ashrae.org/technical-resources/ashrae-handbook/description-2021-ashrae-handbook-fundamentals>
17. Marais H, Christen H, Cho S, De Villiers W, Van Zijl G (2021) Computational assessment of thermal performance of 3d printed concrete wall structures with cavities. *J Build Eng* 41:102431
18. Pessoa S, Guimarães AS, Lucas SS, Simões N (2021) 3D printing in the construction industry – a systematic review of the thermal performance in buildings. *Renew Sustain Energy Rev* 141:110794. <https://doi.org/10.1016/j.rser.2021.110794>
19. Alghamdi H, Neithalath N (2019) Synthesis and characterization of 3D-printable geopolymeric foams for thermally efficient building envelope materials. *Cement Concr Compos* 104:103377. <https://doi.org/10.1016/j.cemconcomp.2019.103377>

20. Briones-Llorente R, Barbosa R, Almeida MG, Montero García EA, Rodríguez Saiz Á (2020) Ecological design of new efficient energy-performance construction materials with rigid polyurethane foam waste. *Polymers* 12(5):1048. <https://doi.org/10.3390/polym12051048>
21. Lymath A (2015) What is a U-value? Heat loss, thermal mass and online calculators explained, NBS. Hubexo. <https://www.thenbs.com/knowledge/what-is-a-u-value-heat-loss-the-rmal-mass-and-online-calculators-explained>
22. Malik M, Bhattacharyya SK, Barai SV (2021) Thermal and mechanical properties of concrete and its constituents at elevated temperatures: a review. *Construct Build Mater* 270:121398. <https://doi.org/10.1016/j.conbuildmat.2020.121398>
23. Strzałkowski J, Sikora P, Chung S-Y, Abd Elrahman M (2021) Thermal performance of building envelopes with structural layers of the same density: lightweight aggregate concrete versus foamed concrete. *Build Environ* 196:107799. <https://doi.org/10.1016/j.buildenv.2021.107799>
24. Cuevas K, Chougan M, Martin F, Ghaffar SH, Stephan D, Sikora P (2021) 3D printable lightweight cementitious composites with incorporated waste glass aggregates and expanded microspheres – rheological thermal and mechanical properties. *J Build Eng* 44:102718. <https://doi.org/10.1016/j.jobbe.2021.102718>
25. 2021 International Energy Conservation Code (IECC), *2021 IECC*, *2021 International Energy Conservation Code (IECC)* (2021).

Effective Cooling with a Novel Design of Thermally Activated Building Components for High Thermal Comfort



Michael Marquardt, Jasper Jürgensen, and Kristina Terheiden

Abstract The EU is committed to achieve climate-neutrality by 2050. Despite the achieved goals, further improvements are still required to reduce the primary energy demand. In particular, the building sector still shows great potential for energy efficiency improvements especially for cooling. While conventional air cooling systems are widely used, their primary energy demand is quite high and their thermal comfort quite low. Thermally activated building systems (TABS) can generally improve the cooling performance due to their large surfaces and thermal masses for heat transfer and storage, but still show potential for improvements in energy efficiency. Therefore, this study investigates further improvements in energy efficiency and user comfort with a novel TABS design in concrete ceilings by e.g. using a higher coolant temperature and manipulating the heat transfer across surfaces. Condensation is avoided by enhancing temperature uniformity at the surfaces. Thus, a lower minimal coolant supply temperature can be used to increase the maximum cooling capacity during challenging weather. The novel TABS is tested for two different heat sink configurations, a heat pump driven by electricity of PV panels and nocturnal sky radiators. Both systems show a good performance. The cooling capacity of the nocturnal sky radiators ensures thermal comfort for up to two storeys, while the heat pump with PV modules ensures it up to 13 storeys for a fixed roof area. However, the cooling capacity of the novel TABS with both heat sink systems strongly depends on the individual site and weather conditions.

Keywords Construction · Energy · Cooling · Comfort · TABS

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1 Introduction

The EU has agreed on the Green Deal to achieve climate-neutrality by 2050 [1]. The Green Deal includes not only the expansion of renewable energy sources but also the reduction of primary energy demand. Thereby, the building sector accounts for a significant share of primary energy consumption, especially for heating and cooling purposes, and thus offers great potential for energy savings [2]. While buildings get increasingly insulated to reduce the heating demand [3], it leads to a higher cooling demand during warm periods, which will further increase due to the climate change. Therefore, providing high thermal comfort with minimal energy consumption will be a major issue for achieving the European Union's goal of climate neutrality.

Central Heating, Ventilation and Air Conditioning (HVAC) systems are widely used in non-residential buildings (NRB's) such as office buildings. HVAC systems adjust the temperature of air and distribute it over the building with air vents, which can be integrated into the building structure or retrofitted. While these systems can be installed at low installation cost, they show several limitations. The air has to be cooled below the actual comfort temperature because of thermal losses of the air vents, which increases the required cooling capacity. Furthermore, dry air (through cooling) ventilation can limit thermal comfort and additional energy is required to drive air ventilation. Radiant cooling systems can overcome these issues by using a large cooled surface for the thermal radiation processes. The perception of temperature depends on the air temperature and the temperature of the surrounding surfaces. Providing a cool surface thus allows the air temperature to be higher while achieving the same thermal comfort compared to HVAC systems. This reduces the overall cooling energy demand and the energy consumption for air circulation to the minimum required for air quality aspects.

Thermally Activated Building Systems (TABS) are radiant cooling and heating systems, which are embedded in structural components like ceilings, floors and walls. They utilize the large surface area of these components as well as their thermal storage capacity. For cooling applications, this allows to lower the peak energy consumption ("peak load shaving") and the operation of the heat sink to be partly decoupled from the heat dissipation in the building interior ("peak shifting", "pre-loading") [4]. These effects can be utilised with advanced control strategies to reduce the primary energy demand of the cooling system. Traditionally, TABS are built by integrating a hydronic system into a building component. A coolant is transported through the pipes with circulation pumps. However, often in traditional TABS, the thermal comfort and efficiency can be limited by temperature non-uniformity at the surface originating from the coolant heating during the flow process, which can cause dew formation and asymmetric heat radiation.

2 Operation of the Novel System with Distinct Heat Sinks

A novel design of TABS is developed to use the capabilities of distinct heat sinks for the cooling of NRB's. The novel system is designed as a thermally activated concrete slab with an advanced piping system that minimises temperature non-uniformity at the cooling surface. It allows a lower thermal resistance compared to conventional systems and therefore a higher energy efficiency. On the other hand, the average ceiling surface temperature can be lowered further towards the dew point without the risk of condensation due to the good temperature uniformity. This enables cooling with high thermal comfort even under challenging conditions such as tropical climates. A detailed description and comprehensive validation of the novel system are presented in Jürgensen et al. [5]. Thus, in this study the operation of the novel system is investigated with two different heat sinks (variant 1 and 2).

The first system (heat sink variant 1, Fig. 1, left) consists of a heat pump connected to photovoltaic (PV) modules that are installed on the roof of the building. The number of PV modules is scaled according to the available roof area and they are used as the main power source for the heat pump. Thus, cooling is only available when solar irradiation is high enough, which is also the major heat source affecting the building [6]. For the other system (heat sink variant 2, Fig 1, center), nocturnal sky radiators (SR) are installed on the roof of the building for heat dissipation during the night. The thermal irradiation from the nocturnal sky is lower than the thermal emission of the radiators, which is facilitated to dissipate heat from the building. Circulation pumps are required to transport heat from the TABS to the SR and to control the system. This allows to cool the building interior during the night where the thermal mass of the TABS is used to store heat during the day (peak shifting). The cooling capacity of SR is limited by the emissivity of the atmosphere at night and the available roof area [7]. The cooling performance of both heat sink systems in combination with the novel TABS is evaluated with numerical simulations.

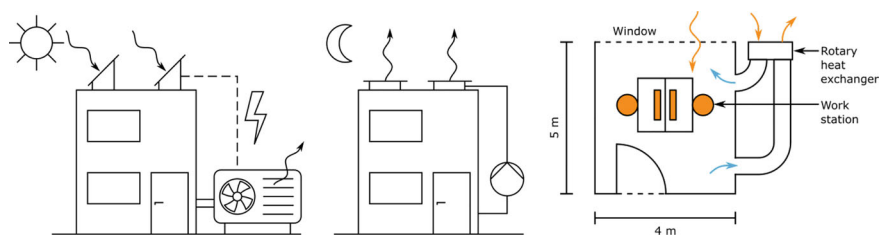


Fig. 1 Schematic sketch of a NRB with a heat pump coupled to PV modules (left) or SR (center) for heat dissipation and interior layout of the NRB (right)

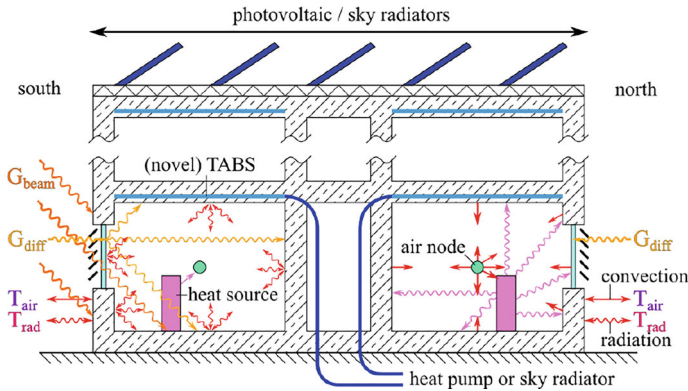


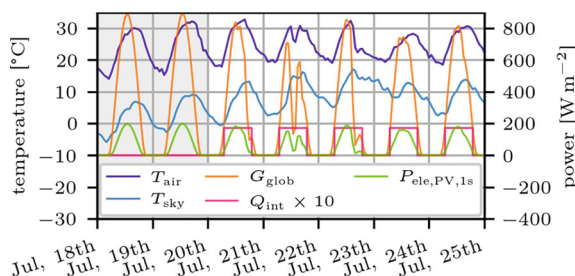
Fig. 2 Simplified sketch of the numerical model of the NRB's

3 Numerical Model of a Non-residential Building

The simulation framework OpenModelica [8] is used to implement one-dimensional numerical models of a NRB with the aforementioned different heat sinks. A simplified graphical representation of the numerical models is shown in Fig. 2. Thermal resistance and capacity elements are used to simulate heat flow through the building components. The model includes multilayer wall structures and heat transfer by convection, short-wave and long-wave radiation. It is assumed that all rooms in the building have the same layout and that half of the rooms are oriented to the north and to the south, respectively.

The geometry of the office rooms, the required components and their material parameters as well as internal loads are determined in accordance to the German standard DIN 18599-10 [9] and VDI 2078 [10] (room type L). In contrast to the specifications, a simplified model of the novel TABS is integrated in the model for thermal storage and heat dissipation. The thermal properties of the novel TABS design are represented by a customised Modelica module. The numerical model of the novel TABS has been validated through extensive testing with a full-scale setup [5]. The windows are equipped with triple thermal insulation glazing and venetian blinds and cover 50 % of the outward facing wall. As shown in Fig. 1 (right), two workstations and users with a heat generation of 100 W and 70 W, respectively, are placed in every office. The working hours are scheduled from 7 am to 6 pm with a net working time of 6 h [9]. The internal heat generation is equally distributed over the working hours. Heat transport through the facade is enabled through the wall and window construction and adaptive blinds which are automatically closed when the global solar radiation exceeds 100 W m^{-2} . All other walls are adiabatic. Ventilation is provided by a rotary heat exchanger with a heat recovery efficiency of 90 % and an air change rate of 1.5 h^{-1} .

Fig. 3 External and internal boundary conditions for the numerical model



The Test Reference Year (TRY) datasets provided by the German national meteorological service Deutscher Wetterdienst (DWD) [11] are used to simulate the influence of weather. For this study, the dataset is generated for the location of the University of Stuttgart (Campus Vaihingen) for a warm summer with air temperatures above the average. The resulting data is shown in Fig. 3 for the reference week with the highest outdoor air temperatures (July, 18th to July, 24th). The outdoor air temperature T_{air} , exceeds 30°C on six out of seven days while the effective radiative sky temperature T_{sky} decreases below 10°C during night. The global solar radiation G_{glob} is almost always close to the possible maximum due to an unfrequent cloud cover. All simulations start from July, 1st to generate reliable conditions independent of the actual initial state.

The electricity production by PV modules on the roof of the building is calculated from the incident solar radiation and a constant efficiency of 20% [12] at an inclination angle of 37° (oriented southwards). The SR are modelled as white panels with a short-wave absorption factor of 0.15 and a long-wave emissivity of 0.95. The panels are equipped with a narrow piping system to transfer heat from the TABS with a circulating coolant. The SR panels are oriented horizontally to increase radiative heat exchange with the night sky. The effective temperature of the night sky is calculated using the downward oriented long-wave thermal radiation taken from the TRY dataset. The system is controlled by activating the coolant circulation only when the effective temperature of the sky is lower than the desired coolant temperature.

For both variants, the coolant supply temperature of the TABS is limited to prevent dew formation at the surface of the TABS. Coolant transport in the cooling circuits is modelled with one-dimensional mass transport to account for the flow travel time and the thermal mass of the coolant.

4 Results and Discussion

The modelling results are used to evaluate the cooling capacity of the novel TABS and the suitability of the distinct heat sinks for the application of cooling of NRB's. The operational indoor temperature T_{op} of the office rooms facing south is used for the comparison of the model results, since the southern facade is exposed to direct

solar irradiation. T_{op} is calculated from the indoor air temperature and the average temperature of all indoor surfaces to take into account radiative heat transfer between users and their environment. According to DIN 18599-10 [9], T_{op} must remain below 26°C to provide sufficient thermal comfort.

4.1 Cooling Capacity of Different Heat Sinks

Figure 4 (left) shows the operational indoor temperature T_{op} and the cooling rate at the heat sink Q_{cool} resulting from numerical modelling of the two-storey office building with a heat pump (HP) and with SR. The results are shown during the five working days in the reference period. In general, the heat pump only operates during daytime when electricity is generated at the PV modules. In contrast, heat dissipation by the SR is only possible during the night due to the absence of solar radiation. These contradictory operation processes can be seen in Fig. 4 (left) where the cooling rate of the office building equipped with a heat pump is zero at night, while cooling only takes place with SR during night.

The results from the simulation of the office building with SR show higher amplitudes of the daily cycle of T_{op} and lower minimum values during the night compared to the system equipped with a heat pump. This is due to the necessary pre-cooling of the TABS during night to absorb the heat over the day. Another interesting effect is that the minimum operational temperature at night increases during the week. This implies that not all the heat entering the building can be dissipated with the installed heat sinks. However, T_{op} does not exceed 26°C and thus ensures the thermal comfort for both heat sink systems. Furthermore, the absence of internal heat generation during the weekend followed by the reference period allows additional cooling of the building. The heat dissipation during the reference week is 2.6 kWh/m² for the heat pump system and 2.3 kWh/m² for the SR system. While both systems require very little energy to provide effective cooling of the office building, it must be noted that environmental effects such as clouds and solar radiation can significantly influence the cooling capacity of both heat sinks.

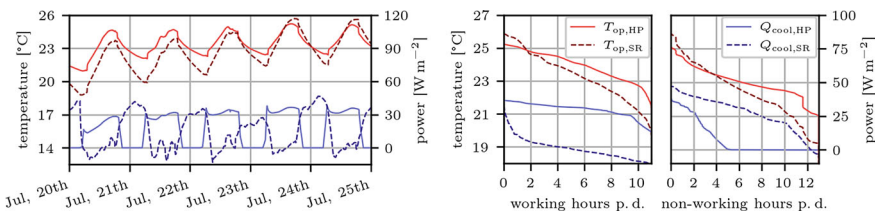


Fig. 4 Resulting values (left) and exceedance duration (right) of the operational indoor temperature T_{op} and cooling rate Q_{cool} (left) of the two-storey office building with a heat pump and PV modules (HP) or with SR

The average daily exceedance duration of the temperature T_{op} and the cooling rate Q_{cool} shown in Fig. 4 (right) can be used to further characterise the presented heat sink systems. The resulting values are grouped into working hours (7 am to 6 pm) and non-working hours (6 pm to 7 am) to evaluate the system performances during the presence of users. While the heat pump provides high cooling rates during the working hours, the SR mainly dissipates heat during night (non-working) hours and heat is stored in the TABS. Therefore, the cooling rate of the SR is around zero during the day. Furthermore, the T_{op} of the SR system is lower in the beginning of the week than for the heat pump system. It exceeds $T_{op, HP}$ during 2 h with 26°C towards the end of the week. Negative cooling rates can be observed during the working hours at the SR. This is caused by the heating up of the panels during daytime as a result of incident solar radiation and high outdoor air temperature. However, the generated heat is not transferred from the sky radiator panels to the TABS since the circulation pumps are deactivated. A bright surface with a low short-wave absorption (0.15) is used to minimise solar heating without the use of shaders. In contrast, a dark surface can lead to strong heating up, which results in a much lower cooling capacity because the coolant needs to be additionally cooled down before actually cooling the TABS.

4.2 Cooling Capacity for Multi-storey Buildings

The number of storeys is increased in additional simulations to evaluate the maximum cooling capacities of the heat sink systems. The roof area available for nocturnal sky radiation or electricity generation with PV modules is calculated from the floor area of the building and is thus constant. The results are shown for 1 to 19 storeys building with the heat pump cooling system in Fig. 5 (left) and for 1 to 4 storeys building with the nocturnal sky radiation cooling system in Fig. 5 (right). The electricity generation of the PV modules is sufficient to enable cooling with $T_{op} < 26^\circ\text{C}$ for up to 13 storeys.

Figure 5 (left) shows that the peaks of the cooling rate Q_{cool} become more narrow for an increasing number of storeys for the heat pump system. This is caused by the limited electric power from the PV modules available in the twilight hours. This can only partly be compensated by higher cooling rates around 12 pm and causes T_{op} to

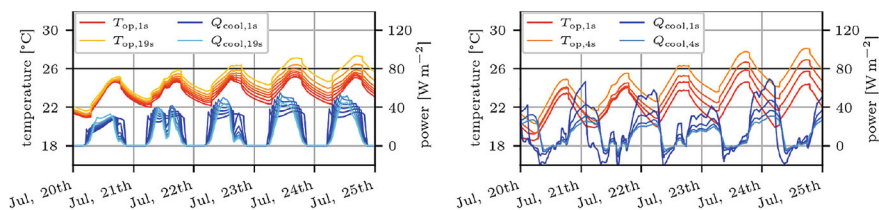


Fig. 5 Operational indoor temperature T_{op} and cooling rate Q_{cool} of the office building with a heat pump and PV modules (left) or SR (right), 1s = 1 storey

increase even for a low number of storeys. A different control strategy might reduce the operational temperature but for high numbers of storeys the system would still be limited by the available PV energy. In particular, the cooling rate for the systems with 16 and 19 storeys is proportional to solar irradiation and thus cannot benefit from a different operation.

Figure 5 (right) shows that the cooling capacity of the SR is lower than that of the heat pump with PV modules. For the sky radiators, only up to two floors can be cooled below 26 °C. Furthermore, the sky radiators used in this study utilise the complete spectrum of thermal radiation. Advanced designs can narrow the absorption to wavelengths close to the atmospheric window between 8 μm and 13 μm , where the atmosphere provides minimal emissivity, which reduces the effective sky temperature [7]. However, a more complex numerical model, which accounts also for local atmospheric properties would be required to investigate such a system.

5 Summary and Conclusion

A novel design of a TABS is integrated into the numerical model of a multi-storey office building to evaluate the cooling performance of TABS with different heat sinks. The first heat sink configuration consists of a heat pump driven during daytime by electricity generated through PV panels that are installed on the roof of the building. For the other heat sink configuration, SR are installed on the roof to dissipate heat through thermal radiation during the night. Both systems are very different with regard to their temporal availability of cooling capacity. Since PV modules only generate electricity when they are exposed to solar irradiation, SR's require the absence of solar radiation for heat dissipation. The thermal mass of the TABS is facilitated to balance the delay between heat generation inside the building and heat dissipation at the heat sinks. The model results indicate that both heat sink systems enable cooling at high thermal comfort and that the novel TABS can be used with a great variety of heat sinks. The cooling capacity of the SR used in this study was shown to ensure thermal comfort for up to two storeys for a constant roof area. In contrast, the heat pump with PV modules can ensure thermal comfort for up to 13 storeys without requiring additional electricity from the grid. Furthermore, when the system is installed in buildings with less than 13 storeys, the surplus PV energy can be utilised for purposes other than cooling. It should be noted that the cooling capacity of both system strongly depends on the individual site conditions, which means that also buildings with more storeys might be sufficiently cooled.

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References

1. European Commission, Secretariat-General (2019) The European Green Deal
2. International Energy Agency (IEA) (2018) The future of cooling. Technical report
3. EU Building Stock Observatory (BSO): BSO database. <https://building-stock-observatory.energy.ec.europa.eu/database/>
4. Wang S, Ma Z (2008) Supervisory and optimal control of building HVAC systems: a review. HVAC&R Research 14(1):3–32
5. J. Jürgensen M, Marquardt K Terheiden (2025) Energy-efficient cooling of non-residential buildings with multi-functional heat pipes in novel thermally activated building components (submitted). Build Environ
6. Görtz J, Jürgensen J, Stolz D, Wieprecht S, Terheiden K (2022) Energy load prediction on structures and buildings—effect of numerical model complexity on simulation of heat fluxes across the structure/environment interface. Appl Energy 326:119981
7. Ali AHH, Taha IMS, Ismail IM (1995) Cooling of water flowing through a night sky radiator. Solar Energy 55(4):235–253
8. Fritzson P, Aronsson P, Lundvall H, Nyström K, Pop A, Saldamli L, Broman D (2005) The OpenModelica modeling, simulation, and development environment. In: 46th Conference on simulation and modelling of the Scandinavian simulation society (SIMS2005), Trondheim, Norway
9. DIN V 18599-10:2018-09 (2018) Energy efficiency of buildings—calculation of the net, final and primary energy demand for heating, cooling, ventilation, domestic hot water and lighting—Part 10: boundary conditions of use, climatic data
10. VDI-Gesellschaft Bauen und Gebäudetechnik (GBG), VDI 2078 (2015) Calculation of thermal loads and room temperatures (design cooling load and annual simulation)
11. Deutscher Wetterdienst (2017) Ortsgenaue Testreferenzjahre von Deutschland für mittlere, extreme und zukünftige Witterungsverhältnisse
12. Vodapally SN, Ali MH (2023) A comprehensive review of solar photovoltaic (PV) technologies, architecture, and its applications to improved efficiency. Energies 16(1)

Smart Management of Indoor Environmental Quality for Energy Efficiency in Residential Buildings: A Systematic Review of Methodologies and Systems



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Abstract The substantial energy demands for climatization in residential buildings place this sector at the forefront of global energy consumption challenges, making it a critical focus area for energy efficiency research. Numerous controllable elements within buildings influence indoor environmental quality (IEQ), rendering manual optimization by humans infeasible. Fortunately, the proliferation of IoT devices and smart home technologies unlocked new opportunities for intelligent algorithms that optimize building energy efficiency by IEQ management. Building energy efficiency can be enhanced through intelligent control systems or user feedback, which always requires decision algorithms to feed the control or user alert systems. For real-time prediction of IEQ and energy consumption, these algorithms rely on models of the buildings and their occupancy. Different approaches and methodologies exist to develop these models, with varying computational requirements, scalability potential, and precision. This systematic review, complying with PRISMA2020 guidelines, aims to evaluate the existing literature on algorithms and methodologies to optimize energy consumption and IEQ. A comprehensive search strategy was developed using thematic blocks of keywords to address the questions raised on the scope of this review. These keywords aggregate terms related to residential buildings, IEQ, energy optimization, algorithms and methodologies, control systems, performance evaluation, and all IEQ components. The search was performed within the Scopus database with inclusion criteria limited to peer-reviewed articles published in English. This review analyzes the IEQ management solutions' type, precision, real-world implementation, and efficiency. It identifies crucial gaps in the current literature, assesses the maturity and limitations of contemporary technologies, and identifies promising areas for future research in smart home energy-efficient solutions.

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Keywords Energy optimization · Indoor environmental quality (IEQ) · Smart home systems · Intelligent automation · Decision algorithms · Building digital twin

1 Introduction

1.1 Rationale

Buildings' indoor environmental quality (IEQ) is crucial for occupants health and well-being, however, to achieve satisfactory levels of IEQ, is required continuous occupant intervention that results on inefficient control, leading to poor IEQ and inefficient energy usage on heating and cooling. Residential buildings energy usage, represent a pivotal domain in global sustainability efforts, accounting for approximately 25–40% of worldwide energy consumption, making it a priority sustainability problem.

Recent technological advancements, particularly in internet of things (IoT) infrastructure and artificial intelligence (AI), have created unprecedented opportunities for developing intelligent residential systems, more efficient, comfortable and resilience to climate change. These systems can dynamically learn and respond to individual user preferences, predict energy consumption patterns, and provide real-time feedback mechanisms.

However, significant challenges remain in translating these technological potentials into practical, scalable solutions due to the complex interplay of occupant behaviour, preferences, technology acceptance and all the variables that affect IEQ, demands a comprehensive, interdisciplinary approach of research and development.

1.2 Objectives

This systematic review aims to comprehensively map and critically analyze the contemporary landscape of smart technologies operated by intelligent algorithms in residential buildings. By synthesizing existing research, the review seeks to provide a nuanced understanding of how innovative technological solutions can simultaneously optimize energy efficiency and occupant comfort and health. This systematic review will adhere to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines, version 2020, to ensure a transparent, reproducible, and methodologically rigorous approach to literature identification, selection, and synthesis.

Table 1 Inclusion and exclusion criteria used for study selection

Inclusion criteria	Exclusion criteria
Studies written in English	Studies in a language other than English
Studies focusing on residential or small office context	Non-residential or small office building studies (e.g., commercial buildings, factory)
Studies about IEQ algorithms	Studies not related to IEQ algorithms
Studies with full text available through open access or institutional subscriptions	Studies for which the full text could not be accessed
Studies published in journals	Studies published in documents other than journals (e.g., conference paper, editorial)

2 Methods

2.1 Eligibility Criteria

The inclusion and exclusion criteria for this systematic review were designed to ensure a focused and high-quality synthesis of relevant studies (Table 1).

Studies were grouped based on their primary methodological approach and objective, specifically distinguishing between (i) control strategies using reinforcement learning (RL), (ii) model predictive control (MPC), (iii) rule-based or conventional methods, and (iv) hybrid or AI-augmented optimization methods. Grouping allowed a comparative synthesis across techniques and facilitated interpretation of performance trends by class.

2.2 Information Sources

The literature search was conducted using the Scopus database, which indexes a wide range of engineering and environmental science journals. The final search was executed on 12/03/2023. No restrictions were placed on publisher or access platform.

2.3 Search Strategy

The search strategy was designed to systematically address the research objectives. A query set was developed using thematic blocks that represent key concepts and ensure both inclusivity and comprehensiveness across the literature. The thematic categories were carefully constructed to capture relevant terms aligned with the research scope.

Using these thematic blocks, several combinations were performed, and search results were analyzed with VOSviewer [32] and Bibliometrix [31] along several

Table 2 Search query blocks rationale

Theme	Rationale
Residential buildings	Includes terms related to various types of residential structures, focused specifically on residential contexts, excluding studies centered on commercial or industrial buildings
IEQ	Includes terms related to IEQ and all of its components individually, used in a complex query that filter studies focused on IEQ components
Algorithms	Used terms related to computational processes and methods used in modeling and controlling IEQ. These terms were crucial for identifying studies that employ advanced algorithmic approaches for optimization
Control	Focus on methods and systems used for controlling IEQ parameters. These terms helped identify studies using building control simulations and case studies
Building controls	This category is used to address elements in buildings that affect or control IEQ. These terms were used to include studies where these elements are controlled by occupants or control mechanisms

iterations to fine-tune the query until it was focused on the research scope aiming to address ≈ 200 publications. Using filters to include only peer-reviewed articles written in English or language undefined, the refined search query, returned 177 results for the screening process (Table 2). The search query executed was the following:

(TITLE-ABS-KEY (building OR edifice OR house OR home OR flat OR residence OR dwelling OR abode OR room OR apartment OR condo OR townhouse OR “living space” OR “domestic premise” OR office) AND (automat* OR control* OR mechaniz* OR actuat* OR manage*) AND (“IEQ” OR “indoor env* quali*” OR (light* OR lux OR luminosity OR visual) AND (acoustic OR sound OR decibel OR db) AND (“indoor air quality” OR iaq) OR (temperature AND humidity AND (gas OR pollution OR co2 OR voc OR tvoc OR pm) AND (“air speed” OR draft)))) AND (“neural network” OR “artificial intell*” OR “data mining” OR “digital twin” OR ((deep OR machine) PRE/1 learn*) OR (algorithm* OR model*)) AND (((thermostat OR window OR door OR opening OR duct* OR hvac OR fan OR vent* OR blind OR curtain OR shutter OR cover* OR sunshade OR shade OR screen OR heat* OR radiat* OR radiant OR *midifier OR boiler OR louvred OR shaft OR facade) W/1 (automat* OR control* OR mechaniz* OR actuat*)) AND (LIMIT-TO (PUBSTAGE, “final”)) AND (LIMIT-TO (LANGUAGE, “English”) OR LIMIT-TO (LANGUAGE, “Undefined”))

2.4 Selection Process

The selection process followed PRISMA guidelines and was conducted, using Rayyan [33], in two phases. First, titles and abstracts of all records retrieved from the database were screened against the inclusion and exclusion criteria. In this phase, clearly irrelevant records were excluded.

In the second phase, full-text articles of all potentially eligible studies were reviewed in detail. Each article was independently assessed by two reviewers. Disagreements were resolved through discussion, and when necessary, a third reviewer was consulted to reach consensus. This dual-reviewer strategy was applied to ensure consistency and reduce selection bias.

2.5 Data Collection Process

Data from each included article were extracted using a standardized data extraction form developed for this review. The form was pilot-tested on a small subset of studies and iteratively refined to ensure completeness and clarity.

The following data items were extracted from each study: bibliographic information (authors, year, title), type of building studied, control strategy employed, monitored IEQ parameters (e.g., temperature, CO₂, PM_{2.5}), type of algorithm or model used, evaluation metrics (e.g., energy savings, comfort improvement), and method of validation (simulation, laboratory, field).

All extracted data were entered into structured spreadsheets for further analysis and synthesis.

3 Results

3.1 Study Selection

A total of 30 studies were included in the final synthesis. The study selection process followed a structured screening protocol, combining automated and manual filtering techniques. Initially, a comprehensive database search yielded numerous records. After removing duplicates and irrelevant items, 67 studies were accessed for full-text reading.

From these, 37 studies were excluded after full-text analysis, primarily because they did not present results related to the application of control algorithms for Indoor Environmental Quality (IEQ). The remaining 30 studies met all eligibility criteria and were included in the final synthesis.

3.2 *Study Characteristics*

The 30 studies included in this review cover a wide range of algorithmic strategies applied to indoor environmental quality (IEQ) management in built environments. Most studies were published in the last five years, reflecting a growing research interest in intelligent control for energy efficiency and occupant well-being.

A majority of the studies focused on regulating thermal comfort and indoor air quality, either independently or in combination (e.g., maintaining classroom comfort while controlling CO₂ levels). Only a few addressed additional components such as visual comfort (daylighting) or noise; for instance, one study optimized daylight usage through automated blinds, another targeted combined thermal and lighting comfort, and none focused primarily on acoustic comfort.

Reinforcement learning (RL) algorithms (including Deep Q-Networks, Double DQN, and related variants) were the most frequently used approaches among the included studies. Other implemented control techniques included model predictive control (MPC), artificial neural networks (ANN), fuzzy logic, genetic algorithms, and various hybrid models that combine multiple techniques.

In terms of application context, the majority of studies relied on simulation-based evaluations, often using tools such as EnergyPlus, TRNSYS or CONTAM coupled with custom control scripts (e.g., in Python or MATLAB). Some studies employed co-simulation strategies, integrating detailed building physics models with data-driven controllers. Only a small subset of the research reported field validation with real-world sensor data or experimental testbeds.

The scenarios modeled in these works ranged from single-zone residential spaces to classrooms and multi-zone office environments, under climate conditions from temperate to hot-humid regions. Studies varied in modeling granularity: some focused on single-room thermal comfort, while others implemented multi-zone or occupant-adaptive control strategies.

3.3 *Risk of Bias in Studies*

Most of the included studies exhibit a moderate risk of bias, primarily due to the frequent use of simulation-based validation without real-world experiments. Several authors explicitly acknowledged methodological limitations in their work. For example, [29] highlighted that their reinforcement learning controller did not consider all external influencing factors, while [26] noted performance degradation under complex real-world visual conditions. Similarly, [15] observed that simple baseline controllers often ignored environmental disturbances, leading to optimistic evaluations of their proposed approach.

Selective reporting is also a concern, as nearly all included studies reported performance improvements without discussing failed scenarios or limitations in detail. No studies reported preregistration or blinded outcome assessment, increasing the

possibility of bias in outcome interpretation. These factors collectively lead us to assess the overall risk of bias as moderate across the included studies.

3.4 Results

All 30 included studies reported improvements in at least one aspect of indoor environmental quality (IEQ), most notably energy efficiency, thermal comfort, or indoor air quality (IAQ). Reinforcement learning (RL) strategies frequently outperformed rule-based and PID controllers, achieving 5–15% energy savings while maintaining CO₂ and temperature levels within comfort thresholds [12, 29]. For example, RL-based HVAC control reduced daily energy costs by up to 8.6% in winter and 7.9% in summer in residential settings.

Model Predictive Control (MPC) approaches demonstrated similar effectiveness. Adaptive MPC reduced HVAC energy use by up to 17% while ensuring CO₂ levels stayed below 600 ppm [12]. In real-world implementations, hierarchical MPC achieved energy savings exceeding 50% when compared to schedule-based systems [26].

Artificial Neural Network (ANN)-based and hybrid methods also delivered consistent results. Occupancy-based cooling using ANN models reduced energy use by 6.7%, while maintaining thermal comfort [26]. Optimized ventilation strategies kept CO₂ below 1000 ppm during most occupied hours and achieved 10–20% ventilation energy savings [29].

Across studies, outcome metrics included PMV indices, temperature tracking errors, CO₂ concentrations, and percentage energy savings. Some trade-offs were noted, such as increased cooling loads in daylight optimization scenarios [10], but annual performance generally remained favorable.

Although the results demonstrate strong potential for intelligent control strategies, methodological heterogeneity in validation methods, climate conditions, and building types, limits direct comparison. Few studies reported sensitivity analyses or robust statistical validation, highlighting the need for more standardized evaluation frameworks in future research.

4 Discussion

This systematic review mapped the landscape of smart IEQ management in residential buildings, revealing a prevalence of AI-driven solutions but also significant research gaps and methodological limitations. Key observations indicate an underexplored focus on holistic IEQ, particularly acoustic comfort and the integrated control of multiple IEQ parameters. Many studies lean heavily on simulation-based validation without robust real-world testing, and a notable heterogeneity in evaluation methodologies complicates comparative analysis of algorithmic performance. The

challenge of monitoring occupant-controlled elements like window openings further limits the precision of IEQ prediction and control model validation.

Addressing these issues requires overcoming substantial technical barriers. The development of effective multi-objective optimization algorithms that can dynamically balance often conflicting IEQ parameters (thermal, air quality, visual, acoustic) remains a critical hurdle. Furthermore, while AI, particularly ML, is central to many approaches, challenges concerning data requirements for training, model interpretability, scalability across diverse building stocks, and the need for comprehensive, low-cost sensing solutions persist.

These findings underscore clear implications for future research. There is an urgent need for:

- The design and rigorous real-world validation of integrated control strategies capable of managing multiple IEQ components holistically, moving beyond siloed approaches.
- The establishment of standardized evaluation frameworks, including common benchmarks, datasets, and performance metrics, to foster more direct comparability and cumulative progress in the field.
- A stronger emphasis on human-centric design, incorporating robust occupant behaviour modelling, direct feedback mechanisms, and advanced sensing for all influential IEQ factors, while addressing user acceptance and privacy.

In conclusion, while smart IEQ management shows considerable promise, advancing from potential to widespread practical impact necessitates focused interdisciplinary research. Addressing the identified gaps in holistic control, real-world validation, and methodological standardization is crucial for developing truly effective, occupant-centric, and energy-efficient residential environments.

5 Other Information

5.1 *Support*

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5.2 Competing Interests

The authors declare no competing interests. No author has any financial stake in companies or products related to smart windows, sensors, or BIM software that could have influenced the review.

References

1. Lopes MB, Kanama N, Poirier B, Guyot G, Ondarts M, Gonze E, Mendes N (2024) A numerical and experimental study to compare different IAQ-based smart ventilation techniques. *Buildings* 14(11). <https://doi.org/10.3390/buildings14113555>
2. Otoo C, Lu T, Lü X (2024) Application of mixed-mode ventilation to enhance indoor air quality and energy efficiency in school buildings. *Energies* 17(23). <https://doi.org/10.3390/en17236097>
3. Verma A, Prakash S, Kumar A, Aghamohammadi N (2022) A novel design approach for indoor environmental quality based on a multiagent system for intelligent buildings in a smart city: toward occupant's comfort. *Environ Prog Sustain Energy* 41(6). <https://doi.org/10.1002/ep.13895>
4. Shi S, Miyata S, Akashi Y (2025) Event-driven model-based optimal demand-controlled ventilation for multizone VAV systems: enhancing energy efficiency and indoor environmental. *Appl Energy* 377. <https://doi.org/10.1016/j.apenergy.2024.124683>
5. Cho J, Heo Y, Moon JW (2023) An intelligent HVAC control strategy for supplying comfortable and energy-efficient school environment. *Adv Eng Inf* 55. <https://doi.org/10.1016/j.aei.2023.101895>
6. Liu P, Justo Alonso M, Mathisen HM (2023) Global sensitivity analysis and optimal design of heat recovery ventilation for zero emission buildings. *Appl Energy* 329. <https://doi.org/10.1016/j.apenergy.2022.120237>
7. Hong X, Lin J, Yang X, Wang S, Shi F (2022) Comparative analysis of the daylight and building-energy performance of a double-skin facade system with multisectional shading devices of different control strategies. *J Energy Eng* 148(3). [https://doi.org/10.1061/\(ASCE\)EY.1943-7897.0000828](https://doi.org/10.1061/(ASCE)EY.1943-7897.0000828)
8. Zhu H-C, Ren C, Cao S-J (2022) Dynamic sensing and control system using artificial intelligent techniques for non-uniform indoor environment. *Build Environ* 226. <https://doi.org/10.1016/j.buildenv.2022.109702>
9. Wang X, Dong B (2023) Physics-informed hierarchical data-driven predictive control for building HVAC systems to achieve energy and health nexus. *Energy Build* 291. <https://doi.org/10.1016/j.enbuild.2023.113088>
10. Yang T, Zhao L, Li W, Wu J, Zomaya AY (2021) Towards healthy and cost-effective indoor environment management in smart homes: a deep reinforcement learning approach. *Appl Energy* 300. <https://doi.org/10.1016/j.apenergy.2021.117335>
11. Wang G, Yu Y, Zhang C (2024) Optimization control strategy for transition season blinds balancing daylighting, thermal discomfort, and energy efficiency. *Energies* 17(7). <https://doi.org/10.3390/en17071543>
12. Afroz Z, Shafiullah GM, Urmee T, Shoeb MA, Higgins G (2022) Predictive modelling and optimization of HVAC systems using neural network and particle swarm optimization algorithm. *Build Environ* 209. <https://doi.org/10.1016/j.buildenv.2021.108681>
13. Grygierek K, Nateghi S, Ferdyn-Grygierek J, Kaczmarczyk J (2023) Controlling and limiting infection risk, thermal discomfort, and low indoor air quality in a classroom through natural ventilation controlled by smart windows. *Energies* 16(2). <https://doi.org/10.3390/en16020592>

14. Yu MG, Pavlak GS (2022) Extracting interpretable building control rules from multi-objective model predictive control data sets. *Energy* 240. <https://doi.org/10.1016/j.energy.2021.122691>
15. Kim SH, Moon HJ (2023) The performance of reinforcement learning for indoor climate control devices according to the level of outdoor air particulate matters. *Buildings* 13(12). <https://doi.org/10.3390/buildings13123062>
16. Kim NK, Kang DH, Lee W, Kang HW (2021) Airflow pattern control using artificial intelligence for effective removal of indoor airborne hazardous materials. *Build Environ* 204. <https://doi.org/10.1016/j.buildenv.2021.108148>
17. Zhan J, He W, Huang J (2023) Dual-objective building retrofit optimization under competing priorities using artificial neural network. *J Build Eng* 70. <https://doi.org/10.1016/j.jobe.2023.106376>
18. Chauhan H, Jang Y, Pradhan S, Moon H (2023) Personalized optimal room temperature and illuminance for maximizing occupant's mental task performance using physiological data. *J Build Eng* 78. <https://doi.org/10.1016/j.jobe.2023.107757>
19. Wang X, Dong B (2024) Long-term experimental evaluation and comparison of advanced controls for HVAC systems. *Appl Energy* 371. <https://doi.org/10.1016/j.apenergy.2024.123706>
20. Li L, Bao R, Cai H, Zhang X, Yin Z (2024) A novel air balancing method based on an improved perceptron under multiple constraints for the energy conservation of ventilation system. *Build Environ* 248. <https://doi.org/10.1016/j.buildenv.2023.111115>
21. Ren C, Cao S-J (2019) Development and application of linear ventilation and temperature models for indoor environmental prediction and HVAC systems control. *Sustain Cities Soc* 51. <https://doi.org/10.1016/j.scs.2019.101673>
22. Fan Y, Ito K (2014) Optimization of indoor environmental quality and ventilation load in office space by multilevel coupling of building energy simulation and computational fluid dynamics. *Build Simul* 7(6):649–659. <https://doi.org/10.1007/s12273-014-0178-3>
23. Kim H, Hong T, Kim J (2019) Automatic ventilation control algorithm considering the indoor environmental quality factors and occupant ventilation behavior using a logistic regression model. *Build Environ* 153:46–59. <https://doi.org/10.1016/j.buildenv.2019.02.032>
24. Wang Y, Kuckelkorn JM, Li D, Du J (2019) A novel coupling control with decision-maker and pid controller for minimizing heating energy consumption and ensuring indoor environmental. *J Build Phys* 43(1):22–45. <https://doi.org/10.1177/1744259118792582>
25. Chen X, Yang H, Sun K (2016) A holistic passive design approach to optimize indoor environmental quality of a typical residential building in hong kong. *Energy* 113:267–281. <https://doi.org/10.1016/j.energy.2016.07.058>
26. Meng Y-B, Li T-Y, Liu G-H, Xu S-J, Ji T (2020) Real-time dynamic estimation of occupancy load and an air-conditioning predictive control method based on image information fusion. *Build Environ* 173. <https://doi.org/10.1016/j.buildenv.2020.106741>
27. Zhu H-C, Ren C, Cao S-J (2021) Fast prediction for multi-parameters (concentration, temperature and humidity) of indoor environment towards the online control of hvac system. *Build Simul* 14(3):649–665. <https://doi.org/10.1007/s12273-020-0709-z>
28. Ahn J (2021) Abatement of the increases in cooling energy use during a period of intense heat by a network-based adaptive controller. *Sustainability* 13(3):1–17. <https://doi.org/10.3390/su13031353>
29. Xu X, Fu B, Wu Z, Sun G (2021) Predictive control for indoor environment based on thermal adaptation. *Sci Prog* 104(2). <https://doi.org/10.1177/00368504211006971>
30. Mahdy M, Fahmy A, El-Dabaa R (2025) A multi-objective optimization for passive adaptive envelope integrating smart materials. *Civil Eng Arch* 13(2):794–812. <https://doi.org/10.13189/cea.2025.130204>
31. Aria M, Cuccurullo C (2017) Bibliometrix: an r-tool for comprehensive science mapping analysis. *J Informet* 11(4):959–975. <https://doi.org/10.1016/j.joi.2017.08.007>
32. VOSviewer. <https://www.vosviewer.com/>
33. Rayyan. <https://new.rayyan.ai/>

Social Housing Regeneration: Qualifying and Making Sustainable Buildings and Public Spaces. A Case Study



Monica Misceo, Francesco Rotondo, Antonio Di Micco, Salvatore Tamburrino, Gaia Pascucci, Michele Parrotta, Tiziano Bibbò, and Vincenzo Loverre

Abstract This paper discusses an energy upgrading on a social housing building in Margherita di Savoia, a small town in the Puglia Region, Italy, and the relationship with urban heating island. The building is one of the pilot sites of the REHOUSE project (funded by Horizon Europe Programme), specifically located in the “Capitanata Zone” considered one of the most socially vulnerable areas. An energy diagnosis was performed to assess the initial energy condition of the building. The objective is to define a baseline consumption, to be used for the evaluation of the energy improvement interventions modelling innovative technology with TRL5. In this way, actions on the envelope and actions on thermal and electrical systems can be defined. Energy efficiency measures are planned on the building envelope and the heating system one. An innovative centralized system will be built using a thermal stratified storage tank. The starting point was the creation of the BIM model of the DEMO building in Margherita di Savoia. This procedure required the validation of the numerical model, in fact, an appropriate calibration of the consumption of both energy carriers was carried out. Building redevelopment becomes a tool for urban redevelopment through the study of the effects of soil desealing of the areas surrounding the building, their greening and the use of certain materials and colors on the facades of the building to limit the negative consequences of phenomena

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such as the heat island. The final objective of the work is to understand which types of building interventions and on the open spaces surrounding the building are the minimum necessary to reach the standards of energy efficiency of buildings required by the European Union.

Keywords Energy efficiency · Urban Heat Island (UHI) · Social housing

1 Introduction

1.1 *Building Energy Renovation and Urban Regeneration*

The buildings energy renovation is a key point of energy policies, as buildings in Europe account for 40% of final energy use and 36% of greenhouse gas emissions related to energy. Additionally, around 75% of buildings are considered inefficient.

Acting on social housing is a strategic way to reach people in energy poverty. These buildings are often 40–50 years [1] old and were built in a historical period with different socio-economic needs and different societal ideals. The article proposes a case study of social housing renovations and how it impacts on neighborhood in terms of Urban Heat Island. The case study of Margherita di Savoia is the pilot case of the REHOSUE (Renovation packagEs for HOListic improvement of EU's bUildingS Efficiency) project, funded by Horizon Europe research Program aims to design and demonstrate, in an operational environment, innovative energy technologies called Renovation Packages. Over the four years of the project, eight innovative and holistic solutions are applying, and by demonstrating their validity in efficient, cost-effective, and sustainable renovation processes, they are moving from a TRL (Technology Readiness Level) of 4/5 to a TRL 8.

The building of the pilot case is located an area faces significant socioeconomic challenges, with socially vulnerable communities. The area around the building is characterized by the lack of accessible meeting areas and green spaces exacerbates social isolation. Improving shared spaces through urban regeneration strategies can enhance both social cohesion and climate resilience, reinforcing the connection between environmental sustainability and social inclusion [2]. Two innovative renovation packages, using off-site construction approach, are designed and applied to a social housing reinforced concrete demonstration building located in Margherita di Savoia (Apulia region, Italy). The renovation packages consist of (i) an ESO-skeleton with multipurpose façade able to provide thermal insulation (using sustainable materials) and renewable energy production through PV colored panels, also able to give a new aesthetic look to the building and (ii) an efficient heat pump system to provide heating, cooling and DHW minimizing energy consumption and increasing the living comfort. While the renovation packages are being developed by some of the project partners, a careful seismic assessment and retrofit is carried out along with a social mediation toward the building tenants to explain the needs of

the assessment process and the purposes of the interventions that will be carried out while listening inhabitants' needs [3]. Paying attention to social aspects also means that all the structural investigations needed to gather the necessary knowledge about the structure are made through low impact activities, for example, avoiding making destructive investigations inside the apartments.

2 Model Description

The energy audit was carried out through an analysis of the actual consumption in the current state of the building-plant system. The objective is to define a baseline consumption, to be used for the evaluation of the energy improvement interventions. In this way, actions on the envelope and on thermal and electrical systems can be defined. These actions can be completed through monitoring systems and integrated with renewable sources. The energy audit has been carried out using TerMus BIM tool (ACCA 2024), a commercial software. The starting point was the creation of the BIM model of the IDSB. In Fig. 1, the three-dimensional model created is shown, in the initial and design conditions. All apartments are supplied with an independent heating system. Five dwellings have a condensing boiler, while the remaining units have a standard boiler. Three apartments have an air conditioning system with heat pump. It can also be used as a heating system. No thermostats or building automation and control devices are present.

It is planned to create thermal insulation of the building envelope, replacing the external windows and doors, providing the building with energy autonomy by energy production systems from renewable sources (Vertical PV panels) and introducing a centralized thermal generation system based on innovative storage technologies, protected by patent. Therefore, to calibrate the model, a consumption analysis was carried out, acting, for each apartment, on the turn-on period of the winter and summer air conditioning systems, as in Fig. 2.

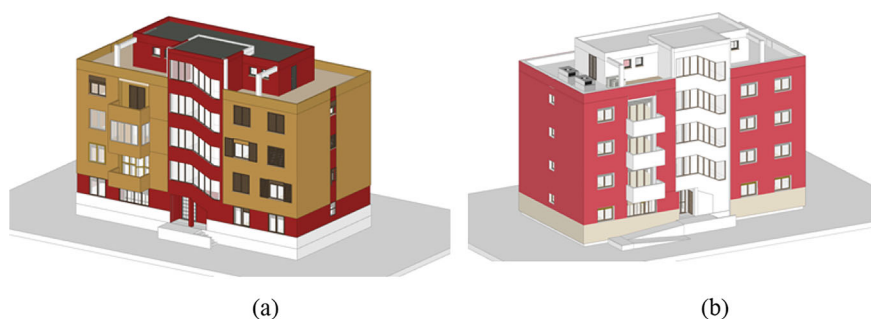


Fig. 1 The three-dimensional model: **a** initial condition and **b** design condition (extracted from TerMus BIM software)

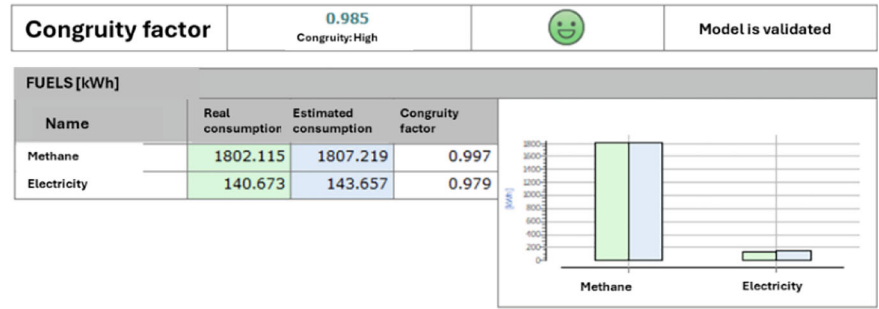


Fig. 2 Validation model

2.1 Smart Thermal Energy Hub System

One of the innovative solutions tested in the demo site deals with the heating/cooling/ DHW system (Smart Thermal Energy Hub). The heating system will be changed: now each apartment has a single boiler, at the end of the renovation process a centralized heating system will be installed, and two boilers will be positioned on the roof. The final energy consumption must remain below the annual energy production of the façade-integrated photovoltaic system, also implemented within the REHouse project. The innovation consists of installing a Smart Thermal Energy Hub constituted by two thermal energy storage tanks using Phase Change Materials (PCMs) of a nominal storage energy of 35 kWh developed and manufactured by Steel Tech srl, coupled with a pair of commercially available high temperature Water-to-Water (W2W) heat pumps of nominal power of 30 kW each. The decision to install dual storage tanks and heat pumps was made to ensure redundancy and enhance reliability. To guarantee service continuity, particularly during the experimental phase which may involve interruptions of the innovative part of the system, a centralized condensing boiler will be installed. The beforementioned Smart Thermal Energy Hub has seven internal layers with differentiated temperatures (4°, 8°, 23°, 37°, 48°, 58°, 68°), operating either as a source or a sink depending on energy demand and the heat pump’s operational state, according to the control logic. The reverse process occurs when cooling is required. The heating system will continue to utilize the existing radiators, now equipped with thermostatic radiator valves, as the emission system, whereas cooling emission will be provided by four ceiling-mounted fan coil units per apartment. The system is therefore distinguished by the use of heat pumps that do not utilize external air as a heat source, but rather the thermal energy contained within the water and PCMs allocated in the tanks. These are commercially available W2W high temperature (up to 85 °C) heat pumps specifically selected for their technical characteristics, suitable for operation in combination with the proposed Smart Energy Hub System based on PCM. Furthermore, the system will be equipped with dry-coolers that, in the event of excessive and prolonged demand for thermal energy from users, exchange energy between the ‘source layers’ within the tanks and the

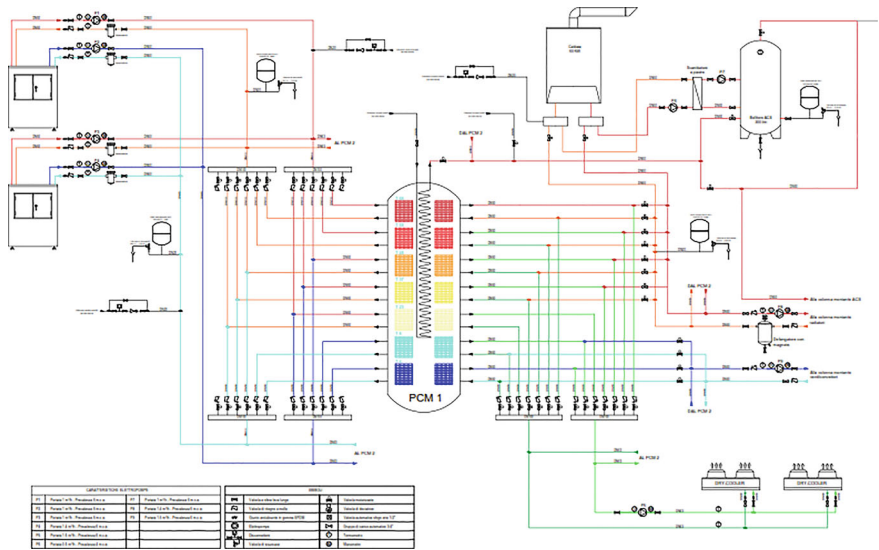


Fig. 3 Boiler diagram

external environment. The entire heating system will be automatically managed and monitored by control systems governed by algorithms that will be optimized during the experimental phase to maximize efficiency. Figure 3 shows a schematic diagram of the central heating system as envisioned during the detailed design phase. The Smart Thermal Energy Hub system provide all the required DHW with an energy efficient way of gradually heating from 23 °C layer up to 68 °C. To eliminate on of the many limits of the centralized DHW, the need of a recirculation system to avoid having more than 30 s for the hot water release, additional 40-L nominal capacity PCM storage tanks are planned within the apartments. This measure ensures an almost immediate supply of DHW, and the PCM has a function of self-recharging when the centralized hot water cross the local tank, helping to reduce water and electricity waste. Such waste of energy for loss and recirculation is a typical problem in centralized systems that use recirculation.

2.2 Results and Discussion

To assess the benefits achievable through energy efficiency measures, an energy diagnosis was carried out, taking into account five different improvement scenario, which are listed as follows: scenario A: Insulation of opaque surfaces and replacement of window frames; scenario B: Insulation of opaque surfaces, replacement of fixtures plus Installation of photovoltaic system; scenario C: Replacement of the central

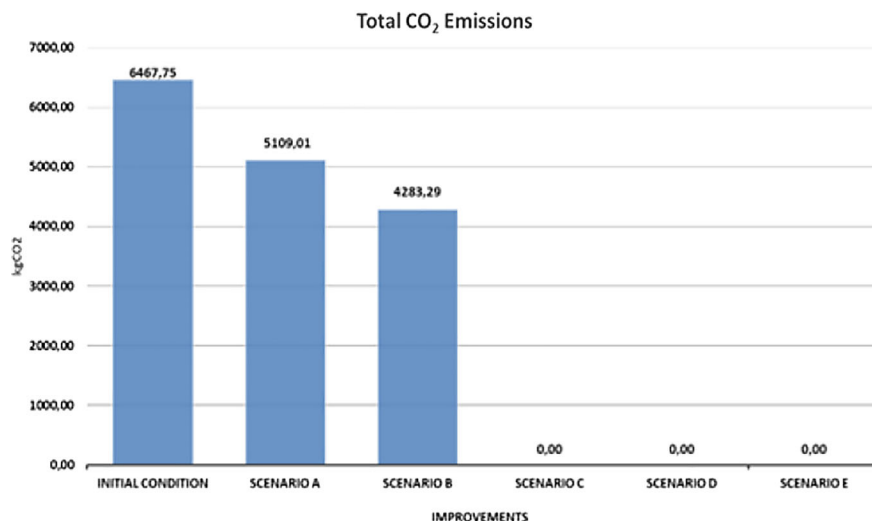


Fig. 4 Total CO₂ emissions

heating plant; scenario D: Replacement of thermal power plant plus Installation of photovoltaic system; scenario E: scenario that includes all improvements.

Figure 4 shows the total CO₂ emissions: as the energy efficiency of the building improves, CO₂ emissions drop dramatically. Even for scenario C, which involves the total replacement of the heating system, it can be observed that CO₂ emissions are zero.

In Fig. 5, it can be noted that the configuration requiring the highest primary energy demand is scenario C. This is due to the new thermal power plant, which provides cooling service to all 8 units that make up the entire building. From the initial condition, in fact, only three residential units (apartments) have summer air conditioning. As designed, the configuration that requires less primary energy demand is scenario E, which includes all the improvements.

In Fig. 6, which shows the energy classes for each of the scenarios considered, it is verified, as expected, that the building's energy efficiency improves with the implementation of the proposed energy efficiency enhancements. It is shown that due to the replacement of the thermal power plant and the installation of photovoltaics, scenario D, the building reaches energy class A4. However, the building achieves nZEB status only by performing all the proposed design improvements.

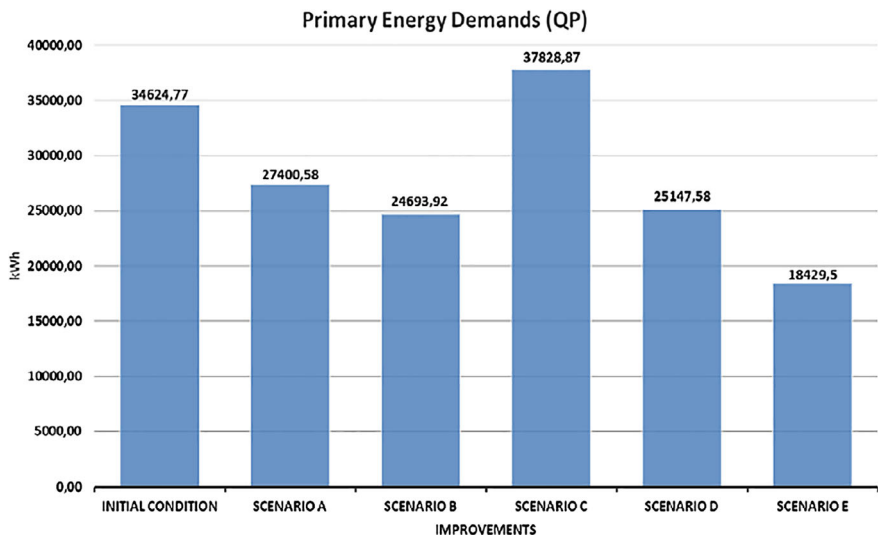


Fig. 5 Primary energy demands

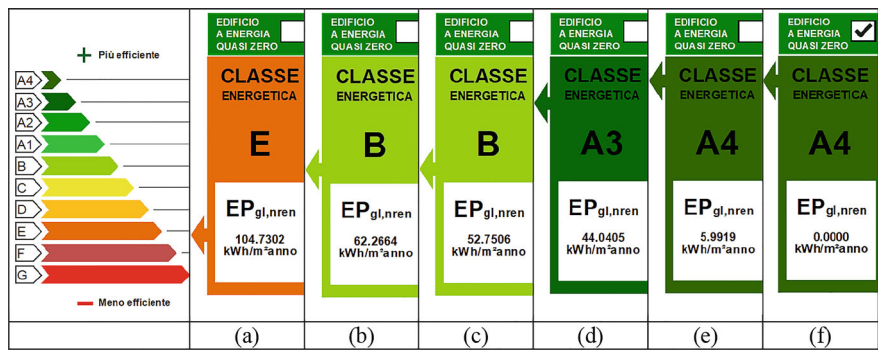


Fig. 6 Energy classes: a initial condition; b scenario A; c scenario B; d scenario C; e scenario D; f scenario E

3 Urban Heat Island (UHI) Effect on the Case Study

One of the most critical issues impacting residents’ health and well-being is the Urban Heat Island (UHI) effect. The increasing number of heat-related deaths in Italy underscores the urgency of addressing urban microclimate conditions, particularly in highly exposed areas like the case study site, where extreme summer temperatures pose a significant risk to its inhabitants [4]. Consequently, alongside energy requalification studies for the building, simulations on the urban microclimate were conducted using the LITE version of ENVI-met, a high-resolution 3D microclimate simulation tool. This software employs a Computational Fluid Dynamics (CFD) model

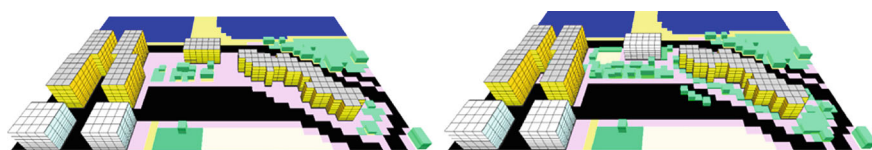


Fig. 7 Model area created with ENVI-met Spaces. As-built scenario (left) and the scenario after building and area renovations (right)

to analyze interactions between buildings, vegetation, and atmospheric conditions. Site-specific materials were stored, and a model area was created (Fig. 7).

One limitation of CFD software is its long calculation time (ten hours in this case). To optimize the study, a representative day from the hottest month—July—was selected. This day was identified by analyzing hourly air temperature data from 2020 to 2024, choosing the one with the smallest sum of the hourly root means square deviations of air temperature (representative day technique) [5]. In the simulation settings, climate data from July 21st, 2022, were entered, and the model was run for ten hours, from 10:00 to 20:00. Results from 15:00 were selected for analysis. The potential air temperature surrounding the building ranged from a minimum of 26.94 °C in the salt pan area to a maximum of 35.65 °C, with values above 30 °C corresponding mostly to cemented areas. Relative humidity varied inversely, between 29.28 and 53.85%. Another crucial parameter for assessing thermal comfort is the mean radiant temperature, which ranged from a minimum of 32.81 °C (in shaded areas) to a maximum of 78.79 °C, particularly in the southern parts of the buildings. Combined with wind velocity and two thermo-physiological factors (clothing and human activity level), these parameters contribute to calculating the PET (Physiological Equivalent Temperature) index, one of the most widely used metrics for outdoor thermal comfort assessment [6]. The PET values ranged from 32.04 to 58.71 °C, mirroring the mean radiant temperature distribution. A second simulation was conducted, modifying the characteristics of the walls and roof of the ReHouse building according to Renovation Package 05: Multipurpose Façade System with Bio-Based Insulation and BIPV. Consequently, the absorption coefficient of the walls drastically increases, the reflection coefficient decreases, and emissivity slightly decreases due to the material changes, replacing yellow plaster with photovoltaic panels. Comparing the two scenarios, it was observed that material modifications led to a slight overall increase in potential air temperature, a slight decrease in relative humidity, and a notable reduction in mean radiant temperature, particularly along the building's southern wall. However, on the northwest side, the mean radiant temperature increased. As previously mentioned, these factors contribute to the PET index (Fig. 8). These results align with the changes in the building materials: the increase in absorption coefficient, combined with the decrease in thermal conductivity and density, leads to higher surface temperatures but reduced heat storage and reduced delayed heat release. During the daytime, the calculated potential air temperature is higher, but it is expected to be lower at night. The simulation runs only until 10:00 PM, and the beginning of this inverse trend can already be observed in the final hour. Higher

surface temperatures may contribute to localized warming, but this heat is not deeply stored within the material. The mean radiant temperature, instead, decreases on the southern façade due to the low reflectivity of the solar panels. On the northwest side, however, it follows the trend of the potential air temperature: during daily hours it's higher, but by the last hour of the simulation (10:00 PM), it becomes equal to or lower than in the initial scenario. Finally, the PET index follows the same pattern, as at 10:00 PM it decreases (or remains equal) all around the building. The third simulation included added vegetation, green spaces, and permeable pavements around the ReHouse building and nearby structures (Fig. 8, right). Comparing the as-built scenario to this greener version, some considerations can be made. The potential air temperature difference during daytime remains negative around the ReHouse building: the greening intervention is not sufficient to fully compensate for the heat emission from the building materials. However, the minimum values in the two scenarios show a slight mitigation of this phenomenon thanks to the vegetation. In the surrounding areas, lower temperatures are observed. Relative humidity shows a similar behaviour: vegetation mitigates the increase in relative humidity around the building (due to the change in materials) and reduces relative humidity in the surrounding area. The mean radiant temperature difference shows some peaks of both decrease and increase near the green areas. Vegetation interacting with solar radiation and other urban reflective surfaces can increase the complexity of the calculation, resulting in a heterogeneous spatial distribution of MRT [7], but an overall reduction was noted. Finally, the PET index shows a similar trend to MRT (in terms of peaks), but with evident improvements in thermal comfort (Fig. 9).

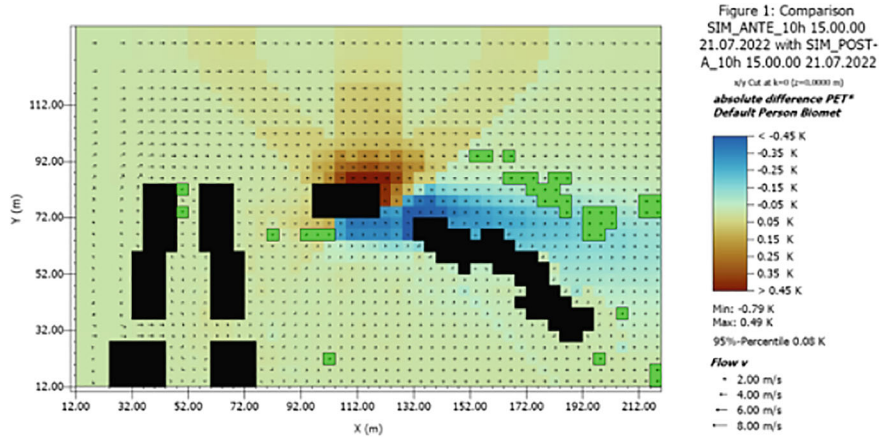


Fig. 8 PET index variation after the renovation of the building

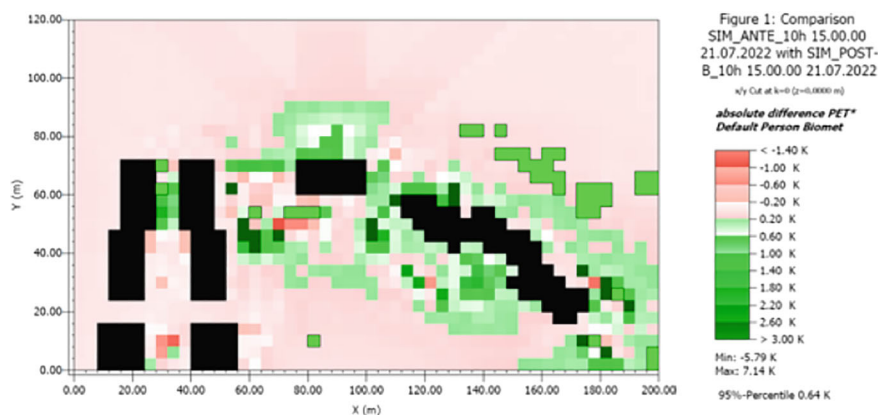


Fig. 9 PET index variation after the building and area renovations

4 Conclusions

Energy poverty has now been recognized as being on a par with other forms of social hardship that need to be prevented and treated. Meeting the ambitious goals that Europe has set with the EPBD, while it may be difficult for homeowners who do not live in particular conditions of economic and social hardship, becomes even more complicated for those who live in poverty. For this reason, as already highlighted by other authors [8–11], identifying low-cost ways to increase the energy efficiency of a building stock built mainly after the Second World War and now obsolete, both from a structural point of view and even more so from an energy efficiency point of view, becomes a significant research and development objective. After an initial phase dedicated to the energy audit, essential for understanding the functioning of the building both in terms of dispersion from the external envelope and in terms of efficiency in the production and use of energy sources, the research objective has been to define a baseline consumption, to be used for the evaluation of the energy improvement interventions modelling innovative technology with TRL5. So, energy efficiency measures have been tested on the building envelope and the heating system one. An innovative centralized system has been built using a thermal stratified storage tank, the Smart Thermal Energy Hub. Using these solutions the benefits achievable through energy efficiency measures have been assessed, taking into account five different improvement scenarios, where the last one includes all improvements. It has been observed that CO₂ emissions are zero and it is shown that due to the replacement of the thermal power plant and with the installation of photovoltaics, in the scenario D, the building reaches energy class A4, but the building achieves nZEB status only by performing all the proposed design improvements in the last scenario E. After reaching a possible satisfactory solution with respect to the building's performance, its relationship with the external areas was investigated to understand the relationship between the interventions on the building's skin, the

insertion of greenery in the external parts, currently mainly made of waterproof materials, with respect to the heat island phenomenon. As already known in literature, favoring green developments can have positive effect also for the health of the population by providing places favorable for the protection of ultraviolet radiation and adapted to the practice of physical activity, in addition to the improvement of air quality [12–14]. Also in this case, different scenarios have been produced in which, in fact, results show a slight mitigation of the heat island phenomenon due to vegetation. Lower temperatures are observed in the surrounding areas. The mean radiant temperature difference shows some peaks of both decrease and increase in proximity to green areas. The changes in the building materials have shown the increase in absorption coefficient, combined with the decrease in thermal conductivity and density, leads to higher surface temperatures but reduced heat storage and reduced delayed heat release. These results need to be integrated with further analyses of external conditions starting from the trend of winds or the dimensions of the spaces compared with those of the surfaces of the buildings overlooking such spaces to better understand where it can be more productive to increase efforts. Rethinking the significant quantity of public housing buildings existing today in Italy as well as in other European nations certainly means rethinking the performances offered by these buildings, but without limiting ourselves to the intervention on the single building but taking advantage of transforming these interventions into opportunities for urban regeneration.

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References

1. Schuurmans A, Dyrbøl S, Guay F (2018) Building in buildings in urban regeneration. In: Urban regeneration-chapter. IntechOpen. <https://doi.org/10.5772/intechopen.81803>
2. Misceo M, Amato A, Diana M, Di Micco A, Sposato P, Tamburrino S (2023) Technical and social innovation actions in social housing: a pilot case in the South of Italy. In: BEHAVE 2023. Maastricht
3. Santarsiero G, Misceo M, Aversa P, Candigliota E, Di Micco A, Hugony F, Manfredi V, Marghella G, Marzo A, Masi A et al (2024) Holistic assessment for social housing retrofitting: integrating seismic, energy, and social aspects in the REHOUSE Project. *Buildings* 14:3659. <https://doi.org/10.3390/buildings14113659>
4. Harlan SL, Ruddell DB (2013) Neighborhood effects on heat deaths: social and environmental predictors of vulnerability in Maricopa County, Arizona. *Environ Health Perspect* 121(2):197–204. <https://doi.org/10.1289/ehp.1104625>
5. Tirabassi T, Rizza C (2005) The representative day technique in the study of photochemical smog pollution in falconara industrial area. *Water Air Soil Pollut* 65–81
6. Taleghani M, Sailor DJ, Wellenius G (2016) Micrometeorological simulations to predict the impacts of heat mitigation strategies on pedestrian thermal comfort in a Los Angeles neighborhood. *Environ Res Lett* 11(2):024003. <https://doi.org/10.1088/1748-9326/11/2/024003>

7. Sinsel T, Simon H, Ouyang W, Dos Santos Gusson C, Shinzato P, Bruse M (2022) Implementation and evaluation of mean radiant temperature schemes in the microclimate model ENVI-met. *Urban Clim* 45:101279. <https://doi.org/10.1016/j.uclim.2022.101279>
8. Ascione F, De Rossi F, Iovane T, Manniti G, Mastellone M (2024) Energy demand and air quality in social housing buildings: a novel critical review. *Energy Build* 319:1–24
9. Diaz Lozano Patino E, Siegel JA (2018) Indoor environmental quality in social housing: a literature review. *Build Environ* 131:231–241
10. Hernández-Cruz P, Uriarte I, Hidalgo-Betanzos JM, Antepara I, Flores-Abascal I (2023) A novel strategy to guarantee a minimum indoor temperature in social housing buildings. *J Build Eng* 76
11. Canale L, Ficco G, Bertini I, Dell’Isola M (2023) About the effect of tailored energy feedback on space heating consumption and indoor air temperature in social housing buildings: an experimental investigation. *Energy Build* 292
12. Bahi H, Radoine H, Mastouri H (2019) Urban heat island: state of the art. In: 7th international renewable and sustainable energy conference (IRSEC). Agadir, Morocco, pp 1–7
13. El-Hakim RA, El-Badawy S (2020) Quantifying effects of urban heat islands: state of the art. In: Badawy S, Chen DH (eds) *Recent developments in pavement engineering*. GeoMEast. Sustainable Civil Infrastructures. Springer, Cham
14. Tehrani AA, Veisi O, Kia H, Delavar Y, Bahrami S, Sobhaninia S, Mehan A (2024) Predicting urban heat island in European cities: a comparative study of GRU, DNN, and ANN models using urban morphological variables. *Urban Clim* 56:1–27

Positive Energy Districts as Contributors to Enhancing Sustainability Pillars in Social Housing Neighbourhoods



Fernanda Rodrigues , Mehrnaz Zargarzadeh , José Carlos da Mota ,
and Paulo Silva 

Abstract Urban areas account for approximately 70% of global energy consumption and CO₂ emissions, making them major contributors to climate change and key targets for mitigation. Transitioning to decentralized, sustainable energy systems is essential for achieving climate and sustainability goals, including the Sustainable Development Goals (SDGs) on clean energy (SDG 7), sustainable cities (SDG 11), and climate action (SDG 13). Policy frameworks such as the European Green Deal and Sustainable Energy Action Plans (SEAPs), alongside Zero Energy and Zero Emissions Buildings (ZEBs) and Positive Energy Districts (PEDs), are driving urban energy transitions. PEDs offer a transformative approach to decarbonization by generating more renewable energy than they consume, achieving a net-positive energy balance. By integrating energy, mobility, and information and communication technology (ICT), they enhance environmental performance, alleviate energy poverty, foster social inclusion, and strengthen local economies. This study expands the conventional energy focus of PEDs by incorporating social and economic resilience as key sustainability components. Despite their potential, PED implementation faces challenges, including infrastructure retrofitting, regulatory fragmentation, financial barriers, and limited public participation. This study systematically reviews a decade of PED research, using the Paris Agreement as a milestone in global climate action. It examines PEDs' evolution, identifies research gaps, and explores their relationship with social housing. While PEDs are well-connected to energy transition and smart cities, their links to social housing, energy poverty, and equity remain weak. The findings underscore the need for further interdisciplinary research to bridge this gap and ensure PEDs contribute to inclusive, sustainable urban development.

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Keywords Positive Energy Districts (PEDs) · Sustainability · Social housing

1 Introduction

Urban areas account for over two-thirds of global energy consumption and more than 70% of annual global carbon emissions, making them key contributors to climate change and high-priority targets for mitigation [1]. With urban populations expected to grow from 55% today to 68% by 2050, the demand for sustainable and efficient energy solutions is increasingly urgent [2]. However, the global energy sector remains dependent on fossil fuels, which still supply over 80% of total energy consumption, driving greenhouse gas emissions and environmental degradation [3].

A major share of urban energy demand comes from buildings, which account for 40% of the EU's total energy consumption and 36% of emissions [4]. Inefficient insulation, heating, and cooling systems lead to significant energy waste at the building level, while the transportation sector further exacerbates air pollution and urban heat effects. These challenges underscore the urgent need for a transition to renewable energy, improved efficiency, and modernized infrastructure, requiring coordinated policies, technological innovation, and international collaboration.

To address these challenges, international and national policies aim to accelerate the clean energy transition. The Paris Agreement, under the United Nations Framework Convention on Climate Change (UNFCCC), provides a global framework for reducing greenhouse gas emissions, reinforced by the Kyoto Protocol, SDG Goal 7 (clean energy), and Goal 13 (climate action). Climate summits such as COP27 and COP28 further emphasize decarbonization, while organizations such as the International Energy Agency (IEA) and the International Renewable Energy Agency (IRENA) support this transition through initiatives such as the IEA's Clean Energy Transitions Program [5, 6]. At the European level, the European Green Deal establishes a long-term strategy for carbon neutrality by 2050, supported by the Fit for 55 Package (2021), which mandates a legally binding 55% reduction in GHG emissions by 2030 (compared to 1990 levels). The Clean Energy Package (2019) promotes energy efficiency and decentralized energy systems, while the Renewable Energy Directive (RED II) sets a target of 42.5% renewable energy by 2030. Recognizing the significant impact of buildings on energy consumption, the Energy Performance of Buildings Directive (EPBD) aims for a climate-neutral building stock by 2050, and REPowerEU (2022) enhances energy security and reduces fossil fuel dependence. However, regulatory inconsistencies across EU member states hinder uniform implementation, requiring stronger policy coordination [7].

National policies align with EU goals but remain fragmented. Spain's self-consumption regulations, Italy's Renewable Energy Communities (RECs), and France's Energy Transition for Green Growth Act (LTECV), SNBC (Stratégie Nationale Bas-Carbone),¹ and MEP (Multiannual Energy Plan or Programmation

¹ National Low-Carbon Strategy.

Pluriannuelle de l'Énergie, PPE)² all target carbon neutrality by 2050. Despite these initiatives, policy fragmentation and regulatory disparities continue to slow large-scale renewable energy deployment, highlighting the need for improved cross-border coordination [8].

One innovative strategy for achieving urban energy sustainability is the development of Positive Energy Districts (PEDs), which aim to generate more renewable energy than they consume. PEDs integrate decentralized energy systems, smart infrastructure, and high-efficiency technologies, contributing to climate-neutral cities and improved energy resilience. The EU has set a target of developing 100 PEDs by 2025 as part of its 100 Climate-Neutral Cities by 2030 initiative [9]. Unlike Net-Zero Energy Districts (NZEDs), which focus solely on balancing annual energy consumption, PEDs prioritize real-time flexibility, surplus energy generation, and decentralized grid solutions [10]. Beyond their environmental benefits, PEDs also enhance economic resilience, lower operational costs, and promote social sustainability through inclusive energy access and sustainable mobility [11]. Despite their potential, PEDs remain in early stages of implementation and require further research and financial support, particularly from EU programs like Horizon 2020 [12].

A key area where PEDs could have a transformative impact is in social housing, which provides affordable housing for low-income and vulnerable populations but often suffers from poor energy efficiency, resulting in high utility costs, greater energy poverty, and reduced indoor comfort [13]. Social housing represents approximately 6% of the EU and OECD housing stock (~ 28 million homes), yet many units lack modern energy infrastructure, leading to high utility costs and inadequate indoor comfort levels. Although energy retrofitting has improved efficiency, rising electricity costs often offset anticipated savings, leaving energy poverty a persistent issue. By applying PED principles, social housing can benefit from enhanced insulation, energy-efficient heating and cooling systems, and decentralized renewable energy generation, reducing dependence on centralized grids and reducing energy poverty [14]. European projects, such as those in Portugal (e.g., POCITYF in Évora), Germany (e.g., Sparcs in Leipzig), and Spain (e.g., Atelier in Bilbao), demonstrate the feasibility of PED integration in social housing, yet further policy advancements and research are needed to enable large-scale adoption [15].

This study systematically examines the role of Positive Energy Districts (PEDs) in enhancing the three pillars of sustainability—environmental, economic, and social—within social housing neighborhoods. It analyzes the evolution of PED research from 2015 to 2025, identifies key research gaps, and explores their relationship with social housing. Additionally, it evaluates PEDs' potential to drive urban resilience, energy transitions, and inclusive development while addressing critical barriers such as financial constraints, regulatory challenges, and technological limitations.

² France's Multiannual Energy Plan.

Table 1 Keywords and search terms

Keywords	Search terms
Positive Energy Districts	((Positive Energy) AND (Neighbourhood* OR District*or Community*) OR (PED*))
Social housing	(Social Housing OR Affordable Housing OR Low-Income Housing)
Sustainability	(Sustainab*)

2 Materials and Methods

2.1 Systematic Review and Bibliometric Analysis

This study employs the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework to conduct a systematic review [16], complemented by bibliometric analysis and text mining using VOSviewer.³ Developed by CWTS at Leiden University, VOSviewer enables bibliometric mapping, clustering, and research trend visualization. Its compatibility with multiple bibliographic databases ensures comprehensive analysis, while advanced visualization tools enhance readability by managing large datasets and minimizing label overlap [17].

To ensure comprehensive analysis of PEDs, social housing, and sustainability, peer-reviewed publications were retrieved from the Web of Science (WOS) database, chosen for its extensive academic coverage. The search terms (Table 1) were formulated using Boolean operators (AND/OR) to optimize the retrieval process:

((Positive Energy) AND (Neighbourhood* OR District*or Community*) OR (PED*)) OR (Social Housing OR Affordable Housing OR Low-Income Housing) AND (Sustainab*)).

Publications were included if they were peer-reviewed journal articles or books in English, published between 2015 and 2025, aligning with the Paris Agreement's influence on sustainable urban policies. The initial filter applied was Web of Science Categories, selecting studies classified under Green and Sustainable Science and Technology, Energy and Fuels, Urban Studies, Regional and Urban Planning, or Rehabilitation. Additional filters were applied as follows:

- Meso level: Sustainability science, energy systems, and climate policies.
- Micro level: Renewable energy, energy security, CO₂ capture, and climate adaptation.
- Refine by Research Areas: Energy Fuels, Urban Studies, Geography, and Construction and Building Technology.

³ <https://www.vosviewer.com/>.

Following the PRISMA framework, titles, abstracts, keywords, and conclusions were reviewed to exclude irrelevant studies, ensuring that only essential research was included.

3 Results and Discussions

3.1 *PRISMA Method Results*

Following the selection process in Sect. 2.1, 98 articles were initially retrieved from the Web of Science (WOS). After removing duplicates and irrelevant studies, 74 records proceeded to screening, with 14 excluded for lacking focus on PEDs or social housing. A full-text assessment of the remaining 60 studies led to the exclusion of 18 more, resulting in a final dataset of 42 studies.

Review analysis shows that 71% of the 42 studies focus on social housing, covering affordability, energy efficiency, policy, and retrofitting, while 29% explored related topics like rental policies and informal settlements. Despite PEDs' potential for urban sustainability, only 19% examine their role in social housing, while 81% focus on decentralized energy and renewable integration without direct housing applications. Regulatory, financial, and governance barriers continue to limit PED adoption in social housing. Methodologically, the studies employ qualitative (26%), quantitative (24%), and mixed-methods (29%) approaches, with case studies (12%) and literature reviews (10%) contributing to the discourse. These findings highlight a significant research gap, emphasizing the need for scalable, inclusive energy positive housing models integrating PED principles.

Figure 1 illustrates the distribution of research by publisher (a) and source title (b), showing that PED studies are frequently published in interdisciplinary journals such as *Energy Policy*, *Sustainability*, and *Renewable and Sustainable Energy Reviews*. This trend reflects a global focus on energy transition and climate resilience, influenced by policy initiatives like the European Green Deal (2019) and the Paris Agreement (2015). The diversity of journal coverage across policy, engineering, and urban planning underscores the complexity of PEDs and sustainable social housing, reinforcing the need for integrated approaches that address social justice, renewable energy, and governance. Since 2020, research in social sciences and humanities has expanded, reflecting growing interest in social acceptance, governance, and policy concerns. This shift aligns with EU frameworks, including the Urban Agenda for the EU and Horizon Europe's Mission on Climate-Neutral and Smart Cities (2021–2027), emphasizing the importance of citizen engagement in sustainable urban development.

The geographical distribution of research, presented in Fig. 1c, reveals a strong concentration in Europe, particularly in Spain, Italy, Poland, Switzerland, and the UK, driven by Horizon programs and EU climate policies. Smaller-scale studies have emerged in North and South America (USA, Argentina, Brazil, Chile), Africa

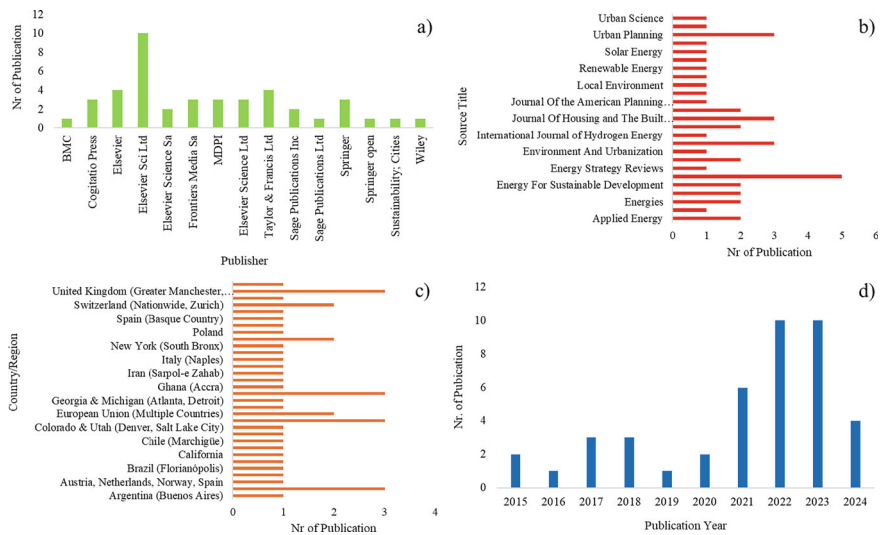


Fig. 1 Bibliometric characterization of the articles from the WOS database **a** publisher, **b** source title, **c** geographical distribution, **d** temporal distribution

(Ghana), Asia (Iran), and Oceania. The temporal distribution of studies, illustrated in Fig. 1d, highlights a research surge in 2017, aligning with the Paris Agreement (2015) and the EU’s Clean Energy for All Europeans initiative (2016–2019). Another peak occurred between 2020 and 2023, influenced by policies like Fit for 55 and the New European Bauhaus, which prioritize climate-neutral cities and energy-efficient housing. A decline in 2024 suggests a shift toward policy implementation, reflected in initiatives such as the Affordable Housing Initiative and the European Green Deal Renovation Wave.

3.2 VOS Viewer Results

A bibliometric analysis using VOSviewer (version 1.6.20) was conducted to explore research trends on PEDs, sustainability, and social housing. The co-occurrence maps provided an initial analytical framework rather than a standalone interpretative method. Figure 2a presents key thematic relationships, while Fig. 2b illustrates the temporal evolution of PED-related research.

Figure 2a shows the complex relationships between Positive Energy Districts (PEDs) and sustainability themes, highlighting their role in urban development through the integration of renewable energy, energy transition, and efficiency with urban planning. Their integration with smart cities underscores their role in data-driven infrastructures, while links to social housing, energy poverty, and justice emphasize the need for equity and inclusivity. Stakeholder engagement, governance,

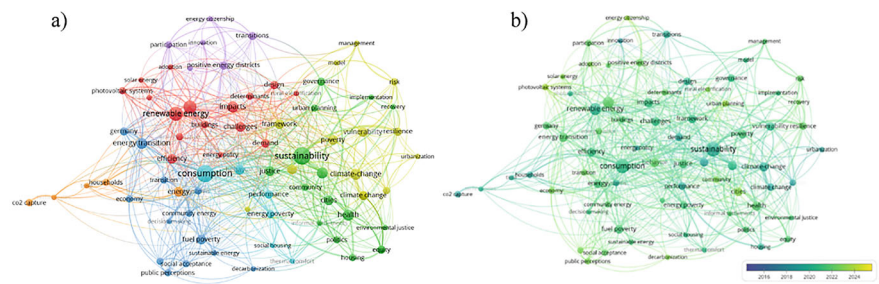


Fig. 2 **a** An overview of the co-occurrence of authors' keywords in scientific literature, **b** temporal distribution of the co-occurrence of relevant authors' keywords within the scientific literature

and public perception further highlight the importance of collaborative approaches among policymakers, urban planners, and local communities. PEDs address both environmental and socio-economic challenges by balancing energy supply and demand through demand management and flexibility while enhancing district-level self-sufficiency. For long-term sustainability, integrated planning frameworks combining energy management with regulatory tools are essential. Beyond energy efficiency, PEDs align technology, governance, and social equity to support broader sustainability goals, particularly in social housing.

Figure 2b illustrates the temporal evolution of PED research. Between 2016 and 2018, studies focused on technical advancements such as energy efficiency, renewable energy, and CO₂ reduction. Over time, governance, community participation, and policy integration became increasingly important. Since 2020, research has emphasized justice, resilience, and governance, positioning PEDs as key components of urban development rather than isolated technical solutions. From 2022 to 2024, the focus expanded to resilience, vulnerability, and economic considerations, particularly in social housing, highlighting the need for a people-centered approach that balances technological innovation with social and economic well-being.

4 Conclusions

This study presents a PRISMA-based systematic review of 42 studies examining the relationship between Positive Energy Districts (PEDs) and social housing. While most research focuses on affordability, energy efficiency, and policy interventions, the direct integration of PEDs into housing strategies remains limited. A bibliometric analysis highlights strong links between PEDs, renewable energy, and smart cities but reveals weak associations with social housing, energy poverty, and equity, underscoring gaps in their social and economic dimensions.

Since 2015, PED research has expanded from a technical focus on energy efficiency and CO₂ reduction to broader discussions on governance, equity, and policy

frameworks. Recent studies (2022–2024) increasingly address resilience, vulnerability, and economic factors, particularly in relation to social housing. However, research remains largely concentrated in Southern and Western Europe, limiting global applicability.

Despite advancements in PED research, several critical gaps remain. First, PEDs and social housing are often treated as separate domains rather than an integrated framework. Second, financial and regulatory challenges, particularly in low-income communities, remain underexplored. Third, social dimensions such as governance, community participation, and affordability receive insufficient attention. To further support these findings, a quantitative synthesis was conducted: among the 60 peer-reviewed studies analyzed, 38 (63%) addressed social resilience and 31 (52%) addressed economic resilience; however, only 17 studies (28%) substantively examined both dimensions in an interconnected manner. These results highlight the fragmented treatment of social and economic factors in PED research.

Fourth, the literature is largely theoretical, relying heavily on policy analysis and techno-economic modeling, with limited interdisciplinary approaches integrating urban planning, social sciences, and energy policy. Additionally, empirical studies and case-based validation are lacking, hindering practical implementation and scalability.

Addressing these gaps requires developing integrated PED-social housing models that enhance energy equity, affordability, and policy alignment. Expanding research beyond Europe is essential to account for diverse socio-economic and policy contexts. Strengthening interdisciplinary collaboration across urban planning, energy policy, and social sciences is crucial to advancing sustainable, energy-positive housing solutions. By highlighting the intertwined roles of social and economic resilience, this study underscores the need for a more holistic, equity-driven approach to PED development. Overcoming these challenges is vital for PEDs to effectively support climate-neutral cities and just energy transitions worldwide.

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References

1. OECD (2021) Empowering cities for a net zero future. OECD. <https://doi.org/10.1787/7a222c8b-en>
2. UN-Habitat (2022) Envisaging the future of cities.
3. IEA (2024) World energy outlook
4. Maduta C, D'Agostino D, Tsemekidi-Tzeiranaki S, Castellazzi L, Melica G, Bertoldi P (2023) Towards climate neutrality within the European Union: assessment of the energy performance of buildings directive implementation in member states. *Energy Build* 301:113716

5. IPCC (2022) Climate change 2022: impacts, adaptation, and vulnerability. IPCC. <https://doi.org/10.1017/9781009325844.Front>
6. IEA (2023) Clean energy transitions programme 2022. <https://doi.org/10.1787/dfc77c9e-en>
7. Glicker J, Toth Z, Volt J, De Groote M, Rodriguez Fiscal Reviewers P, Jeffries B, Fabbri M, Barrett M, Gaitani N (2022) Positive energy neighbourhoods drivers of transformational change
8. European Commission (2020) Integrated national energy and climate plan for France
9. Nguyen MT, Batel S (2024) Which energy citizenship in positive energy districts? A governmentality social psychological analysis of participatory governance. *J Environ Planning Policy Manage* 26:117–130
10. Casamassima L, Bottecchia L, Bruck A, Kranzl L, Haas R (2022) Economic, social, and environmental aspects of positive energy districts—a review. *Wiley Interdiscip Rev Energy Environ* 11:1–15
11. Sertsöz M (2024) Towards a synthetic positive energy district (PED) in İstanbul: balancing cost, mobility, and environmental impact. *Buildings*. <https://doi.org/10.3390/buildings14103153>
12. Bruck A, Díaz Ruano S, Auer H (2022) One piece of the puzzle towards 100 positive energy districts (PEDs) across Europe by 2025: an open-source approach to unveil favourable locations of PV-based PEDs from a techno-economic perspective. *Energy* 254:124152
13. Volpe R, Bisello A, Tuerk A et al (2025) Linking environmental impact assessment and positive energy districts: a literature review. *Clean Environ Syst* 16:100264
14. Gohari S, Silvia SC, Ashrafian T, Konstantinou T, Giancola E, Prebreza B, Aelenei L, Murauskaite L, Liu M (2024) Unraveling the implementation processes of PEDs: lesson learned from multiple urban contexts. *Sustain Cities Soc* 106:105402
15. Leone F, Reda F, Hasan A, Hur R, Nigrelli FC, Nocera F, Costanzo V (2023) Lessons learned from positive energy district (PED) projects: cataloguing and analysing technology solutions in different geographical areas in Europe. *Energies*. <https://doi.org/10.3390/en16010356>
16. PRISMA (2021) PRISMA. <http://prisma-statement.org/>
17. Van Eck NJ, Waltman L (2010) Software survey: VOSviewer, a computer program for bibliometric mapping. *Scientometrics* 84:523–538

Engaging Small Communities in the Clean Energy Transition: Results from the LIFE LOCAL GoGREEN Project



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Abstract Achieving Europe's mid-term decarbonization targets by 2030 is an ambitious challenge for local authorities. However, small and rural municipalities face significant barriers, including structural, institutional and economic challenges. To facilitate the achievement of this ambitious goal, it is essential to strengthen local administrative capacities through targeted support. This is indeed the main objective of the European LIFE22-CET LOCAL GoGREEN project, which is aimed to accelerate the clean energy transition in six small communities across Bulgaria, Croatia, Slovenia, Italy, Germany, and Spain. In particular, it supports them in developing strategic actions in five priority areas: sustainable transport and e-mobility, energy efficiency in buildings, renewable energy expansion, land-use planning for carbon sequestration, and waste-to-energy solutions. This is achieved through a range of activities, including stakeholder engagement, local capacity building, providing analytical tools for energy planning, conducting pre-feasibility studies, and developing roadmaps and action plans. This paper presents the groundwork for the preparation of action plans and feasibility studies by the pilot cities, i.e. the characterization of the state of the art from an energy and planning perspective. It focuses on the analysis of the self-assessments carried out by the pilot cities, the database of their current climate and energy plans and programmes, and the definition of a common set of key indicators to characterize their planning performance. The results obtained so far show a two-speed behavior in the planning practices of small municipalities across

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Europe, with lagging municipalities able to learn and adopt good practices from the leading examples in the project in horizontal mainstreaming.

Keywords Clean energy transition • LIFE LOCAL GoGREEN • Small municipalities • Pilot communities • Key indicators • SECAP

1 Introduction

The European Union's climate and energy targets for 2030 (EU Directive 2023/1791) and progress towards the European Green Deal goal of climate neutrality by 2050 are the levers for implementing the clean energy transition at municipal level. This includes promoting the use of renewable energy, energy efficiency, community involvement and local planning. Local authorities also have a key role in providing information to National Climate and Energy Plans (NECPs) [1], so that their needs, challenges and opportunities are taken into account in planning on a national scale.

However, a gap persists between small and medium-sized municipalities: small and rural municipalities face significant challenges in embarking on an effective decarbonization pathway [2]. They face obstacles such as a general lack of awareness and consensus among policy makers, challenging transformation of infrastructure, as well as a lack of specific expertise, experienced technical staff and financial resources [3]. Aware of the existence of such barriers, effective capacity-building activities should be promoted to make authorities active, informed and aware actors, as these actors 'are generally more successful than others in implementing clean energy policies' [4]. This highlights the need to support municipalities in their decarbonization efforts by enhancing the skills and capacities of their political and technical staff.

To this end, the European LIFE22-CET LOCAL GoGREEN (LGG) project (<https://localgogreen.eu/>) aims to help accelerate the clean energy transition in 6 small municipalities in Bulgaria, Croatia, Slovenia, Italy, Germany and Spain. The project aims to empower local authorities and build their capacity to develop, implement and monitor ambitious short- and medium-term plans to accelerate the clean energy transition and achieve the 2030 targets. Activities will focus on improving the expertise of local authority staff in the transition to clean energy, while increasing stakeholder motivation, cooperation and commitment. In addition, the project intends to facilitate an effective transfer of knowledge through a range of activities including stakeholder engagement, capacity building, provision of analytical tools for energy planning, conducting pre-feasibility studies, and developing roadmaps and action plans and networking between municipalities. The LGG pilot municipalities are guided throughout the project in the development of robust, locally tailored pathways to low-carbon communities by 2030. This pathway will take the form of integrated energy and climate plans (ICEPs) and related long-term investment projects. In addition, capacity building and networking will serve to create an enabling environment for replication, standardization and scaling-up beyond the six pilot communities.

The purpose of this study is to present the basic methodology of the LGG approach, and the first results obtained at the beginning of the second year. It is structured in four sections. Section 2 briefly presents the methodological approach, Sect. 3 presents the results of the characterization activities of the baseline situation of the 6 pilot municipalities, and Sect. 4 presents the conclusions and future developments of this study.

2 Methodological Framework

The LGG project is based on three basic pillars: knowledge transfer, knowledge acquisition and knowledge capitalization, as described in [5]. As one of the main expected outcomes of the project activities, municipalities will be supported to increase their capacity to construct integrated climate and energy plans (ICEPs). These plans aim to meet energy needs by optimizing investments, efficiency, socio-economic benefits and emission reductions adapted for the local requirements.

The implementation of ICEPs is based on an accurate knowledge and description of the baselines of the pilot municipalities, mainly in terms of local energy balances and related greenhouse gas (GHG) emissions. The main steps in the development of ICEPs are illustrated in Fig. 1.

The first step (*building a database of plans*) was to get an overview of the climate and energy plans in place in each pilot municipality. This was achieved by collecting key information directly from the pilot cities, which were involved and guided in this key step, and supported in the preparation of a common reporting document, here referred to as the ‘self-assessment report’ (SAR) [5]. The second step was to identify a set of indicators through which to analyze and compare the knowledge gathered (SARs and existing plans in the pilot municipalities). This set includes 74 indicators, organized in the following 11 categories:

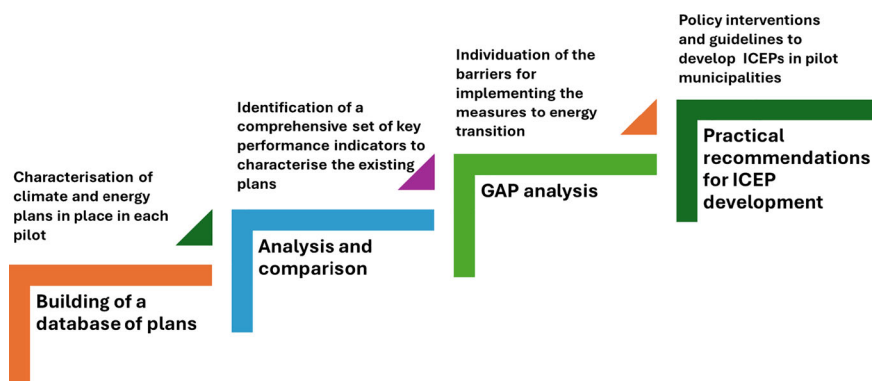


Fig. 1 Pathway in developing integrated climate and energy plans in pilot municipalities

1. GHGs
2. Local Air Pollutions
3. Overall Energy targets
4. RES target by sector
5. EE target by sector
6. Mitigation actions by sector
7. Climate Risks and Vulnerabilities (RVA)
8. General and transversal issues
9. Links to other planning tools
10. Funding of the planned actions (EU or National)
11. Monitoring and Evaluation process.

The next steps will be to conduct a gap analysis of the barriers to clean energy transition in the partner communities and to provide practical recommendations for the development of their ICEPs.

3 Preliminary Results and Discussions

Results of the first step of mapping the current state of planning instruments in the pilot municipalities through the self-assessment reports are summarized in Fig. 2. The first column shows that 4 out of 6 municipalities are very small, with a population of less than 15,000 inhabitants. Regarding their energy and climate planning framework, although all the pilot municipalities reported having one or more planning documents, a closer analysis of these reveals a very poor initial situation. In fact, Ormož (SI) has a new Sustainable Energy and Climate Action Plan—SECAP developed in the framework of the Global Covenant of Mayors (GCoM) European initiative (website), that has not yet been updated and/or approved by the technical support unit of the GCoM. Tito (It) has a SEAP adopted in 2012 but it expired five years ago in terms of commitment, and in all other cases, there are no climate and energy planning instruments, but rather programmes (as in the case of Dryanovo (BG), Antunovac (HR) and Albstadt (DE)), or concepts (Ormož (SI) and Albstadt (DE)) or an urban agenda (Ponferrada (ES)).

Figure 3 shows for each municipality how all types of existing plans, programmes, policies and urban agendas cover the predefined categories of indicators. It shows that the Risk and Vulnerability Assessment (RVA) was not selected by any of the pilot communities and that there was a general lack of any adaptation assessment.

Mitigation actions by sector, general and transversal issues, links to other planning tools, EU or national funding of planned actions, M&E process are the 5 out of 11 categories selected by all municipalities. In terms of overall category coverage, Tito and Dryanovo selected a higher number of categories (9 out of 11), while Antunovac selected the fewest (5).

Particularly, it is relevant to note that all municipalities have prepared a monitoring process to evaluate the progress of their policy documents. Although there are

	General description	Plan (year)	Commitment (year)	Quantit. Target	Network (year)
Ormož (SI)	No. of inhabitants: 11,920 Surface area (Km ²): 141.6 Příekija province, Slovenia	• Local Energy Concept (2021) • Sustainable Energy and Climate Action Plan (SECAP)*	• (GCoM)	-40% by 2030 climate neutrality by 2050	• GCoM (2021) • URBACT (EcoCore project - TRA)
Dryanovo (BG)	No. of inhabitants: 7,369 Surface area (Km ²): 248.5 Gabrovo district, Bulgaria	• S-T (2020-2023) Programme for RES & biofuels (2019) • L-T (2020-2030) Programme for RES & biofuels (2020)	• Integrated Development Plan (2021)	-	-
Tito (PZ)	No. of inhabitants: 7,134 Surface area (Km ²): 283 Basilicata Region (capital city), Potenza province, Italy	• Sustainable Energy Action Plan (SEAP) (2012)	• Climate Emergency Declaration (CED) (2024)	-20% by 2020	• GCoM (2011)
Ponferrada (ES)	No. of inhabitants: 63,747 Surface area (Km ²): 283 El Bierzo region (capital city), León province, Spain	• Urban Agenda of Ponferrada (2024) • Sustainable Urban Mobility Plan (SUMP) (2014)	• (GCoM)	-	• GCoM (2020) • Red Española de Ciudades por el Clima (2005)
Antunovac (HR)	No. of inhabitants: 3,411 Surface area (Km ²): 56.8 Osijek-Baranja County, Croatia.	• Implementation Programme 2021-2025 (2021)	• Development Strategy (2020) • Inventory of environm. & natural resources (2021)	-	-
Albstadt (DE)	No. of inhabitants: 47,271 Surface area (Km ²): 134.4 Baden-Württemberg, Zollernalbkreis district, Germany.	• Climate protection concept (2015) • Municipal Heat Plan (2023)	• Urban Development Concept Albstadt 2030+ (2018) • Electromobility concept (2019) • Climate Law - Baden- Württemberg (2023)	-25% by 2020 -90% by 2050 GHG-neutral heat generation by 2040	- * not yet validated / approved

Fig. 2 Status of climate planning in LGG pilot municipalities

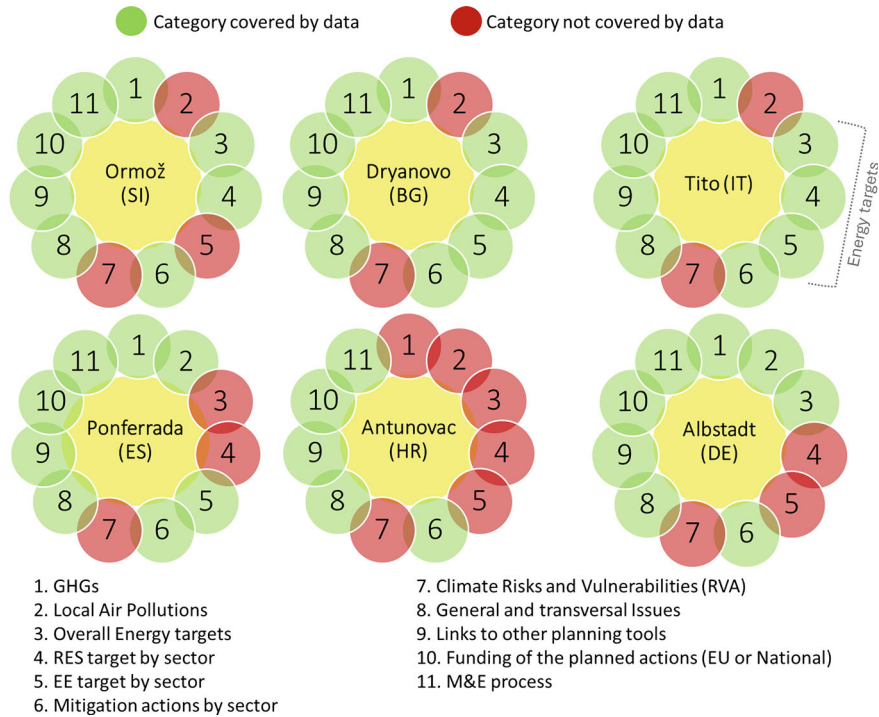


Fig. 3 Analysis of the categories of indicators that are covered in the existing plans

several differences between the pilot communities (e.g., in terms of geographical, demographic, policy frameworks), each of them has set targets for energy efficiency and renewable energy systems, demonstrating preparedness to take action on the transition to clean energy.

4 Conclusions and Further Developments

The LOCAL GoGREEN (LGG) project aims to assist local authorities in accelerating the clean energy transition through a project-oriented methodological approach. This approach is grounded in a long-term strategic vision and emphasizes structured engagement with both local and transnational stakeholders.

To this end, it promotes the creation of a stable and committed institutional structure over time, capable of integrating the planning of economic sectors and taking into account various stakeholders' requirements, as well as fitting into the regional planning procedures of each local context.

The project activities carried out so far have focused on the analysis and characterization of the energy and climate planning instruments in force in the LGG pilot cities. The results showed a rather diverse and fragmented situation. This underlines that the path towards a clean energy transition of existing urban systems in small and rural areas needs a more coherent and comprehensive planning framework, such as the Sustainable Energy and Climate Action Plans promoted by the Covenant of Mayors.

The next phases of the project activities will be devoted to the identification of barriers for the implementation of energy transition measures and the definition of policy interventions and guidelines for the development of integrated climate energy plans in the pilot municipalities.

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References

1. National and Sub-national Policies and Institutions (2023) In: Climate change 2022—mitigation of climate change. Cambridge University Press, pp 1355–1450. <https://doi.org/10.1017/9781009157926.015>

2. Linton S, Clarke A, Tozer L (2020) Strategies and governance for implementing deep decarbonization plans at the local level. *Sustainability* 13:154. <https://doi.org/10.3390/su13010154>
3. Kamenders A, Rosa M, Kass K (2017) Low carbon municipalities. The impact of energy management on climate mitigation at local scale. *Energy Proc* 128:172–178. <https://doi.org/10.1016/j.egypro.2017.09.038>
4. Bayulgen O (2020) Localizing the energy transition: town-level political and socio-economic drivers of clean energy in the United States. *Energy Res Soc Sci* 62:101376. <https://doi.org/10.1016/j.erss.2019.101376>
5. Salvia M, Dimitrova C, Santopietro L, Hueber B, Cosmi C, Pietrapertosa F, Pajaziti E, Mikulic I, Jakob U, Vollmer E, Milich L, Soler B, Kekec R (2024) Empowering local authorities to accelerate the clean energy transition: the Local Gogreen Project. In: *Sustainable development and planning 2024 conference publication—WIT transactions on ecology and the environment*, pp 847–858. <https://doi.org/10.2495/SDP240701>

Identifying Behavioural Drivers Influencing SMEs' Decisions on Energy Efficient Retrofitting of Commercial Buildings in Ireland Using Multi-method Analysis



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Abstract The commercial built environment accounts for considerable energy consumption and carbon emissions across Europe, making it a critical focus for achieving climate action goals. Retrofitting existing building stocks plays a crucial role in supporting the climate action goals in the region. Despite available policies and efforts to promote energy-efficient practices, small and medium enterprises (SMEs) are still lagging in implementing retrofitting measures. In Ireland, SMEs dominate the commercial built sector but face unique challenges that hinder their interest in retrofitting. This shows a clear gap between what is expected in policies and action plans, and what is actual implementation on the ground. To better understand how to bring SMEs to the retrofitting journey it is significant to understand behavioural drivers that trigger decision-making on energy efficiency retrofitting. This study employs a multi-method analysis that covers surveys, workshops, and interviews with SMEs on the decision-making processes related to energy efficiency retrofitting actions within SMEs. Findings from the study reveal that drivers such as perceived financial benefits, environmental values, regulatory awareness, and organisational culture significantly impact decision-making processes. The findings underscore the need for tailored communication strategies and targeted support mechanisms to accelerate energy-efficient retrofitting in Irish SMEs. This research offers insights for policymakers and stakeholders aiming to foster sustainable practices within commercial buildings.

Keywords Behavioural drivers · SMEs · Retrofitting · Commercial buildings

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1 Introduction

Following the adoption of the Paris Agreement in 2015 [1], both Ireland and the European Union (EU) have increased their commitments to climate change mitigation. Instruments such as the European Green Deal [2], the EU Taxonomy framework [3], and the Corporate Sustainability Reporting Directive (CSRD) [4] have been developed as essential frameworks for transitioning towards a low-carbon, resilient economy, at all levels through business entities. Ireland has adopted the Climate Action Low Carbon Development (Amendment) Act (2021), establishing a legally binding objective to cut national CO_{2eq} emissions by 51% by 2030, progressing towards a climate-neutral economy by 2050 [5].

The commercial building sector is a key focus in reducing emissions due to its significant direct and indirect carbon footprint. Construction and building use contribute heavily to global emissions, with estimates suggesting 35–60% of the carbon budget for a 2 °C target may be used for construction [6]. In developed countries, buildings account for around 40% of total energy use and emissions [7].

According to the [8] average SME in Ireland could reduce its energy bill up to 30% and almost 1800 kT of CO₂ (Cumulative) will be abated to 2030 through energy efficacy measures [8]. These interventions not only improve insulation, lighting, and appliance efficiency but also promote the adoption of low-emission technologies and on-site renewables like solar panels to support a decarbonised built environment [9, 10].

In Ireland, in the first nine months of 2024, over 38,000 home energy upgrades were completed, marking an 11% increase compared to the same period in the previous year [11]. In contrast, there is a clear lag in the SME sector for the uptake of energy efficient retrofits. The absence of current data suggests a potential lag in retrofit activities among the SME sector, which led to understand drivers that help SMEs to uptake energy efficient retrofits. This paper aims to understand these hidden behavioural drivers by discussing responses gathered through a multi-method approach including (i) online survey, (ii) workshops, and (iii) in-depth interviews within the Irish SME sector. This approach helps to go beyond economic considerations to capture behavioural drivers that motivate retrofitting decisions across diverse SME profiles. Addressing the limited research in the area, the key question being explored in the study is: What behavioural drivers motivate SMEs to make the decision to retrofit their premises.

2 Methodology

This study follows the multi-method analysis where different approaches were used to gather required insights and validate from the SME sector. This approach is intended to strengthen validity through triangulation [12], deepens understanding by revealing both specific mechanisms and broader context [13]. Depending on the interest of the

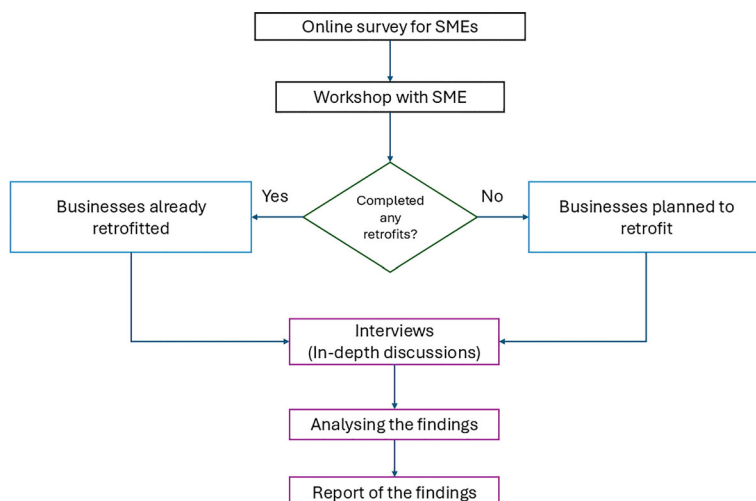


Fig. 1 Simplified conceptual model

participants, this study gave opportunity to the responders to select in which means they want to interact with the study as shown in Fig. 1. 17 SMEs were engaged in the study that leads to valuable insights on behavioural drivers to retrofit.

Once the insights were collected through three primary methods, they were analysed to derive meaningful interpretations, aiming to identify the key behavioural drivers that could motivate the SME sector to get on the retrofitting journey. While the online survey provided direct and structured responses from participants, the insights gathered through workshops and interviews were more unstructured. To ensure consistency in the analysis, the authors utilised NVivo qualitative data analysis software to categorised participants' opinions into 11 broader themes. Finally, by understanding the broader themes, the study provides policy recommendations to encourage the SME sector to adopt energy efficient retrofits.

2.1 Workshops and Survey Design

Initially the authors identified the set of drivers by reviewing literature in a European context, that triggers SME to retrofit their buildings and as list of drivers based on [14]. Then these drivers were validated through different means i.e. workshops, interviews, and online surveys. Figure 1 shows the flow chart of the simplified conceptual model followed by the study.

2.2 *Online Survey*

An online survey was conducted prior to the commencement of the workshops to gather demographic information and inductive responses on drivers that influence the decisions in SMEs to carry out energy efficient renovations. The survey used semi-structured questions including both open and closed questions to gather required insights from the participants.

Demographic and business information like location, sector, and ownership were included in the form while the question on motivations is the key question that sought to inductively identify the key drivers behind renovation decisions.

2.3 *Workshops on Commercial Building Retrofitting for SMEs*

Using a sector-focused strategy, the ENACT consortium planned ten specialised workshops between May and June 2023, covering three main counties i.e. Galway, Cork and Dublin. But 3 out of those 10 were cancelled due to poor attendance. These interactive sessions engaged SMEs from five key sectors: hospitality, retail, warehouse, office, and leisure with the goal of enhancing their understanding of the factors influencing their decisions on energy efficiency retrofits.

The workshops began with an exemplary presentation, and attendees completed an online survey to select the most important decision-making drivers for energy retrofitting from a set of predefined options (closed questions). The project team delivered a presentation on behavioural drivers, after which participants took part in-person roundtable discussions to prioritise the behavioural drivers they considered most significant. These insights were analysed, and policy recommendations were concluded based on this information.

2.4 *Interviews with SMEs*

During the workshops held, the research team identified two groups that further in-person meetings were conducted with to get in-depth ideas of the behavioural drivers that they motivated. SMEs who have already been retrofitted and SMEs who have not retrofitted yet were the two groups identified during the sessions.

Six exemplary SMEs (four in hospitality and two in the office sector) that have retrofitted were interviewed to gain qualitative insights into their decision-making drivers beyond predefined factors. Additionally, six post-roundtable interviews were conducted with SMEs who were considering undertaking retrofits to understand the behavioral motivations behind their decisions.

Sector	Survey Responses	Workshop on Retrofitting	Interviews
Hospitality	2	2	5
Offices	2	2	2
Warehouse	1	1	0
Leisure	1	1	0
Service Providers	6	6	5
Government department staff	2	2	0
Estate agents	2	2	0
Financial service providers	1	1	0
Total	17	17	12

Fig. 2 SME sector engagement data

3 SME Sector Engagement Data

Figure 2 illustrates SME engagement in ENACT’s four approaches, highlighting the challenge of involving SMEs in energy efficiency initiatives. Since SMEs prioritise core business activities, they may not focus on energy renovations [15]. This explains lower participation in surveys, workshops, and interviews. However, all workshop participants completed the online survey during the session, providing insights into behavioral drivers.

4 Results and Discussion

Drivers identified from three different methods were analysed to get the overall idea of the study. Table 1 shows how drivers were selected by the respondents, attendees of the workshop and interviewees corresponding to their circumstances. The drivers were then categorised into 11 broader themes.

According to Table 1, a clear picture of what behavioural drivers motivated the sector can be understood. Regulatory and policy drivers such as legislations, policy limits and planning permission are significant in making retrofitting decisions. Tax reliefs and grants influence SME to invest in energy efficient projects, that was validated by an interviewee mentioning that their decision to build a highly energy efficient extension with funding support from SEAI. Payback and the return on investment is one of the key drivers that are categorised under market and economic theme that helps SME to understand how the cashflow works. Particular quotes that support this statement are “*I have to satisfy myself that there was a return on investment.*”, “*You know, if it pays for itself over a period of five to seven years, then yeah, I will do it*”. This reveals that grants and external funding influence these decisions that will help to reduce the payback period and increase the number of retrofits completed. Positive impact on brand and customer expectations are also other drivers that can motivate the sector under this category.

Table 1 Categorisation of the identified drivers from the SME sector engagement

Categories	Survey responses	Workshop selections	Interview themes
Regulatory and policy	Laws, limits and policy	Law, limits and policy Taxes and grants	Law, limits and policy Taxes and grants
Market and economic	Financial performance Energy costs Customer expectations Positive impact on brand Increasing building valuation	Payback	Financial performance Energy costs Payback Access to finance
Social and ethical	Health	Participation—empowerment—localism Moral obligation Public opinion and branding Health Emotive Local circumstances	Participation—empowerment—localism Moral obligation Public opinion and branding Health Emotive Local circumstances Social responsibilities
Environmental	Decarbonisation targets	Environmental damage	Decarbonisation Environmental damage Climate change
Organisational and leadership	Better working conditions for staff	Organisational management—leadership Stakeholder expectations Commitment Futureproofing	Organisational management—leadership Stakeholder expectation Commitment Futureproofing Organisation culture

(continued)

Table 1 (continued)

Categories	Survey responses	Workshop selections	Interview themes
Knowledge and awareness		Effective communication Education information and awareness Previous experience Profiling—understand the audience Advocacy Indicators and measurements Feedback	Effective communication Education information and awareness Previous experience Profiling—understand the audience Advocacy Indicators and measurements Feedback Data Exemplars
Capacity building and skill development		Upskilling—agency—capability Technical assistance	Upskilling—agency—capability Technical assistance
Innovation and development		Technology Learning by doing Product labelling	Technology Learn by doing Innovation
Networks and collaborations		Networks and collaborations Sharing—distributional justice Exploring synergies Co-management	Networks and collaborations Exploring synergies Sharing—distributional justice
Recognition and reward		Recognition/visibility/legitimation	Recognition/visibility/legitimation
Barriers and challenges		Distrust/skepticism Remove barriers Infrastructure Obsolescence	Distrust/skepticism Infrastructure Obsolescence
Normative and cultural		Norms Procedural justice One thing leads to another Co-execution of works Chronology/timing	Norms One thing leads to another Co-execution of works Chronology/timing

Beyond monetary-related drivers, participants frequently highlighted themes such as social and ethical considerations, environmental impact, organisational leadership, and knowledge and awareness. These insights support policymakers in making well-informed decisions across various domains. SMEs are integrating corporate social responsibility (CSR), accountability, and sustainability into their core strategies, recognising their importance for both business performance and participation in societal impact. Participated businesses acknowledge the need of community acceptance and aesthetic considerations in retrofitting decisions stating, *“I can’t put wind-mills up in the center of Westport... they wouldn’t look good”* This quote underscores the importance of aligning sustainability projects with community standards and aesthetics. Environmental impact and decarbonisation are key factors among the environmental drivers mentioned. The following quotes from industry stakeholders highlight the significant influence of these drivers on retrofit decisions: *“Now we have a big responsibility, and some of these islands are disappearing because sea levels are rising,”* and *“With everything going on, it made us in the hotel more aware of the environmental impact we were having in the area.”*

Organisational commitment to sustainability must start at the top and extend throughout all levels of staff. Knowledge, education, and awareness play a dual role as both drivers and barriers to sustainability in SMEs. Many businesses emphasise the importance of understanding energy-related data to support informed decision-making, as reflected in this participant’s statement: *“Once you have the numbers and understand them, all you need to do is act on them.”*

Findings from sector engagement have informed key policy recommendations to promote energy-efficient retrofitting among SMEs. These recommendations include: (i) Supporting exemplary SME initiatives, (ii) Enhancing capacity building and skill development, (iii) Providing incentives and fostering local engagement and innovation, (iv) Streamlining regulatory processes and (v) Developing and promoting clear metrics and indicators. These recommendations aim to guide policymakers in shaping effective policies that empower SMEs to accelerate their investment in energy-efficient retrofits.

5 Conclusion

In conclusion, this study underscores the multi method approach to understand the behavioural drivers influencing SMEs’ decision-making processes regarding energy efficiency retrofitting in Ireland. The findings reveal that, beyond financial support and incentives, factors such as social influences, environmental considerations, and awareness also play a crucial role in driving these decisions. The policy recommendations from the findings show a collaboration between the policy makers, industry leaders and SME themselves to support this transition within the SME sector. Although this survey focused on Irish commercial buildings, [14] highlights similarities that may also apply to communities and individuals’ decision. Drivers such as

future-proofing, environmental concerns, and stakeholder expectations could be relevant across the EU, excluding geo-political factors like taxes, grants, and national policies. Ultimately, this study provides valuable insights into the key behavioral drivers and the policy focus required to support SMEs in adopting energy efficiency retrofits.

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References

1. United Nations Framework Convention on Climate Change (2015) Paris Agreement. <https://unfccc.int/process-and-meetings/the-paris-agreement>. Accessed 6 Feb 2024
2. The European Commission. The European Green Deal. https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en. Accessed 21 Nov 2024
3. European Commission (2020) EU taxonomy: sustainable finance. https://finance.ec.europa.eu/sustainable-finance/tools-and-standards/eu-taxonomy-sustainable-activities_en. Accessed 6 Feb 2024
4. European Union. Corporate sustainability reporting directive (CSRD). <http://data.europa.eu/eli/dir/2022/2464/oj>. Accessed 13 Dec 2023
5. DECC (2021) Climate action plan 2021. <https://www.gov.ie/en/publication/6223e-climate-action-plan-2021/>. Accessed 28 Jan 2025
6. Arehart JH, Hart J, Pomponi F, D'Amico B (2021) Carbon sequestration and storage in the built environment. *Sustain Prod Consum* 27:1047–1063. <https://doi.org/10.1016/j.spc.2021.02.028>
7. Chuai X, Huang X, Lu Q, Zhang M, Zhao R, Lu J (2015) Spatiotemporal changes of built-up land expansion and carbon emissions caused by the Chinese construction industry. *Environ Sci Technol* 49(21):13021–13030. <https://doi.org/10.1021/acs.est.5b01732>
8. Motherway B, Scheer J (2011) Economic analysis of residential and small-business energy efficiency improvements. <https://www.seai.ie/sites/default/files/publications/Economic-Analysis-of-Residential-and-Small-Business-Energy-Efficiency-Improvements.pdf>
9. ACEEE (2023) The role of energy efficiency in building a clean energy future. Technical report
10. WGBC (2022) Advancing net zero: a global action plan for the built environment. Technical report
11. SEAI (2024) National retrofit plan—quarterly progress report quarter 3 2024
12. Carter N, Bryant-Lukosius D, Dicenso A, Blythe J, Neville AJ (2014) The use of triangulation in qualitative research. *Oncol Nurs Forum* 41(5):545–547
13. Creswell JW (2009) Research design: qualitative, quantitative, and mixed methods approaches, Illustrated. SAGE Publications
14. Vincent Carragher and Sarah McCormack (2018) Reviewing and testing the factors that drive the sustainable behaviour and transition of communities, groups and individuals
15. Rizzi F, Annunziata E (2015) Electricity consumption and efficiency trends in the European Union. Status report 2014, European council for an energy efficient economy (ECEEE)

Enhancing Urban Sustainability: Modeling Positive Energy Districts in a Mixed-Use Bari District



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Abstract Positive Energy Districts (PEDs) have emerged as a critical strategy to mitigate climate change and reduce urban energy consumption. By integrating renewable energy generation energy efficiency measures and smart grid solutions at the neighborhood scale, PEDs lower greenhouse gas emissions while enhancing urban sustainability and resilience. This innovative approach accelerates the energy transition by promoting decentralized, adaptable, clean energy solutions. This paper presents the outcomes of the Italian National PRIN project NETPLUS (Neighborhood Energy Transition: towards Positive energy Balance and Carbon Neutral Districts), which investigates PED development and performance through the definition and modeling of district archetypes. Focusing on a mixed residential district in Bari, the study develops specific archetypes for both residential and non-residential buildings to capture unique energy consumption patterns and operational characteristics. A comprehensive modeling framework was employed to simulate the district's annual energy demand, and simulation results were calibrated against multiple data sources—including actual building energy bills and other benchmarks—resulting in discrepancies below 10%. This level of accuracy confirms the model's reliability for evaluating energy performance and guiding retrofit strategies. Furthermore, the project assessed the potential benefits of combining energy retrofit measures with on-site renewable energy generation. In a retrofit scenario, on-site renewable systems could supply 57% of the district's annual energy needs. The benchmark data and reference models derived from this study are highly applicable to the Mediterranean region and similar climates, underscoring the transformative potential of PEDs in achieving energy self-sufficiency and advancing decarbonization efforts.

Keywords Positive energy district · Mixed use · Energy transition

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1 Introduction

Urban areas account for a considerable share of global energy consumption [1]. Addressing energy-related challenges within cities has become increasingly significant, driven by rising urban populations, increasing energy demands and pressing international climate goals. To support the achievement of these targets, the concept of Positive Energy Districts (PEDs) has increased importance. According to JPI Urban Europe [2], PEDs are defined as “energy-efficient and energy-flexible urban areas or groups of connected buildings that produce net-zero greenhouse gas emissions and actively manage an annual local or regional surplus production of renewable energy. They require integration of various systems and infrastructures, including interaction between buildings, users, and regional energy, mobility and ICT systems, while securing energy supply and ensuring high quality of life aligned with social, economic and environmental sustainability”.

Despite the promising potential of PEDs, an analysis of the PED Database reveals a significant gap: in Southern Italy, only one case of a PED has been documented. This underrepresentation indicates that the diffusion and practical implementation of PED models in this region remain extremely limited, highlighting the need for targeted research and policy initiatives.

This study aims to bridge this gap by developing a representative modeling framework for PEDs that can be tailored to the unique characteristics of Southern Italian urban environments. The framework is validated through detailed energy simulations calibrated against multiple measured consumption data sources, achieving discrepancies below 10%. This level of accuracy confirms the model’s reliability for evaluating energy performance and guiding retrofit strategies. Additionally, the study evaluates the impact of retrofit measures and the integration of on-site photovoltaic systems, demonstrating that renewable energy generation could cover up to 57% of the district’s annual energy requirements. By analyzing a mixed-use district in Bari as a case study, this paper provides validated reference models and practical insights to support urban planners, energy policymakers and researchers in transitioning toward sustainable and energy-positive urban districts, particularly in regions with scarce PED implementations.

2 Methodology

The study began with a comprehensive collection of spatial data through Geographic Information Systems (GIS), which provided essential geometric details and building usage classifications for the district. From the building stock analysis, four distinct building typologies were identified:

1. Residential buildings with 7 floors;
2. Residential buildings with 5 floors;
3. Residential tower buildings;

4. A non-residential building (the school).

These building archetypes were subsequently analyzed using City energy analyst [3] to simulate the annual energy demand.

In order to assess the quality of the model, each of the four archetypes underwent a calibration process.

For residential buildings with available electric bill data, calibration was performed against the actual consumption values.

For residential tower buildings, where electric bills were not available, model calibration was based on heating demand using reference values from the Tabula project for Italy [4]. Similarly, the school was calibrated using consumption data from an RSE study that estimated the energy use of Public Administration buildings in Italy [5].

These data serve as the key references for evaluating and validating the simulated results.

To accurately model the usage characteristics of the two main building typologies (residential and school), the study employed the following standards: EN 16798-1:2019 [6] for residential buildings and ISO 18523-1:2016 for the school [7].

The energy consumption of the archetypes in the district is then compared with the reference data. The calibration process is considered successful if the difference between simulated and reference is less than $\pm 10\%$.

Following the calibration of the archetypes, an energy analysis was conducted for the district in its existing state (baseline).

Based on this analysis, retrofit hypotheses were formulated to bring the district as close as possible to the PED target.

Accordingly, three renovation scenarios have been formulated:

1. The first scenario focuses on reducing energy consumption by installing natural-based insulation (cellulose fiber) in the walls and roofs. The quantity of insulation to be installed is determined with the objective of achieving a lower thermal transmittance value than that required by the minimum requirements decree [8], which varies according to the climate zone. Given that Bari is in climate zone C, the renovation must ensure that the thermal transmittance values are below $0.33 \text{ W/m}^2 \text{ K}$ for roofs and walls and below $2.2 \text{ W/m}^2 \text{ K}$ for windows.
2. The second retrofit scenario involves replacing the existing systems with hydronic systems. Although this scenario leads to an increase in energy consumption—thereby making it more challenging to achieve the PED target—it is considered essential from a decarbonization perspective.
3. The final retrofit scenario involves the installation of 830 kW of monocrystalline photovoltaic panels on the 50% of the available roofs ($16,620 \text{ m}^2$). The energy generation from these panels is evaluated using the PVWATTS [9] software.

An annual comparison between on-site renewable generation and district energy consumption will be conducted to verify if the PED target is met, or to quantify the shortfall and assess the district's proximity to reaching the target.

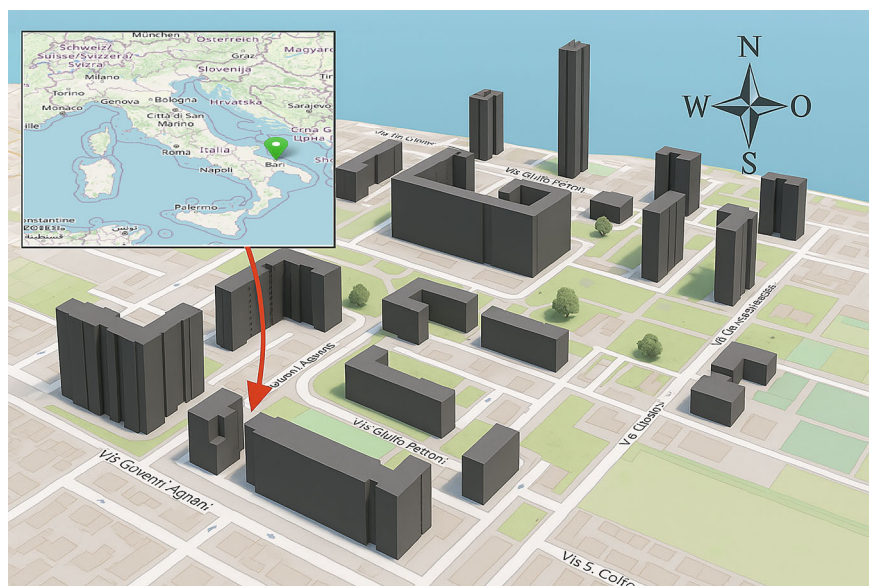


Fig. 1 The case study

3 The Case Study

The district comprises 63 buildings constructed during the 1970s and 1980s. These buildings have never undergone any renovation process, resulting in generally high thermal transmittance characteristics. Specifically, the thermal transmittance values are approximately $6 \text{ W/m}^2 \text{ K}$ for windows, $0.8 \text{ W/m}^2 \text{ K}$ for roofs, and $1.2 \text{ W/m}^2 \text{ K}$ for external walls. In terms of building systems, the installations are predominantly served by gas boilers with only one building equipped with a heat pump system.

Figure 1 presents a map of the district's buildings, generated using QGIS and OpenStreetMap data. The dark-colored polygons represent the buildings included in the analysis.

4 Results

Figure 2 illustrates the outcomes of the calibration procedure for the building archetypes.

Archetype 1 reveals deviations ranging from -2 to $+3\%$ between simulated and actual electricity consumption. Similarly, Archetype 2, exhibits a small discrepancy from -2 to -4% . For Archetype 3, heating demand the deviations range from -0.13% to $+0.04\%$. The final archetype shows a deviation of -8% .

Overall, these deviations remain within the $\pm 10\%$ acceptance threshold,

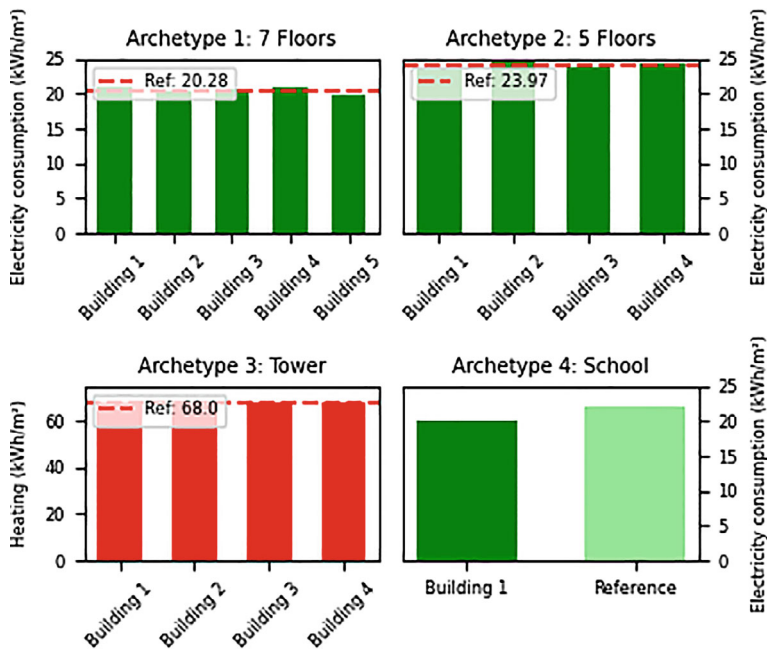


Fig. 2 Calibration results

The baseline scenario’s monthly energy demands for heating, cooling and electricity are detailed in Fig. 3.

The baseline annual consumption is approximately 3900 MWh for heating, 254 MWh for cooling and 1722 MWh for electricity.

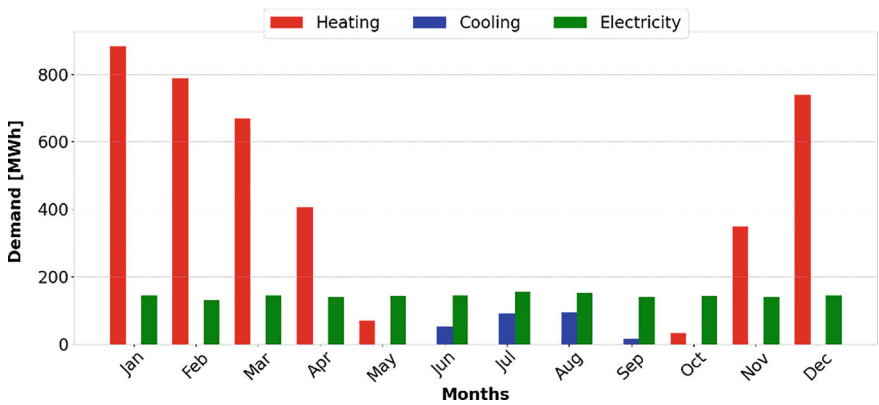


Fig. 3 Energy results of baseline district

The figure shows that the heating demand varies, with a minimum of 389 MWh in April and a maximum of about 882 MWh (in January). Cooling peaks at roughly 91 MWh in July. Electricity demand remains relatively stable throughout the year, ranging between about 135 and 155 MWh per month.

5 PED Renovation Assessment

A comparative assessment of energy demands before and after the retrofit interventions is shown in Fig. 4.

Over the course of the year, heating demand in the renovated scenario is always lower than in the baseline, with monthly reductions ranging from about 27 MWh (in October) to over 270 MWh (in January).

By contrast, cooling demand, which remains small in the baseline (mostly below 90 MWh), becomes considerable in the renovated scenario in July and August, reaching 532 MWh and 559 MWh, respectively.

It is important to note that in the baseline simulation only one building is equipped with a heat pump. In the retrofit scenario, however, all the buildings are upgraded with heat pumps which results in a substantially higher cooling demand. Electricity usage generally rises after renovation, as evidenced by monthly increases from around 6 MWh (in January) up to 64 MWh (in July).

Figure 5 provides an in-depth analysis of the electricity balance for the renovated district scenario.

In the winter months, the generation ranges roughly from 39 MWh (December) to 61 MWh (February), while consumption range between 140 and 220 MWh, resulting in net imports from the grid. In summer, however, production rises to more than 137 MWh, covering part of electricity consumption.

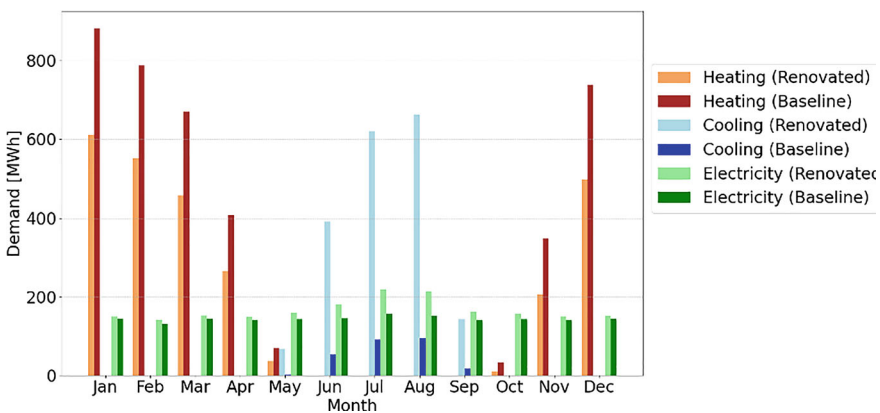


Fig. 4 Comparison of demand between renovated and baseline scenario

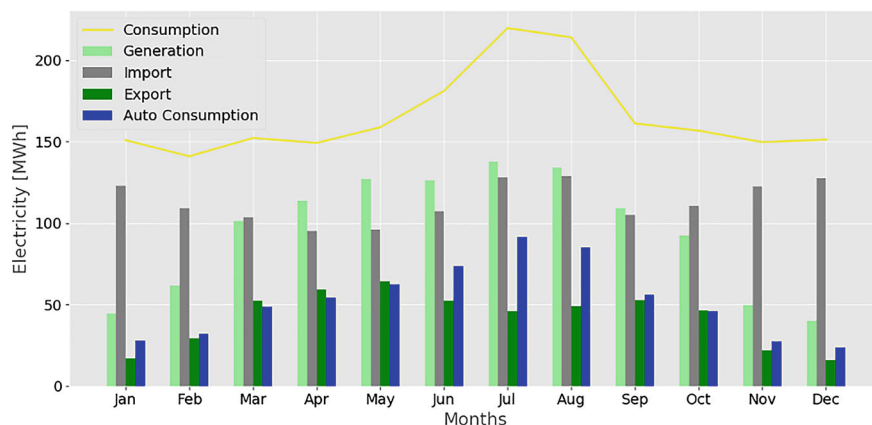


Fig. 5 Electricity balance of the renovated district

A summary of key energy indicators is provided in the Table 1.

In the baseline scenario, the district shows a heating demand of 3937.23 MWh, a cooling demand of 254.58 MWh and an electricity consumption of 1722.39 MWh. In contrast, the renovated scenario demonstrates a marked reduction in heating demand to 2633.03 MWh, approximately a 33% decrease—while cooling demand rises substantially to 1882.12 MWh, representing an increase of about 740%. Additionally, electricity consumption increases to 1986.19 MWh, marking roughly a 15% increase. The introduction of photovoltaic panels contributes 1136 MWh of on-site renewable generation, which corresponds to about 57% of the renovated electricity consumption. Despite this, the overall energy balance reveals that the district still imports 1356.94 MWh and exports 506.85 MWh, with 629.25 MWh being self-consumed. These indicate that while the renewable installation substantially offsets the electricity demand, it is insufficient to achieve a net-positive balance or fully meet the PED target.

Table 1 Comparison of energy results between baseline and renovated district

	Scenario baseline	Scenario renovated
Heating demand (MWh)	3937.23	2633.03
Cooling demand (MWh)	254.98	1882.12
Electricity consumption (MWh)	1722.39	1986.19
Electricity generation (MWh)	–	1136
Electricity import (MWh)	1722.39	1356.94
Electricity export (MWh)	–	506.85
Auto consumption (MWh)	–	629.25

6 Conclusions

This study demonstrates the substantial potential of adopting PED strategies in mixed-use urban areas of the Mediterranean region by examining three distinct retrofit interventions and their combined impact on district-level energy performance. First, installing natural-based insulation in walls and roofs reduced annual heating demand from approximately 3937–2633 MWh.

Next, replacing older heating systems with hydronic solutions caused a moderate increase in overall electricity consumption, which climbed from 1722 to 1986 MWh. At the same time, however, contributed to a notable rise in cooling demand—rising from about 254–1882 MWh. The rise in cooling demand in the retrofit scenario is due to the assumption that all buildings are equipped with heat pumps, whereas only one building in the baseline scenario has a heat pump, with the rest depend on gas boilers. This highlights a critical issue that may become increasingly significant in the future, particularly in regions like Southern Italy. As climate change drives higher temperatures and more frequent heat waves, the need for efficient cooling solutions will become essential in urban energy planning.

Finally, the installation of monocrystalline photovoltaic panels added approximately 1136 MWh of annual generation capacity, covering about 57% of the post-retrofit electricity consumption of 1986 MWh. Although seasonal fluctuations lead to periods of grid exports, the overall energy balance does not yield a net surplus.

These results provide practical insights for urban planners and policymakers. However, the initial analysis did not meet the PED target. Future studies will focus on formulating additional hypotheses and identifying other suitable areas for renewable energy installations. Moreover, incorporating advanced energy management solutions—such as energy storage systems and smart grid technologies—could further optimize the local energy balance.

References

1. Shukla PR, Skea J, Slade R, Al Khourdajie A (2022) IPCC, 2022: Climate change 2022—mitigation of climate change. Contribution of working group III to the sixth assessment report of the intergovernmental panel on climate change. Cambridge University Press. <https://doi.org/10.1017/9781009157926>
2. Urban Europe-Positive Energy Districts (PED). <https://jpi-urbaneurope.eu/ped/>. Accessed 5 Jan 2025
3. Fonseca JA, Nguyen TA, Schlueter A, Marechal F (2016) City energy analyst (CEA): integrated framework for analysis and optimization of building energy systems in neighborhoods and city districts. *Energy Build* 113. <https://doi.org/10.1016/j.enbuild.2015.11.055>
4. Loga T et al (2012) Typology approach for building stock energy assessment. Main results of the TABULA project. www.building-typology.eu www.iwu.de
5. Ricerca sul Sistema Energetico—RSE SpA (2024) RSEview RIFLESSIONI SULL'ENERGIA—I consumi della Pubblica Amministrazione Soluzioni e impatti economici per edifici pubblici più efficienti
6. British Standards Institution (2019) BS EN 16798-1:2019 energy performance of buildings—ventilation for buildings
7. ISO 18523:1 (2016) Energy performance of buildings-Schedule and condition of building, zone and space usage for energy calculation-Part 1: non-residential buildings. www.iso.org
8. Ministro dello sviluppo economico (2015) Decreto interministeriale 26 giugno 2015—Applicazione delle metodologie di calcolo delle prestazioni energetiche e definizione delle prescrizioni e dei requisiti minimi degli edifici
9. NREL. PVWatts V8. <https://developer.nrel.gov/docs/solar/pvwatts/v8/>. Accessed 30 Nov 2023

Investigating Dwelling Overheating Risks in Cooler Climates Using Ensemble-Based Machine Learning Surrogates of Parametric Dynamic Simulation Models



Omprakash Ramalingam Rethnam , Ciara Ahern , and Mark Mulville 

Abstract Most research on housing overheating focuses on extreme heat events in countries with tropical climates during the summer. For countries with temperate climates, with typically mild summer periods, the focus, to date, has been on retrofitting existing dwellings to reduce heating energy consumption in the cold months. However, because of climate change, there is an expected rise in temperature, particularly during summer, which poses a significant risk to dwellings of cooler climates, especially in areas that do not have cooling systems. Hence, to investigate the risk of overheating in summer in cooler climates, the research aims to quantify the effect of climate change on overheating risk in the context of Ireland and appraise the significant contributory factors among the building features towards overheating using a mid-floor apartment typology. The research employs an ensemble-based machine learning surrogate methodology using the dataset generated from the parametric dynamic simulation models. The study indicates that dwellings that fall under more energy-efficient classes may be at greater risk of overheating, with window specification and thermal mass as key contributory factors. Researchers and policymakers can replicate and implement the methodology adopted in the research to investigate possible climate adaptation strategies in countries with similar colder climates, thus moving towards creating climate-resilient dwellings.

Keywords Cold climate · Contributory factors · Dwelling · Dynamic simulation · Overheating

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1 Introduction

The recent UN Climate Change Conference (COP29) reiterated the international commitment to combating climate change efforts for faster progress in halving global emissions this decade [1]. Despite all these efforts, global emissions are still at record-high levels, and the world is warming by well over 2 °C, causing climate harm to become more severe [2]. Following a prolonged period of abnormally high monthly global mean temperatures, the World Meteorological Organization (WMO) has listed that 2024 is the warmest year on record, with the global average temperature between the months of January and September 1.54 (± 0.13) °C above the pre-industrial level [3]. Over the past few years, extreme events have become more frequent and intense due to climate change, and global warming has affected people's health and well-being [4]. Forecasts indicate that within the next several decades, high-heat events in urban areas will increase in frequency and severity [5]. According to studies, between 50 and 85% of fatalities during severe heat extremities are caused by high internal heat [6]. On the other hand, due to the potential impact on energy costs, some people, even though they feel warmer, stop using air conditioners [7]. In Ireland, a similar trend is observed where climate change is predicted to be a clear challenge for the built environment, per the Environmental Protection Agency [8]. In the context of overheating in homes, it is noted that most of the studies to date have been predominantly in warm climates, such as those found in southern Europe and Australia [9].

However, it is becoming more widely acknowledged that homes in temperate climates with an average annual temperature of about 13 °C, characterised by a lengthy winter heating season and a low prevalence of air conditioning—may also be vulnerable to overheating [10]. Since the amount of literature dealing exclusively with the effects of climate change on overheating risks in dwellings in cooler climates is limited, it is much needed for future research to delve into detail in this regard. This study explicitly addresses one aspect of overheating in the context of Ireland by focusing mainly on the building envelopes, which are conventionally considered the major contributory factors responsible for the heating and cooling load of the building [11, 12]. A single-dwelling typology, a two-zone middle-floor apartment of the Irish building stock, is considered for this study. The paper's main objective is to compare dwellings based on the relative overheating risk and understand the influence of each contributory factor, which includes orientation, air permeability, thermal mass, overall heat transfer coefficients of walls and windows, and total solar energy transmittance of windows [13].

2 Literature Review

In several temperate marine regions, the magnitude and intricacy of the overheating issue have been measured and documented, particularly in Scotland and England. During the warmest UK summer of 2018, Lomas et al. [14] conducted a comprehensive study on summertime overheating in 750 English households, estimating that 15% of the living rooms and 19% of the bedrooms are overheated overall. Additionally, compared to other dwelling types, the study discovered that overheating was much more common in the living rooms of apartments and tiny homes with a floor space of less than 50 m². Evidence of overheating was also found by Morgan et al. [15] in the post-occupancy evaluation of a heterogeneous group of 26 low-energy homes in Scotland. According to the passive house requirements, overheating occurred in four of the five certified passive house residences observed. Even in different regions of Ireland, overheating in homes is becoming a widespread challenge that needs immediate attention. A recent study, for instance, investigated the risk of overheating in 1100 social housing units in Dublin, Ireland, considering 2022 external climatic reports and internal temperature data [16]. According to the static criteria of Passivhaus, the results show that 42% of homes experienced overheating. Although countries with cooler climates presently face overheating challenges, as observed, the magnitude of overheating is expected to increase multifold because of the rising temperature with climate change. Limited studies detail how climate change influences building overheating and the adaptive measures that can be deployed to increase the resilience of the present building systems.

In Ireland, the study by Mulville et al. [9] is the first to review overheating risk in dwellings utilising localised future weather files to demonstrate climate change's impact on overheating projections. The study results echoed with some of the UK-based studies where it is found that the highest levels of overheating risk are found in middle and upper-floor apartments and other small homes, especially those that face south and west and have low thermal mass, which may be at risk due to the lack of solar protection. Hence, this study considers middle-floor apartments as its pivotal focus because of the high overheating risk documented amongst the Irish domestic building stock and to explore in detail the effect of various building contributory factors that are responsible for overheating, which include wall material, glazing type, site orientation, air permeability, and thermal mass [11–13]. Although their significance attributing to overheating is widely recognised, their relative importance to the overheating potential, considering the future weather, is a gap that this study tries to address. Such an investigation will help us to plan appropriate adaptive strategies and to invest in a feasible action plan that can be considered in the present so that the large-scale retrofitting programs can be further beneficial, increasing the resilience of the buildings against overheating in the future.

3 Research Methods

The research utilises ensemble-based machine learning surrogates of parametric dynamic simulation models to investigate the overheating risk of the typology dwelling. The overall schematic representation of the methodology used in the research is given in Fig. 1.

This research set out to understand overheating risk in dwellings in Ireland with a temperate climate, using the archetype middle-floor apartment dwelling in the greater Dublin Area as a case study. The building geometry is as per the recent study that used the Building Energy Rating (BER) database and Central Statistics Office (CSO) database to develop updated representative typologies for Ireland [17], internal gains and occupancy profiles as per TM59 [18], 20% window opening areas, and modelled using Met Eireann’s Translate weather files for Dublin (DSY1) representing the future climate of the 2050s. The parametric modelling is carried out using the IES Virtual Environment (version 2023.2.0.0) software with the contributory factors discussed in the literature, i.e. wall material (and u-value), glazing type, site orientation, air permeability, and thermal mass. All the key inputs used for the parametric simulation are detailed in Table 1, with a total of 288 output files generated.

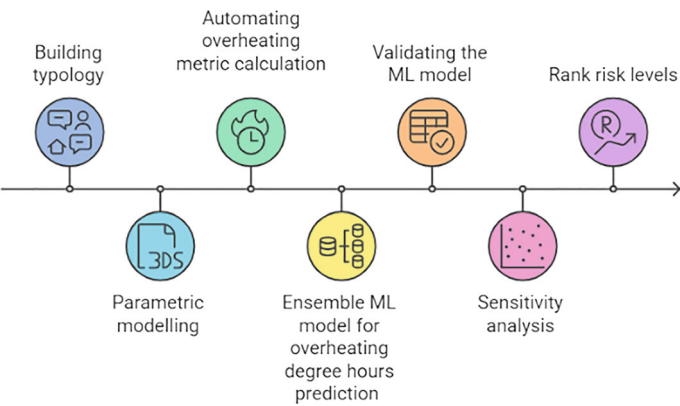


Fig. 1 Overall methodology used for evaluating the overheating risk of the typology dwelling

Table 1 DSM parametric inputs

Features	Input
Orientation	North, South, East, West
Thermal mass	140, 315 (KJ/m ² K)
Air permeability	3, 7 (m ³ /h/m ² @50pa)
Wall U-value	0.15, 0.30, 0.45 (W/m ² K)
Window U-value	0.8, 1.2, 2.2 (W/m ² K)
Window g-value	0.5, 0.7

The parametric analysis is carried out hourly for the entire year. For residences with mechanical ventilation and bedrooms with natural ventilation, CIBSE recommends an upper-temperature threshold of 26 °C [18]. The present study considers only the bedroom as it can be occupied for extended hours during sleep, making people more vulnerable to heat stress, unlike other rooms with intermittently occupied hours. Accordingly, the results from the parametric runs are used to investigate the overheating degree hours (Dh) exceeding the threshold (not the compliance) defined by the standard for the bedroom under all cases, which is automated through Python scripting. Then, considering Dh as the dependent variable, with all the building features as the input variables, a Random Forest (RF) ensemble-based machine learning model that is best known for capturing non-linear relationships between input and target variables is employed to create a model that can predict Dh based on orientation [19]. The ensemble-based ML models are further validated for accuracy using the coefficient of determination (R^2) and mean absolute error (MAE) metrics, with 20% dataset con. After validation, the Sobol sampling technique is applied to the ML model to generate datasets to check the impact of the independent building contributory factors on the dependent Dh for each bedroom orientation. The variance-based sensitivity analysis technique measures the proportion of variation that each parameter adds to the model output's unconditional variance [20]. These amounts are represented as Sobol's Total-Order Index, which signifies the impact of a single parameter or the interplay of two or more parameters over the Dh. The dwellings are finally compared based on the relative overheating risk, and the low-risk and high-risk dwellings, along with the relevant contributory factors, are identified.

4 Findings and Discussion

The validation results of the RF ensemble-based machine learning model showed the R^2 value for all the orientations to be greater than 0.95 and the MAE to be less than 12 DH, proving the model's reliability. The Sobol total order sensitivity indices that were obtained by performing the Sobol sampling using the validated ML models are shown in Fig. 2.

The window's total solar transmittance (g-value) was observed to have the highest impact on overheating, with the Sobol total index greater than 0.4 in all orientations except the north. With the northern façade, the thermal mass had the highest impact with a total index of about 0.5, with the window g-value having the following highest implications for overheating. In all the orientations, air permeability comes next to the window g-value and the thermal mass, having the Sobol total index ranging between 0.15 and 0.25. However, the wall and window's thermal transmittance (U-Value) had the least impact on overheating, with a very low index score of less than 0.1. The results show that the solar gain through windows and the thermal mass of the envelope are the highest influencers of overheating in comparison to the thermal transmittance of the building envelope. Further to the sensitivity test, the overheating

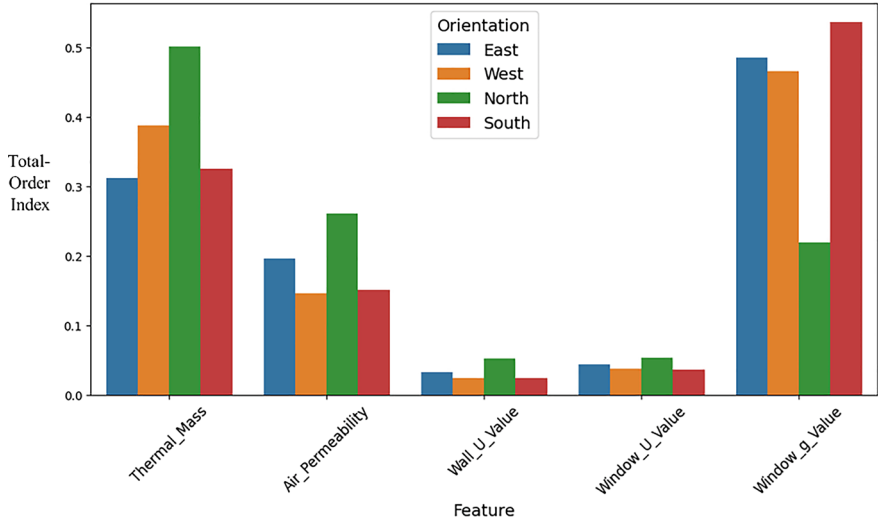


Fig. 2 Sobol total order sensitivity indices of different features

degree hours were evaluated for the building façade facing different orientations to identify the lowest-risk and highest-risk dwellings, along with the relevant building features. The results are shown in Fig. 3 along with the relative overheating risk fractions.

The dwellings were initially compared based on their respective highest risk levels at each orientation. It was observed that the apartment dwelling, with a north-facing orientation, had a relative overheating risk of 18.4%, with only 83.4 Dh, even with a high g-value of 0.5, compared with dwellings with other facades exposed to the sun. The dwelling with the exposed southern façade exhibited the highest risk of overheating with 453.2 Dh (relative overheating risk of 100%), with the western façade having 402.2 Dh (relative overheating risk of 88.7%) and the east façade having 316.2 Dh (relative overheating risk of 69.8%). When the best contributory

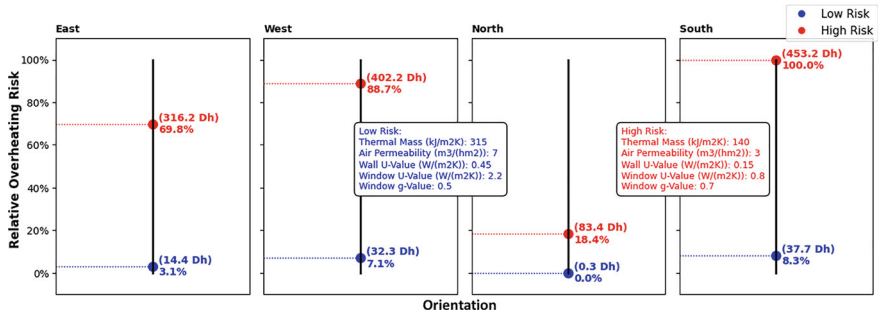


Fig. 3 Low-risk versus high-risk dwellings for each orientation

factors were selected as the scenario of lowest-risk levels for each orientation, it was observed that around 415.4 Dh reduction is possible in the southern façade bringing down the relative overheating risk to 8.3%, with a low window g-value and high thermal mass, high air permeability, and high U-value of walls and windows. The possible reduction was 370 Dh in the dwelling with an exposed western façade (reduced relative overheating risk of 7.1%), 302 Dh reduction for the east façade (reduced relative overheating risk of 3.1%), and the lowest reduction of 83 Dh for the northern façade. In all cases, the best configuration of building contributory factors to reduce the overheating risk was observed to have the lowest window g-value and the highest values of thermal mass, air permeability, and U-value of windows and walls when tested within the parameters chosen for the analysis.

5 Conclusions

This research utilised ensemble-based machine learning surrogates of parametric dynamic simulation models to investigate the effect of different building contributory factors on the overheating risk of the Irish middle-floor apartment typology. The results indicate that the dwelling with the exposed southern façade is at the highest overheating risk, and the one with the northern façade is at the least overheating risk based on the indoor temperature of 26 °C threshold. It was also found that the solar gain through the windows is the highest contributor out of all the selected building features on overheating without considering the solar shading, which is a limitation of the study, with the thermal mass coming next and the air permeability following it. The thermal transmittance of the building envelopes, which is conventionally considered to be best at its lowest value based on Passivhaus standards, on the contrary, seems to increase the risk of overheating because of the intrinsic property to retain the trapped heat within the dwelling in the hotter months of the year. The conclusions aid in developing strong regulatory standards and guidelines by focussing on the right contributory factors that reduce the risk of overheating in homes in cooler climates, considering the anticipated effects of climate change.

References

1. COP29 UN Climate Conference Agrees to Triple Finance to Developing Countries, Protecting Lives and Livelihoods | UNFCCC. <https://unfccc.int/news/cop29-un-climate-conference-agrees-to-triple-finance-to-developing-countries-protecting-lives-and-> Accessed 6 Mar 2025
2. C. C. Committee (2022) COP27: key outcomes and next steps for the UK. <https://www.theccc.org.uk/publication/cop27-key-outcomes-and-next-steps-for-the-uk/>
3. 2024 is on track to be hottest year on record as warming temporarily hits 1.5°C. <https://wmo.int/news/media-centre/2024-track-be-hottest-year-record-warming-temporarily-hits-15degc>. Accessed 6 Mar 2025

4. Mora C et al (2017) Global risk of deadly heat. *Nat Clim Chang* 7(7):501–506. <https://doi.org/10.1038/nclimate3322>
5. Bartos MD, Chester MV (2014) Assessing future extreme heat events at intra-urban scales : a comparative study of Phoenix and Los Angeles
6. Cadot E, Rodwin VG, Spira A (2007) In the heat of the summer: lessons from the heat waves in Paris. *J Urban Health* 84(4):466–468. <https://doi.org/10.1007/s11524-007-9161-y>
7. Soebarto V, Bennetts H (2014) Thermal comfort and occupant responses during summer in a low to middle income housing development in South Australia. *Build Environ* 75:19–29. <https://doi.org/10.1016/j.buildenv.2014.01.013>
8. Research 418: Built Environment Climate Resilience and Adaptation | Environmental Protection Agency. <https://www.epa.ie/publications/research/climate-change/research-418-built-environment-climate-resilience-and-adaptation.php>. Accessed 6 Mar 2025
9. Mulville M, Harrington S, Li C, Raushan K, Essien-thompson E, Ahern C (2025) Dwelling overheating in risk in cool climates : assessing the risk in the context of retrofit and climate change in Ireland, vol 2, no August 2024. <https://doi.org/10.1016/j.indenv.2025.100072>
10. Colclough S, Salaris C (2024) Quantifying overheating in nZEB Irish residential buildings. An analysis of recorded interior temperatures of Irish newbuild and retrofit residential buildings against CIBSE, Passive House and WHO overheating criteria and recorded occupant satisfaction. *Energy Build* 303, no September 2023. <https://doi.org/10.1016/j.enbuild.2023.113571>
11. Rethnam OR, Thomas A (2024) A modeling-based decision support system for enabling mass net-zero energy retrofit of building communities in developing countries. *J Arch Eng* 30(3):1–15. <https://doi.org/10.1061/JAEIED.AEENG-1738>
12. Rethnam OR, Thomas A (2023) A customizable community-building-energy-modeling decision support system (CCBEM-DSS) for net-zero planning in developing countries. In: 2023 winter simulation conference (WSC), pp 3166–3177. <https://doi.org/10.1109/WSC60868.2023.10407443>
13. Mulville M, Stravoravdis S (2016) The impact of regulations on overheating risk in dwellings. *Build Res Inform* 44(5–6):520–534. <https://doi.org/10.1080/09613218.2016.1153355>
14. Lomas KJ et al (2021) Dwelling and household characteristics' influence on reported and measured summertime overheating: a glimpse of a mild climate in the 2050's. *Build Environ* 201. <https://doi.org/10.1016/j.buildenv.2021.107986>
15. Morgan C, Foster J et al (2015) Overheating in Scotland: lessons from 26 monitored low energy homes. In: infoscience.epfl.chC Morgan, JA FOSTER, T Sharpe, A Poston proceedings of international conference CISBAT 2015 Future, 2015 infoscience.epfl.ch. https://infoscience.epfl.ch/record/213311/files/2_MORGAN.pdf. Accessed 7 Mar 2025
16. Sajadirad F, Kinnane O, O'hegarty R (2024) PLEA 2024 WROCLAW (re)thinking resilience incidence of overheating in Irish homes for the range of building energy rated dwellings. In: PLEA 2024 WROCLAW. <https://www.researchgate.net/publication/388559679>
17. Li C, Raushan K, Essien-Thompson E, Mulville M, Ahern C (2025) Next generation reference dwellings for ireland: a short communication. Dublin
18. Technical Memorandum 59: Design methodology for the assessment of overheating risk in homes | CIBSE. <https://www.cibse.org/knowledge-research/knowledge-portal/technical-memorandum-59-design-methodology-for-the-assessment-of-overheating-risk-in-homes>. Accessed 12 Mar 2025
19. Krishnan S et al (2024) Evaluating the capabilities of surrogate modeling techniques in predicting hourly building energy consumption. In: Proceedings of the European conference on computing in construction, vol 5. <https://doi.org/10.35490/EC3.2024.263>
20. Nossent J, Elsen P, Bauwens W (2011) Sobol' sensitivity analysis of a complex environmental model. *Environ Model Softw* 26(12):1515–1525. <https://doi.org/10.1016/J.ENVSOF.2011.08.010>

Green Roofs and Green Walls to Enhance Buildings Energy Efficiency



Maria Manso  and Alena Harbiankova 

Abstract In order to address concerns on buildings energy efficiency and their sustainability in urban development, there is a necessity to identify solutions that contribute to improve buildings thermal performance. Green roofs and green walls are nature-based solutions which contribute to improve buildings' thermal performance and reduce energy consumption for heating and cooling. However, their effectiveness is influenced by variations in their design, material properties, and thermal characteristics. The focus of this study was to collect and analyze the thermal characteristics of different types of green roofs and walls. A bibliometric analysis of the existing literature was conducted using an adapted PRISMA approach to review the thermal characteristics of extensive, semi-intensive, and intensive green roofs, as well as living walls and green facades. The study focused on variations in design, material properties, and specific parameters such as thermal resistance, thermal conductivity and U-values. The findings provide a comprehensive overview of the thermal characteristics of green roofs and walls, emphasizing their variability across different system types. This demonstrates the necessity for updated construction regulations to facilitate the effective adoption of these systems in urban development, ensuring their optimal thermal performance and contribution to sustainability goals.

Keywords Nature-based solutions · Green roofs · Green walls · Energy efficiency · Sustainable development

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1 Introduction

The EU has issued directives to address energy efficiency, with the most significant ones being the Energy Efficiency Directive [1] and the Energy Performance of Buildings Directive [2]. The Energy Efficiency Directive (EED) is pivotal in reducing energy consumption and promoting efficiency across sectors. Its primary objectives are to reduce energy consumption, efficiency and security, as well as concerns related to energy poverty and climate adaptation [3]. The EU is committed to improving building energy performance, as set out in the revised Energy Performance of Buildings Directive, which follows on from previous initiatives. By 2030 the annual energy renovation rate of buildings should double and deep renovation is encouraged. Vulnerable citizens and SMEs are being supported via the Social Climate Fund [4].

Another issue is a deficit of green spaces in urban areas. The average percentage of urban green spaces in EU capital cities is about 7% [5]. Recent studies present mostly a traditional approach to improving building energy performance with limited response to sustainable development. Integrating nature-based solutions into building design is expected to be an effective approach to address both economic and environmental issues [6].

2 Materials and Methods

The bibliometric analysis employed an adapted PRISMA framework to ensure a systematic and transparent review process. The literature search targeted peer-reviewed publications of greening systems, focusing on thermal performance indicators such as thermal conductivity, U-values, and thermal resistance. Articles were selected based on their quantitative data on these parameters, with attention to design variations like substrate thickness, vegetation type, and ventilation gap between the system and the support. The categorization by greening system (GS) type allowed for comparative analysis, revealing both strengths and gaps in the existing research.

A literature search was conducted on the Web of Science and Scopus in April 2024, with a further search in October 2024. The search was limited to papers related to the terms and subject areas (see Fig. 1). The timespan considered was from 2012 to 2024, with the aim of achieving a contemporary and comprehensive scope. The review encompassed 66 studies across diverse contexts and typologies of GSs. A full-text examination led to the exclusion of 41 studies, leaving 25 that meet the defined inclusion criteria. This study attempts to explain in more detail the methodology used in the recently published review article [7].

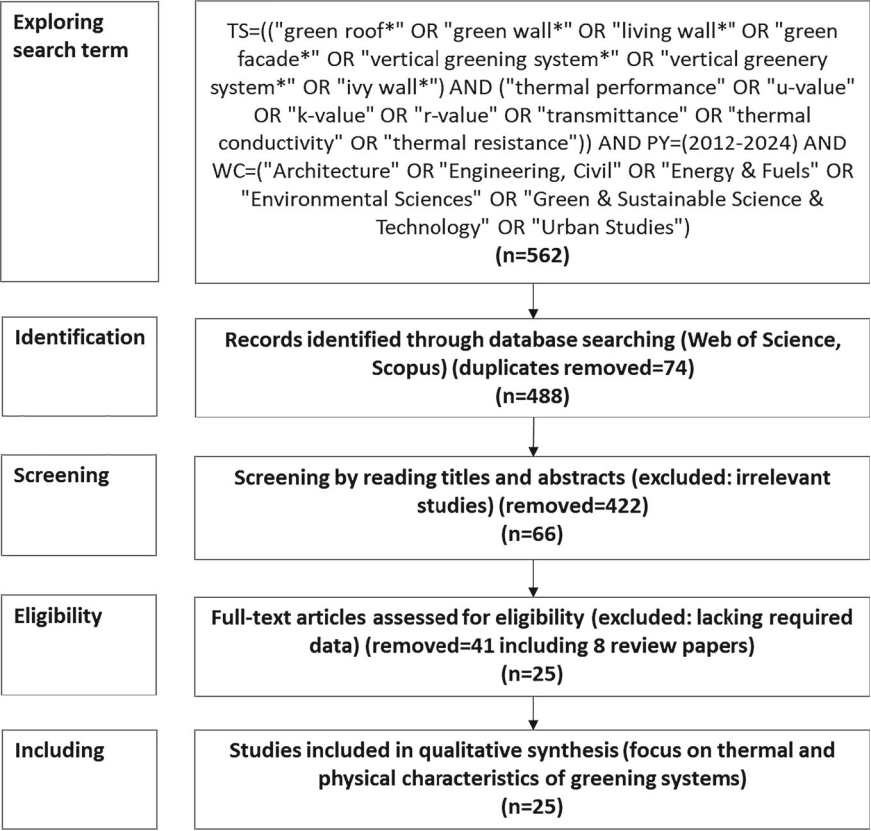


Fig. 1 The PRISMA flow diagram

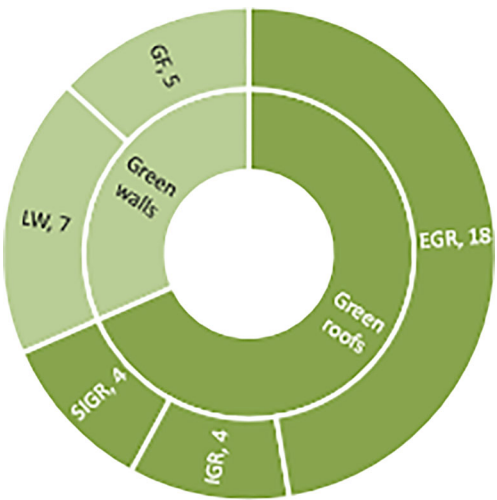
3 Results and Discussion

A strong research focus on extensive green roofs (EGR) was identified, with growing interest in living walls compared to green facades (Fig. 2). The observed imbalance between green roofs (GRs) and green walls (GWs) research indicates a necessity to further explore the thermal performance of vertical greening systems.

Most research focuses on the combined cooling and heating effects of GS (16 studies), with significant attention to cooling alone (8 studies) and minimal focus on heating (1 study). This distribution indicates a necessity for further research on winter performance to balance the understanding of GS thermal benefits across seasons, particularly in colder climates.

Further research on the thermal performance of GS is predominant on Temperate climates (Fig. 3), including 21 studies, constituting 58.3% of the total. Notably, Csa (warm-summer Mediterranean) exhibits the highest prevalence, accounting for 9

Fig. 2 Number of studies analyzed considering GS type: *EGR* extensive green roofs, *SIGR* semi-intensive green roofs, *IGR* intensive green roofs, *GF* green facades, *LW* living walls



studies. This observation suggests that research is focused on climates where conditions are moderate, and where GS can address the dual needs of summer cooling and winter insulation.

The comparative analysis of study types reveals that 14 papers employed a simulation approach and 11 utilized an experimental method (Fig. 4). It is noteworthy that the majority of experimental studies encompass more extensive data sets on the thermal characteristics of GS across diverse types.

The results on numerical data of thermal characteristics indicate considerable variability across various GS types (Table 1). This variation is influenced mostly

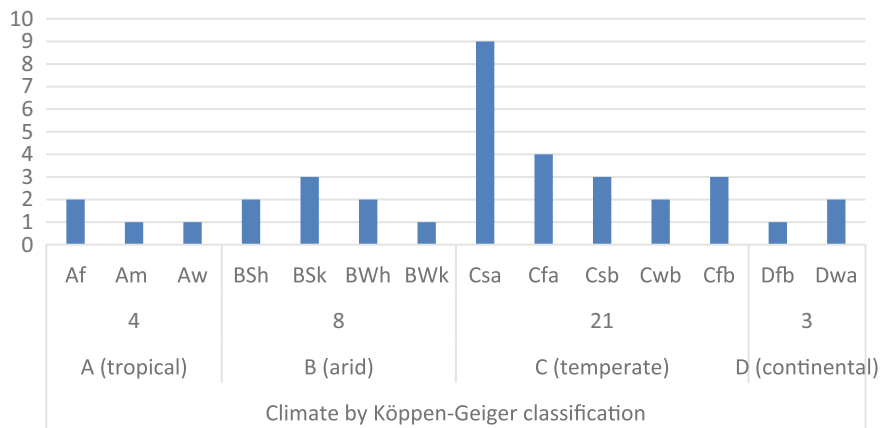


Fig. 3 Number of analyses considering Köppen-Geiger climate classification. *Note:* some articles analyzed more than one type of climate



Fig. 4 Number of studies by type, including simulation and experimental

by design aspects (ventilation gaps, building zoning), and physical characteristics (moisture of materials, outdoor temperature considering season). Although 25 articles were used for this research analysis, Table 1 presents only the references that summarize the thermal characteristics of GRs and GWs considering all their layers.

The variability in thermal performance indicates that GRs and GWs can enhance energy efficiency, although their implementation requires context-specific designs. EGRs, with U-values as low as 0.19 W/m² K, are well-suited for retrofitting, while LWs provide cooling benefits in summer because of evapotranspiration. However, data gaps for SIGRs, IGRs, and GFs limit standardization, as referenced in [7]. These findings are consistent with recent reports, such as one on designing for maximum energy benefits, which emphasizes optimizing design elements for different climates [18].

The data provided offers a comprehensive comparison of thermal properties—thermal transmittance (U-value) and thermal resistance (R-value) across various roof and wall constructions, including green roofs and green walls. These parameters are critical for evaluating building thermal efficiency and energy performance.

U-values indicate the rate of heat transfer through building elements, with lower values signifying better insulation. Green roofs show improved thermal performance compared to uninsulated standard roofs, with U-values ranging from 1.75 to 0.33 W/m² K as insulation increases. Cool roofs similarly improve with insulation, matching green roofs at 0.35 W/m² K [8]. These values align with other studies where extensive green roofs typically range from 0.79 to 1.40 W/m² K depending on vegetation and substrate thickness, while semi-intensive and intensive green roofs can achieve

Table 1 Thermal characteristics of green roofs and green walls

GS type	Thermal characteristics of greening systems							
	U-value, W/m ² K				R-value, m ² K/W			
	Min	Max	Average	References	Min	Max	Average	References
EGR	0.19	1.75	0.7268	[8–13]	0.80	2.01	1.37	[14]
SIGR	0.17	0.426	0.3363	[12, 15]				
IGR	0.248	0.305	0.2765	[13]				
GF	0.362	1.15	0.7043	[15, 16]	0.87	1.48	1.175	[16]
LW	0.12	0.62	0.3133	[16, 17]	2.97	5.08	4.025	[16]

U-values as low as 0.17–0.33 W/m² K, comparable or superior to cool roofs and insulated standard roofs.

R-values represent the material's resistance to heat flow; higher values indicate better insulation. Green roofs demonstrate significantly high resistance, ranging from 0.8 to 2.01 m² K/W depending on substrate depth and composition. Green walls show even greater thermal resistance; modular green walls reach R-values near 3.38–4.67 m² K/W, and linear green walls exceed 5.0 m² K/W, substantially improving upon conventional brick or concrete walls, which typically have R-values below 1.5 m² K/W. This indicates that green walls can provide substantial insulation benefits, reducing heat loss in winter and heat gain in summer.

Optimal thermal performance for green roofs and walls is characterized by low U-values (ideally ≤ 0.3 W/m² K) and high R-values (≥ 1.5 m² K/W for roofs, and ≥ 3.0 m² K/W for walls). Intensive green roofs and modular or linear green walls meet or exceed these benchmarks, reflecting their effectiveness in reducing heat transfer and improving building energy efficiency. The dynamic nature of greening systems—such as moisture content affecting substrate thermal properties—means actual performance can vary [16]; for instance, green roofs' U-values can increase when substrates dry out [11]. Therefore, while static values provide useful benchmarks, they should be interpreted in the context of operational conditions.

Current construction regulations, such as EU Directive 2018/844, promote energy-efficient renovations but often overlook the dynamic thermal properties of NbS. To illustrate, the moisture content of substrates has been demonstrated to enhance thermal conductivity, thereby impacting performance, yet this aspect is typically not specified in existing guidelines. Consequently, there is a critical need for updated standards that consider NbS variables to ensure their optimal integration into urban environments. This recommendation is evidenced by recent studies demonstrating that green roofs can reduce heat gain during cooling months, underscoring their potential in highly insulated buildings [15, 19].

4 Conclusion

In conclusion, green roofs and green walls are essential for improving both building energy efficiency and urban resilience. The bibliometric analysis reveals their variability in thermal performance, with EGRs and LWs showing significant potential, but data gaps for other types underscore the need for further research. Updated building codes that include thermal conductivity, U-values, and design-specific guidelines are essential for effective adoption. Future research should focus on field validation and standardized testing, particularly in diverse climates, to fill these gaps and support sustainable urban development goals.

Furthermore, the long-term durability of green roofs and walls is a significant consideration. While these systems demonstrate considerable benefits, their effectiveness over time is contingent on proper maintenance and the longevity of the materials utilized. Several factors can impact the thermal performance and overall

functionality of these systems, including degradation of substrates, failure of irrigation systems, or loss of vegetation. Inadequate maintenance has been demonstrated to result in diminished insulation effectiveness over time, particularly in systems such as living walls where irrigation systems are essential [20]. Similarly, extensive green roofs risk substrate degradation or vegetation loss without regular monitoring, thereby reducing their energy-saving capacity [21].

Addressing these challenges requires a comprehensive approach to research, encompassing not only the optimization of initial design but also investigating long-term performance, including durability, maintenance needs, and cost-effectiveness. By addressing these aspects, policymakers and relevant practitioners can develop more advanced guidelines and strategies for implementing green roofs and walls, thereby ensuring their sustainability and effectiveness in the context of urban development.

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References

1. Directive (EU) 2023/1791 of the European Parliament and of the Council of 13 September 2023 on energy efficiency and amending Regulation (EU) 2023/955. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=OJ:L_2023_231_R_0001. Accessed 23 May 2025
2. Directive (EU) 2024/1275 of the European Parliament and of the Council of 24 April 2024 on the energy performance of buildings (recast). https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=OJ:L_202401275&pk_keyword=Energy&pk_content=Directive. Accessed 23 May 2025
3. Energy Efficiency Directive. Energy Efficiency Directive. Accessed 20 June 2024
4. Energy Performance of Buildings Directive. https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficient-buildings/energy-performance-buildings-directive_en. Accessed 20 June 2024
5. Percentage of total green infrastructure, urban green space, and urban tree cover in the area of EEA-38 capital cities (excluding Liechtenstein). <https://www.eea.europa.eu/en/analysis/maps-and-charts/percentage-of-total-green-infrastructure#related-content>. Accessed 31 Jan 2025
6. Borràs JG, Lerma C, Mas Á, Vercher J, Gil E (2022) Contribution of green roofs to energy savings in building renovations. *Energy Sustain Dev* 71:212–221. <https://doi.org/10.1016/j.esd.2022.09.020>

7. Harbiantkova A, Manso M (2025) Integrating green roofs and green walls to enhance buildings thermal performance: a literature review. *Build Environ* 270:112524. <https://doi.org/10.1016/j.buildenv.2025.112524>
8. Gagliano A, Detommaso M, Nocera F, Evola G (2015) A multi-criteria methodology for comparing the energy and environmental behavior of cool, green and traditional roofs. *Build Environ* 90:71–81. <https://doi.org/10.1016/j.buildenv.2015.02.043>
9. Coma J, Pérez G, Solé C, Castell A, Cabeza LF (2016) Thermal assessment of extensive green roofs as passive tool for energy savings in buildings. *Renew Energy* 85:1106–1115. <https://doi.org/10.1016/j.renene.2015.07.074>
10. Berardi U, La Roche P, Almodovar JM (2017) Water-to-air-heat exchanger and indirect evaporative cooling in buildings with green roofs. *Energy Build.* 151:406–417. <https://doi.org/10.1016/j.enbuild.2017.06.065>
11. Zheng X, Yang Z, Yang J, Tang M, Feng C (2022) An experimental study on the thermal and energy performance of self-sustaining green roofs under severe drought conditions in summer. *Energy Build* 261:111953. <https://doi.org/10.1016/j.enbuild.2022.111953>
12. Maurer B, Lienert J, Cook LM (2023) Comparing PV-green and PV-cool roofs to diverse rooftop options using decision analysis. *Build Environ* 245:110922. <https://doi.org/10.1016/j.buildenv.2023.110922>
13. Khabaz A (2018) Construction and design requirements of green buildings' roofs in Saudi Arabia depending on thermal conductivity principle. *Constr Build Mater* 186:1119–1131. <https://doi.org/10.1016/j.conbuildmat.2018.07.234>
14. Collins S, Kuoppamäki K, Kotze DJ, Lü X (2017) Thermal behavior of green roofs under Nordic winter conditions. *Build Environ* 122:206–214. <https://doi.org/10.1016/j.buildenv.2017.06.020>
15. Thermal performance of green façades using a numerical evaluation. <https://fenix.tecnico.ulisboa.pt/downloadFile/281870113702950/Extended%20Abstract%20Diogo%20Serpa.pdf>. Accessed 1 July 2024
16. Mohammad Shuhaimi NDA, Mohamed Zaid S, Esfandiari M, Lou E, Mahyuddin N (2022) The impact of vertical greenery system on building thermal performance in tropical climates. *J Build Eng* 45:103429. <https://doi.org/10.1016/j.job.2021.103429>
17. Tudiwer D, Korjenic A (2017) The effect of living wall systems on the heat resistance value of the façade. *Int J Earth Environ Sci* 2(2). <https://doi.org/10.15344/2456-351X/2017/141>
18. Manso M, Teotónio I, Silva CM, Cruz CO (2021) Green roof and green wall benefits and costs: a review of the quantitative evidence. *Renew Sustain Energy Rev* 135:110111. <https://doi.org/10.1016/j.rser.2020.110111>
19. Cascone S, Gagliano A, Poli T, Sciuto G (2019) Thermal performance assessment of extensive green roofs investigating realistic vegetation-substrate configurations. *Build Simul* 12(3):379–393. <https://doi.org/10.1007/s12273-018-0488-y>
20. Feng H, Hewage K (2014) Lifecycle assessment of living walls: air purification and energy performance. *J Clean Prod* 69:91–99. <https://doi.org/10.1016/j.jclepro.2014.01.041>
21. Bondi C, Concialdi P, Iovino M, Bagarello V (2023) Assessing short- and long-term modifications of steady-state water infiltration rate in an extensive Mediterranean green roof. *Heliyon* 9(6):e16829. <https://doi.org/10.1016/j.heliyon.2023.e16829>

The Potential of Urban Digital Twins for Renewable Energy Communities



Sebastiano Anselmo  and Maria Ferrara 

Abstract In the current context of the energy transition, specific interest has arisen around the concept of Renewable Energy Communities. These consist of collective cooperations of energy related activities which have the potential to improve the sustainability of the whole energy system but require accurate analyses of both the energy demand and potential production from Renewable Energy Sources before implementation. Therefore, a strong need for tools supporting all interested actors in dimensioning and managing the energy community emerges. Geographic Information Systems are powerful tools to model extensive areas by spatially displaying and integrating multiple data to produce new information. This study presents the findings of the DT4Energy.com project, implemented in Ivrea, Italy. The project goal was to develop a Urban Digital Twin platform to support decision-making for the creation of a new energy community by leveraging earth observation and detailed energy data. Both authoritative sources (as the Energy Performance Certificates) and proprietary information (as consumption data made available by the project partners) have been integrated into a 3D geometric model to model the total energy demand. The potential electricity production from solar energy has been evaluated through solar radiation modelling from open-source GIS tools. Thanks to the developed platform it is possible to verify the compliance with the normative requirements and the consumption and solar production profiles, and to quantify the self-consumption potential and the possible benefits of the energy community. The findings highlight the potential of the platform and outline future developments.

Keywords Energy Performance Certificate · Energy planning · Urban Energy Modelling · Consumption analysis · Photovoltaic potential

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1 Introduction

Energy Communities are comprehensive solutions which foster collaboration around energy-related activities [1], tackling simultaneously different dimensions of sustainability in the energy sector. Indeed, by promoting self-production, Energy Communities aim to tackle social and environmental problems derived from the use of fossil fuels.

In Europe, the Renewable Energy Directive 2018 recast [2] introduced the concept of Renewable Energy Community, promoting local production of renewable energy autonomously from traditional energy stakeholders. The participation to the REC, regulated as a legal entity, is open and voluntary, with shared ownership.

One of the principal barriers for citizens and Public Administrations in the creation of RECs is the need for tools for preliminary assessments, including the identification of suitable areas and the dimensioning of the REC. The project Digital Twin for Energy Communities (DT4Energy.com), carried out by AEG Coop and Idea System S.r.l. with the scientific support of the Polytechnic University of Turin, aims to fill this gap.

Digital Twins, virtual representations of a physical object alone and in its environment [3], have the potential to support energy practitioners in multiple applications, such as the optimization of energy consumption patterns [4] and the photovoltaic potential prediction [5]. Three-dimensional city models, adequately enriched with semantic information, serve as basis for estimating both consumption and potential production from renewable sources.

2 Methodology

The project DT4Energy.com adopted San Lorenzo district as a pilot area. The 2 km² case study, located in Ivrea, a small size city in North-Western Italy, is highly heterogeneous in terms of both land uses and building morphologies. From North to South, variations pertain mainly to the building morphology, with residential buildings transitioning from small detached villas to high-rise condominiums, reaching heights of 30 m (equal to 9 floors). On the other hand, from East to West there is a shift from a wide industrial shopfloors to dense residential buildings.

This heterogeneity is reflected in both the consumption—with different uses showing different patterns and quantities—and potential production—with varying heights casting complex shadows to be modelled and different installation surfaces resulting in different photovoltaic potentials.

2.1 *Energy Demand Analysis*

In order to define the energy demand on the scale of the volumetric unit, data from Energy Performance Certificates and proprietary data made available by AEG Coop were exploited. Both electricity and gas were considered, while district heating, albeit present in the area, was not included in the calculation. As for electricity, consumptions were assumed to be independent from the outdoor climatic conditions: mechanical ventilation consumptions were removed from EPC consumptions and peak powers greater than 3 kW were excluded from AEG data. On the other hand, gas consumption from the EPCs was corrected to account for the climatic conditions of the year of AEG data, 2023. A direct correlation between consumptions and Heating Degree Days was used for this end.

The building stock has been subdivided into sixteen segments, according to six classes on the use of the building and four building morphology classes. The information necessary for this step was gathered from the Regional Technical Map of Piedmont Region. The number of dwellings per building was calculated for all buildings based on the average dwelling dimension of every building segment. This information was then used to scale energy data to the whole building, after they had been aggregated by address. The only exception is represented by buildings with EPC issued for the whole building, not to be scaled up.

When available—in 27.7% of cases—AEG data are preferred, as metered consumptions are believed to be more accurate, despite possible malfunctions to a single meter, compared to simulated data from EPCs, often resorting to default values as inputs. For the same reason, AEG data were also used to compute—for each of the sixteen segments previously identified—two indicators: the average Energy Usage Intensity and a correction factor for EPC data. While the EUI is applied to compute the energy demand of buildings with no available data, the correction factor is applied to the 299 cases in which only EPC data are available in order to better return the variability within the different segments, while correcting the inaccuracies pointed out in literature [6].

2.2 *Photovoltaic Potential Estimation*

The photovoltaic potential is calculated according to a formula which integrates solar radiation with indicators on the performance of the system, the efficiency of the panel and the exploitable area. Recognized in a recent review by Anselmo and Ferrara [7] as the most used when calculating the photovoltaic potential with GIS tools, it is presented as Eq. 1:

$$E = I * \eta * PR * A \quad (1)$$

where E is the electricity output, I the incoming irradiation, η the conversion efficiency of the panel (27.8% according to literature [8]), PR the performance ratio of the system (80% according to the mentioned review) and A the installation area.

The irradiation is computed through the `r.sun.insoltime` tool in QGIS v3.34.11. Based on a high-resolution Digital Surface Model and derived products (slope and aspect layers), it models shadows and resulting share of radiation components (direct, diffuse, reflected). The radiation intensity is calculated starting from two meteorological parameters, that are the Linke turbidity factor and the diffuse-to-global radiation ratio. The Digital Surface Model derives from an aerial LiDAR acquisition carried out in the context of DT4Energy.com in March 2024 and has a ground sampling distance equal to 0.5 m. The weather parameters are calculated as the average of the values returned by multiple sources, including PVGIS, SoDa, ENEA, Meteotest AG.

The classified LiDAR point cloud from which the DSM was extracted served also as basis for extracting roof geometries. Installation area was calculated as the total area of each pitch after having removed a 1 m buffer for installation and maintenance. Suitable pitches are selected as the ones with an area that allows for the installation of 3 kW_p of peak power (>15 m²), with favorable orientation and little shading.

3 Results

3.1 Total Energy Demand

The total energy demand is equal to 148.7 GWh/year of electricity and 58.25 GWh/year of gas. Considering a non-renewable primary energy conversion factor equal to 1.05 for natural gas and 1.95 for electricity according to the Italian legislation, it clearly emerges the prevalence of electricity, accounting for 83% of the total primary energy demand. A high share of the energy demand is concentrated in the Eastern part, with industrial buildings consuming 36% of electricity and 17% of gas. Another energy-intensive cluster is located in the Western part, with several buildings consuming more than 40 MWh/year of both electricity and gas.

Based on AEG data, Energy Usage Intensity appears to be highly correlated to building morphology, as show in Fig. 1. Detached houses consume on average 377 kWh/m² of gas and 619 kWh/m² of electricity, opposed to towers which consume just 35 kWh/m² and 51 kWh/m², respectively. On the other hand, lower correlation emerges when comparing energy consumption and building use. Residential buildings show the lowest values in terms of gas consumption—with this being justified by the presence of district heating, reducing the heating demand satisfied with gas boilers—, while in terms of electricity they differ by just 16 kWh/m² from industrial buildings. On the other hand, no clear patterns emerge from EPC data, from which the principal outcome is the high energy-intensity of industrial buildings in terms of gas consumptions, with values up to 20 MWh/m².

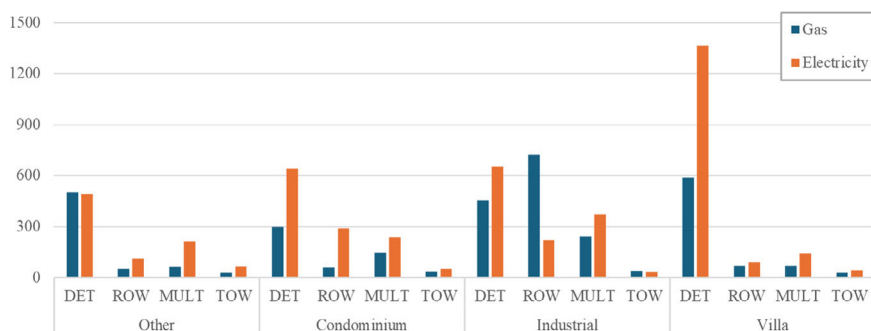


Fig. 1 Average specific consumptions of different building morphologies according to AEG data

When observing the estimated energy demand, condominiums consume 75.8% and 66.33% of gas and electricity consumption, respectively, of the whole district. Considering they account for 63% of the total floor surface, they emerge as the principal category to be addressed when considering possible retrofit measures. Similarly, towers consume 95% and 83% of gas and electricity, respectively, as they account for 98% of the total floor surface.

3.2 Photovoltaic Potential

Based on the selection criteria, 46% of the pitches has been identified as suitable for photovoltaic panels installation. Based on the elaborations performed with *r.sun.insoltime*, the 2605 suitable pitches have an average annual radiation equal to 1.3 MWh/m² on a 49.1 m² area. They are homogeneously spread throughout the district, with 87% of volumetric units having at least one pitch suitable for panels installation. Assuming the panel efficiency to be 27.4% and the Performance Ratio 80%, the total production of the district amounts to 48.6 GWh.

19% of the total production derives from industrial and commercial buildings. Indeed, these buildings are the ones with the highest average productivity, 96.8 MWh/year, as they are generally characterized by wide roof surfaces. This makes them suitable for big-scale systems, targeting the satisfaction of the electricity demand not only of the building itself, but also of other members of the REC. Condominiums produce 70% less than industrial buildings, 29.6 MWh/year on average. Nonetheless, thanks to their wide presence throughout the district, they are the single category producing the most, 22.3 GWh/year, nearly three times the annual productivity from industrial buildings. It is therefore crucial to consider these buildings for a widespread grid of small-scale systems, targeting the satisfaction of individual buildings.

Based on the incidence of the exploitable area on the total production, the most productive buildings are the ones with the widest roof surfaces, located in the Eastern and Western extremes of San Lorenzo, as shown in Fig. 2. Most buildings located in

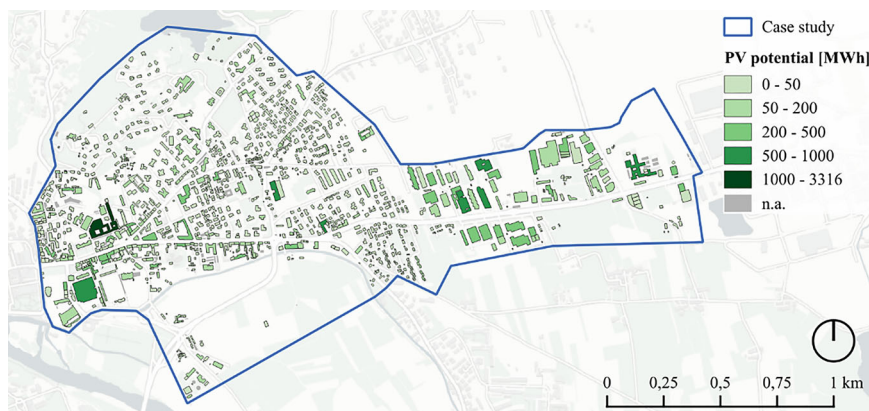


Fig. 2 Photovoltaic potential

the industrial area are characterized by shed roofs, with a nearly-optimal slope (that is 41° according to PVGIS). Other high-productive buildings are part of a mixed-use area in South-West and condominiums located at the foot of the hill.

3.3 Self-production Potential

The feasibility analysis for the creation of a Renewable Energy Community is defined according to the share of energy demand that can be met through photovoltaic panels. This supports the dimensioning of photovoltaic systems and the identification of specific buildings where to locate big-scale arrays serving the whole community.

Figure 3 shows local variations of this indicator. The most positive value can be observed for a building located in the South-Western part, characterized by a 8385 m^2 wide shed roof, resulting in 654 MWh/year production, and low consumption, quantified according to a whole-building EPC.

35% of buildings have the potential to self-produce less than 50% of their electricity demand, thus highlighting the need for centralized systems producing electricity to be distributed within the whole community. These should be localized on the most productive buildings, mostly located in the industrial area. On the other hand, the 491 units (32%) satisfying their energy demand with a surplus up to ten times their needs are the most suitable for self-production.

Finally, it is possible to consider alternative measures for the surplus energy demand. A good example is the installation of heat pumps. In the cases in which it is impossible to connect to the district heating network, it is possible to consider to phase out natural gas boilers and substitute them with electricity-powered heat pumps. This applies in particular to single-family buildings, as the ones located on the hill, self-producing more than their energy demand.

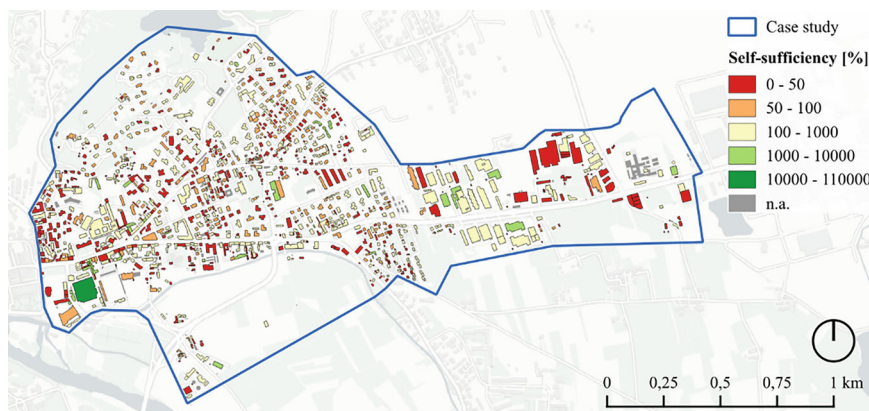


Fig. 3 Self-sufficiency index

4 Discussion and Conclusions

This study described the methodology and the principal findings of the project DT4Energy.com, carried out in the city of Ivrea, Italy. In order to support the dimensioning of a Renewable Energy Community, both the electricity demand and the potential production from photovoltaic panels have been calculated. Open and proprietary data, part of which acquired in the framework of the project, have been exploited, using a geospatial approach to show spatial patterns and identify the key areas for the REC implementation. Results showed a high potential for electricity self-production, with a 5.74 GWh/year in the buildings producing more than ten times their energy needs.

All findings were integrated into a synthetic platform, showed in Fig. 4. Urban Digital Twins are effective tools for data sharing and publication, as the three-dimensional components facilitates understanding also for people not directly involved in the process. At the same time, they allow a data-driven approach to REC design with the possibility to automate processing steps. While it is still debated if the real-time update is a key constituent of a Digital Twin, this data platform can ensure high update rates—whenever new consumption data are fed into the model—and constant access for all.

The principal limitation is data coverage. Despite the possibility to consider metered data, generally very difficult to be gathered, these cover slightly more than 25% of the building stock. EPC data widened the dataset, but components such as the share of heating demand satisfied through district heating could not be addressed. Furthermore, the inclusion of the heating component can help in fully unlocking the potential of the Digital Twin, considering the possibility of identifying worst-performing buildings and estimate the impact of refurbishment. For both the energy reduction measures and the photovoltaic panels installation, it is necessary to consider economical aspects, on different levels. First, a life cycle assessment can

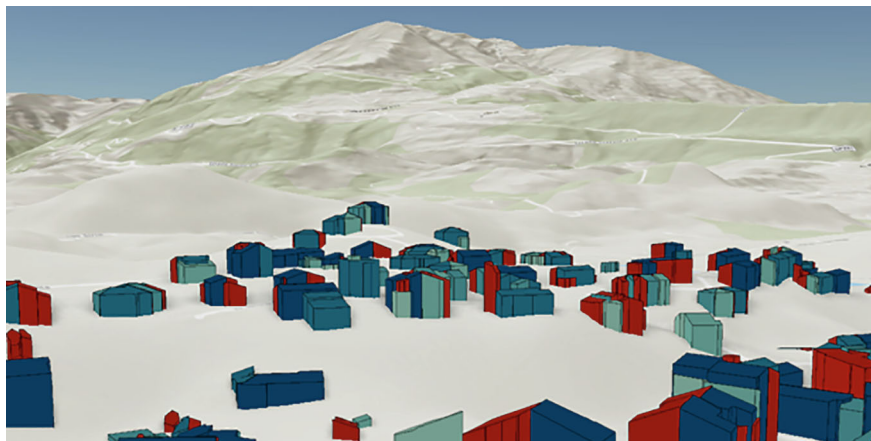


Fig. 4 3D city model for data publication

be performed, considering discount rates and possible variations in the Net Present Values. Second, complex formulas for estimating the payback time can be elaborated, potentially exploring alternative solution and assessing how their integration affects the investment and payback time. Third, more complex economic indicators can be considered.

The creation of a Renewable Energy Community has a variety of impacts on the whole territory. First, there is a technological impact for the energy companies, which lose their central role in energy grids to favor a distributed model with prosumers. This is then reflected in social aspects, with increased participation and empowerment. Shared ownership and collective management results in the possibility for both Public Administrations and single citizens to adopt a steering role, reducing their dependency on energy companies. As a result, there is a market impact, because of which traditional energy suppliers need an organizational restructuring, shifting towards structures able to support RECs from different points of view.

In conclusion, the principal finding of the project DT4Energy.com is the high potential to create a Renewable Energy Community in the San Lorenzo district. Once having recognized the possibility to produce a significant share of the electricity demand from photovoltaic arrays, it is possible to foresee alternative uses for the energy surplus. The inclusion of renewable energy in the energy mix is valuable per se, but it also involves the possibility to redistribute profits and promote awareness on energy aspects in local communities. However, it is to be stressed that the current state of the tool is intended for the dimensioning of the REC rather than for its management and energy balance control.

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References

1. Roberts J, Frieden D, d’Herbement S (2019) Energy community definitions
2. European Parliament and Council (2018) Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources (recast)
3. Minerva R, Lee GM, Crespi N (2020) Digital twin in the IoT context: a survey on technical features, scenarios, and architectural models. *Proc IEEE* 108:1785–1824. <https://doi.org/10.1109/JPROC.2020.2998530>
4. Francisco A, Mohammadi N, Taylor JE (2020) Smart city digital twin-enabled energy management: toward real-time urban building energy benchmarking. *J Manag Eng* 36. [https://doi.org/10.1061/\(ASCE\)ME.1943-5479.0000741](https://doi.org/10.1061/(ASCE)ME.1943-5479.0000741)
5. Idrissi Kaitouni S, Pfafferoth J, Jamil A et al (2023) A holistic digital workflow methodology to shifting towards net zero energy urban residential buildings in a semi-arid climate. *Sol Energy* 263:111959. <https://doi.org/10.1016/j.solener.2023.111959>
6. Herrando M, Cambra D, Navarro M et al (2016) Energy performance certification of faculty buildings in Spain: the gap between estimated and real energy consumption. *Energy Convers Manag* 125:141–153. <https://doi.org/10.1016/j.enconman.2016.04.037>
7. Anselmo S, Ferrara M (2023) Trends and evolution of the GIS-based photovoltaic potential calculation. *Energies* 16:7760. <https://doi.org/10.3390/en16237760>
8. Green MA, Dunlop ED, Yoshita M et al (2024) Solar cell efficiency tables (version 63). *Prog Photovolt Res Appl* 32:3–13. <https://doi.org/10.1002/pip.3750>

Optimizing Supply Temperature Control in District Heating Networks via Differentiable Dynamic Simulation and Gradient Descent



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Abstract District Heating Networks (DHNs) are central to sustainable energy transition, but their efficiency depends on effective supply temperature control. Rule-based strategies, such as heating curves, remain common for their simplicity, but tuning them often requires long periods of suboptimal operation. In this paper, we propose an alternative approach that directly optimizes control parameters via gradient descent, based on a differentiable dynamic simulation model. We apply this approach to optimize the parameters of various heating curve formulations and evaluate its performance on a real meshed network using monitoring data. Results show a reduction of heat losses compared to both manual regulation and gradient-free optimization, demonstrating the potential of gradient-based methods for DHN control.

Keywords District heating · Control · Thermal networks · Heat distribution · Optimization

1 Introduction

District Heating Networks (DHNs) play a critical role in sustainable energy transition scenarios [1] as they allow the efficient distribution of thermal energy from centralized or decentralized sources to consumers in urbanized settings [2]. Many existing networks follow the design principles of 3rd-generation DHNs [3], where there is a significant temperature difference between the working fluid and the surrounding soil. In such systems, supply temperature control is crucial: higher temperatures ensure that consumer demand is met but come at the cost of increased energy losses. Conventional control methods rely on simple rules or linear dependencies on outdoor temperature, known as heating curves [4]. These curves are typically tuned over long periods, often a full year, with parameters slowly adjusted based on observed

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performance. While straightforward and stable, this approach leads to long periods of suboptimal control and increased energy waste. Moreover, when major changes occur in the network, the tuning process must be repeated, making it difficult to adapt efficiently to evolving conditions.

This paper addresses these limitations by formulating an optimization-based approach to control strategy design. Using a differentiable dynamic thermal model, we optimize the control parameters of heating curves directly through gradient-based methods, allowing for systematic performance improvements without the need for extensive trial-and-error tuning. We study the performance of these optimized strategies on a real network and compare them against both manual settings and gradient-free optimization, demonstrating their potential to increase efficiency and reduce energy waste in DHN operations.

Given the constraints on data availability, we focus our analysis on a representative 5-day period. However, the proposed method can be extended to longer periods, provided that the gradient computation is adapted to manage computational costs and maintain numerical stability.

2 Methodology

2.1 Case Study Network

For this study, we used the DHN of Verbier, Switzerland, as described in [5]. At the time of data collection, the network comprised 165 active substations, 35 dedicated to ramp defrosting, and three heat plants (MAIN, SEC1, SEC2). These have no accumulators, limiting their potential for temperature control and increasing the importance of an accurate control strategy. The distribution network had a meshed topology with six internal loops, a total pipe length of 28 km, and covered an altitude difference of 126 m. Most pipes were buried at 0.8 m, with some passing through basements or parking lots.

Flow, temperature, and pressure data were collected (Jan 10–22, 2022) and resampled at 15-minute intervals. During the monitoring period SEC2 operated sporadically with insufficient data and was therefore excluded from the analysis. Outdoor air temperature data was collected from the nearby MeteoSwiss weather station in Montagnier, Val de Bagnes (839 m asl), and the soil temperature at network depth estimated as -2.23°C for the whole period. For further details, we refer the reader to the original work (see [5]).

An overview of the monitored data is given in Fig. 1. Unlike conventional setups where the supply temperature is regulated based on air temperature, here it is manually set. The demand peaks at around 9 am, which is met by increasing the mass flow rate and, consequently, lowering the supply temperature. Around 10 pm, as demand decreases, the mass flow rate is reduced, and the supply temperature is increased to compensate for the longer travel time and prevent excessively low temperatures

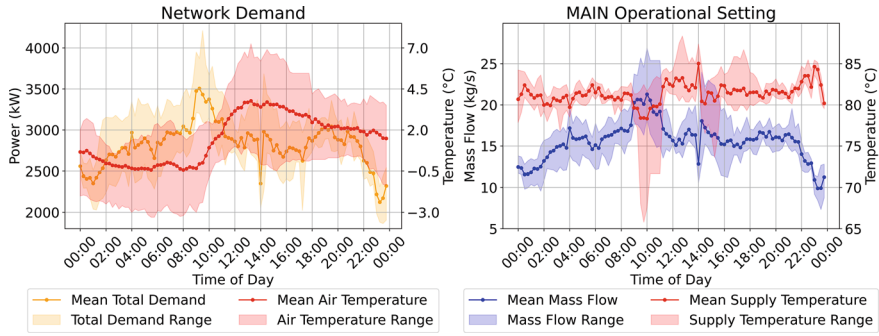


Fig. 1 Daily variations in monitoring data, showing mean daily values and ranges. Left: total power demand (kW) and air temperature (°C). Right: mass flow (kg/s) and supply temperature (°C) at the MAIN plant. Shaded regions indicate the variability

at consumer substations. A different control strategy is used for SEC1, where the temperature and mass flow are kept almost constant at 82°C and 5 kg/s respectively.

2.2 Dynamic Model of the DHN

In this section, we present the dynamic thermal model used in this work, that is adapted from [5] and has been validated on the considered case study. We focus solely on the thermal dynamics of the network, assuming a predefined mass flow based on the results of the above study. First, we outline the modeling assumptions, then we describe the components and convergence strategy.

Modeling assumptions. We assume that the DHN is a closed system, with no leaks or injections of water, represented as a directed graph $\mathcal{G} = (\mathcal{V}, \mathcal{E})$, with edges as components (pipes, consumers, producers) and vertices as junctions. Producers and consumers have fixed mass flow directions, and their outlet vertices have no other incoming edges.

Component functions. For each component, we model the outlet temperature, θ_{out} (°C), as a function of the inlet temperature, θ_{in} (°C):

$$\theta_{\text{out}} = \psi(\theta_{\text{in}}). \quad (1)$$

In pipes, this relationship was originally adapted from the two-capacity Lagrangian model in [6]. Pipes are treated as hollow cylinders with three layers: internal wall, insulation, and casing. Water is discretized into variable-sized volumes with constant temperature. The internal wall is segmented using the same spatial discretization as the water. Unlike [6], at each time step t , we first solve the source problem to update the temperatures of water volumes and pipe wall segments. The heat loss of a water

segment v with volume V_v and temperature θ_v from time step $t - 1$ to t is given by:

$$Q_v^{(t)} = (\theta_v^{(t-1)} - \theta_v^{(t)}) \rho^{(t-1)} V_v c_p^{(t-1)} \frac{1}{h}, \quad (2)$$

where $h = 3600$ J/Wh, and the water density ρ and specific heat capacity c_p are evaluated at the initial temperature of the time step, following the relationships in [7]. Next, volumes are advected, and pipe outlet temperature is obtained as the volume-weighted sum of exiting water temperatures. If the incoming volume V_{in} exceeds the pipe's capacity V_{max} , the excess must be added to the outflow. To account for this, we define a blending parameter α as:

$$\alpha = \max \left(0, \frac{V_{in} - V_{max}}{V_{in}} \right), \quad (3)$$

which represents the fraction of inlet water that surpasses the pipe's capacity. The outlet temperature is then given by:

$$\theta_{out} = \alpha \cdot \theta_{in} + (1 - \alpha) \cdot \bar{\theta}_{out}, \quad (4)$$

where $\bar{\theta}_{out}$ represents the volume-weighted average temperature of the portion of outflow originating from water already in the pipe at the start of the time step. The process is illustrated in Fig. 2. Consumers are modeled as fixed temperature difference components, thus we enforce:

$$\theta_{out} = \theta_{in} - \Delta\theta_{set}. \quad (5)$$

Finally, the outlet temperature of producers is imposed as boundary condition independently from the inlet temperature (slack nodes).

Overall convergence. The convergence criterion is based on nodal energy conservation. At each time step, we assume that the orientation of the j -th edge aligns with the positive direction of the flow. As a first condition to determine the temperature θ

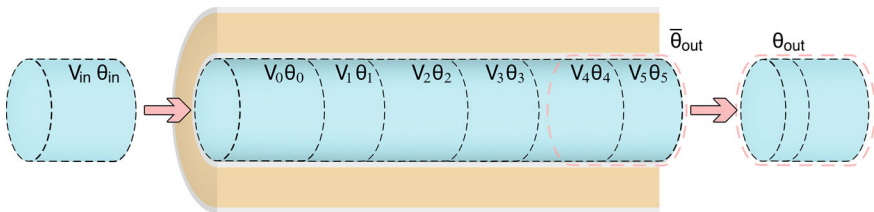


Fig. 2 Illustration of the pipe model. Here, the incoming volume is less than the total pipe volume ($\alpha = 0$), and the outlet temperature is computed as the volume-weighted average temperature of the portion of water highlighted by the red dashed border

at each node in the network, we impose that the inlet temperature of an edge matches the temperature of its starting vertex:

$$\theta_{\text{in},j} = \theta_{t(j)}, \quad \forall j \in \mathcal{E}, \quad (6)$$

where the notation $t(j)$ indicates the starting vertex (tail) of edge j . We then set the ending vertices of producers as slack nodes, indicated with the subscript s , and impose their temperatures as that of the corresponding unique incoming edge $\theta_{\text{imp},i}$ ($^{\circ}\text{C}$):

$$\theta_i = \theta_{\text{imp},i}, \quad \forall i \in \mathcal{V}_s. \quad (7)$$

Finally, we impose the conservation of energy at the remaining vertices. Following (1) and (6), this can be written as:

$$\sum_{j \in \mathcal{I}_i} \dot{m}_j \cdot c_p \cdot \psi_j(\theta_{t(j)}) - \left(\sum_{k \in \mathcal{O}_i} \dot{m}_k \right) \cdot c_p \cdot \theta_i = 0, \quad \forall i \in \mathcal{V} \setminus \mathcal{V}_s, \quad (8)$$

where $\mathcal{I}_i$ is the set of edges entering node i , $\mathcal{O}_i$ is the set of edges leaving node i , $\dot{m}_j$ is the mass flow rate (kg/s) through edge j , and θ_i is the temperature ($^{\circ}\text{C}$) at node i . c_p is the specific heat capacity that we assume to be constant at $4180 \text{ J}/(\text{kg} \cdot \text{K})$ within the energy balance calculation. This assumption neglects the temperature dependence of c_p , which has limited impact over typical DHN operating ranges (0°C – 120°C). However, it ensures linearity of Equation System (8), provided the edge-wise temperature transfer functions $\psi_j(\cdot)$ are themselves linear. As this condition is met using the component models previously described, combining (7) and (8) we obtain a square system of linear equations in the form:

$$\mathbf{A}\vec{\theta} = \vec{b}, \quad (9)$$

that is solved using LU factorization. Note that if non-slack nodes with zero mass flow are present, $\mathbf{A}$ is singular. Therefore, the equations of such nodes are removed from System (9) and assigned with the average value of the temperatures of adjacent water volumes in pipes.

2.3 Control Strategies

We consider two base heating curves: a constant model and a piecewise linear model. For both, we test variants with preheating, night setback, or both. The piecewise linear model is controlled by 4 (learnable) parameters, $\theta_a, \theta_b, \theta_c, \theta_d$:

$$\theta_{\text{out}} = f_l(\theta_{\text{air}}) = \begin{cases} \theta_c, & \theta_{\text{air}} < \theta_a \\ \theta_c + \frac{(\theta_{\text{air}} - \theta_a)(\theta_d - \theta_c)}{\theta_b - \theta_a}, & \theta_a \leq \theta_{\text{air}} \leq \theta_b \\ \theta_d, & \theta_{\text{air}} > \theta_b \end{cases} \quad (10)$$

with the requirements that $\theta_a < \theta_b$ and $\theta_d < \theta_c$. The models with preheating have 3 additional parameters: the starting time t_0 , the duration $\mathcal{T}$, and the temperature difference Δ . Given $t_1 = t_0 + \mathcal{T}$ and assuming $t_0 < t_1$:

$$\theta_{\text{out}} = f_l(\theta_{\text{air}}) + \Delta^*, \quad (11)$$

$$\Delta^* = \Delta [\sigma(k(t - t_0)) - \sigma(k(t - t_1))] . \quad (12)$$

Here σ is the sigmoid function and $k = 100$. Δ^* is used to avoid discontinuity induced by a sudden change of temperature. For daily transitions, t is interpreted over a continuous daily cycle. The same formulation is used for setback, with the temperature delta constrained to be negative.

2.4 Optimization Approach

Given a control strategy, we seek to find its optimal sets of parameters, for MAIN and SEC1, and compare the performance of the optimized strategy against both the manually controlled supply temperatures used during the monitoring period and a gradient-free baseline. We frame this optimization problem as follows:

$$\min_P \left(\sum_{t=1}^T \sum_{i \in \mathcal{E}_p} Q_i^{(t)}(P) + \lambda \sum_{t=1}^T \sum_{j \in \mathcal{E}_{c \setminus r}} Q_j^{(t)}(P) \right) \quad (13)$$

$$Q_j^{(t)} = \begin{cases} c_p \dot{m}_j^{(t)} \frac{\Delta t}{h} \delta_j^{(t)}, & \delta_j^{(t)} > 0 \\ 0, & \text{otherwise} \end{cases} \quad (14)$$

$$\delta_j^{(t)} = \theta_{\text{ret},j}^{\min} - \theta_{\text{ret},j}^{(t)} \quad (15)$$

Here, Δt (s) is the time-step size, $\mathcal{E}_p$ represents the set of pipes where energy losses $Q_i^{(t)}(P)$ are evaluated, while $\mathcal{E}_{c \setminus r}$ denotes the subset of consumers excluding ramps. The penalty term $Q_j^{(t)}(P)$ accounts for violations of the minimum return temperature. The deviation $\delta_j^{(t)}$ (K) measures how much the simulated return temperature $\theta_{\text{ret},j}^{(t)}$ (°C) falls below the reference value $\theta_{\text{ret},j}^{\min}$ (°C), estimated as the minimum return temperature observed during the monitoring period.

Since the simulation model (Sect. 2.2) and the heating curves (Sect. 2.3) are differentiable, we can adjust the parameters P using gradient descent. At each k -th iteration of gradient descent, the full trajectory of T time steps is evaluated with a fixed set of parameters $P^{(k)}$, which is then updated as:

$$P^{(k+1)} = P^{(k)} - \eta \nabla \mathcal{L}(P^{(k)}),$$

(16)

where $\mathcal{L}$ is the objective function to minimize in Eq. (13) and η is the learning rate. In addition to the T time steps, an initial period of 24h is also simulated at each iteration using the conditions of the first time step to initialize the temperatures of water volumes and pipe walls.

For each heating curve variant we perform 50 steps of gradient descent with an initial η of 0.01. If the loss does not improve after 5 iterations, η is reduced by half, up to a minimum of 0.0001. To prevent instabilities from large parameter updates in a single step, the update of temperature-related parameters is clipped to the range $[-1, 1]$. The λ factor in Eq. (13) is chosen as 1000. Further analysis is conducted using the optimal parameter set found for each heating curve.

3 Results and Discussion

Results are shown in Table 1, alongside those obtained using a gradient-free method, Differential Evolution (DE). Under manual control, total heat losses amounted to

Table 1 Performance of each curve optimized with our method and DE

Curve	Loss Diff. (kWh)		Temp. μ ($^{\circ}\text{C}$)		Temp. σ ($^{\circ}\text{C}$)	
	Ours	DE	Ours	DE	Ours	DE
C	− 90 (−0.2%)	16 (0.0%)	(81.0, 82.0)	(81.5, 81.1)	(0.0, 0.0)	(0.0, 0.0)
$C+p$	−283 (−0.7%)	284 (0.7%)	(80.8, 82.5)	(81.7, 82.1)	(2.6, 2.8)	(1.1, 1.1)
$C+s$	427 (1.0%)	278 (0.6%)	(82.0, 82.6)	(80.6, 86.3)	(2.8, 2.2)	(0.9, 1.5)
$C+p+s$	438 (1.0%)	1025 (2.4%)	(80.5, 88.0)	(84.0, 79.0)	(2.4, 1.5)	(2.3, 1.4)
L	526 (1.2%)	343 (0.8%)	(82.3, 82.3)	(82.5, 79.6)	(1.1, 1.1)	(0.0, 0.0)
$L+p$	69 (0.2%)	− 39 (−0.1%)	(81.6, 82.1)	(81.4, 80.9)	(2.3, 2.5)	(0.4, 0.7)
$L+s$	105 (0.2%)	1330 (3.1%)	(81.0, 83.7)	(84.3, 80.8)	(1.0, 0.7)	(1.0, 3.2)
$L+p+s$	− 82 (−0.2%)	1006 (2.3%)	(81.2, 82.9)	(81.8, 87.0)	(3.1, 3.0)	(2.4, 4.1)

Total heat loss differences relative to manual control (in kWh and %) are reported, along with the mean (μ) and standard deviation (σ) of supply temperatures, shown as (MAIN, SEC1). Bold values indicate the lowest heat loss for each variant; no bold means manual control performed best. Curve types: C (constant), L (linear), p (preheating), s (setback)

42,921 kWh, with average supply temperatures of 81.4°C (MAIN) and 81.7°C (SEC1), and standard deviations of 2.2°C and 1.3°C, respectively. For DE, we used SciPy's [8] implementation with default settings and ran each optimization for 40 min, the maximum time our method took across all heating curves. As DE does not require gradient computations, function evaluations are faster, reaching around 210 evaluations per run.

Our gradient-based approach outperformed DE in most cases, although a more rigorous study is needed to assess whether this holds across different initializations and DE settings. The performance gap widens as the number of parameters increases, suggesting that DE struggles with higher-dimensional parameter spaces within the fixed evaluation budget. The lowest losses were achieved using a simple constant curve with preheating, a strategy that closely mirrors the manual operations observed during the monitoring period and used as boundary conditions. In this configuration, the supply temperature is held at 80.0°C for MAIN and 81.7°C for SEC1. preheating is activated at 10 PM for both plants, increasing the temperature by 9–10°C for about 2 h. This compensates for the decrease in mass flow and replicates the supply temperature rise observed under manual control.

In general, optimized curves consistently initiate preheating around sharp drops in MAIN's mass flow, at 11 AM, 2 PM, or 10 PM, rather than during morning peaks. Setback variants performed poorly, with the optimizer minimizing their effect. These trends suggest that gradient descent effectively navigates the model's solution space, confirming its viability.

Regarding scalability, the memory footprint of the simulation grows linearly with the number of water volumes, which is determined by the number and length of pipes, their flow rates, and the chosen time step size. In practice, the model can handle larger networks efficiently, and if memory becomes a constraint, adjacent volumes can be dynamically merged to reduce the footprint with minimal impact on accuracy. To compute gradients over longer horizons, the simulation trajectory must also be truncated, both to mitigate vanishing gradients and to reduce memory usage. At the same time, the physical influence of a control decision is inherently limited: it persists only while the affected water volume remains in the network or continues to influence pipe wall temperatures in a non-negligible way. This reinforces the case for truncation, typically implemented using (overlapping) Truncated Backpropagation Through Time (BPTT).

4 Conclusion and Future Work

In this work, we proposed a gradient-based approach to DHN control optimization using a differentiable dynamic thermal model. Specifically, we used it to tune heating curves for a real network based on monitoring data over a 5-day period. Despite using boundary conditions from a monitoring period where mass flow was adjusted to demand, and supply temperature was not set based on outdoor air temperature, results show a reduction in heat losses compared to manual operation. Our method

also outperformed a gradient-free baseline based on Differential Evolution in most cases, particularly for curves with more parameters.

Future work should expand this approach to longer time horizons, which will require addressing computational challenges in gradient calculation over extended periods of time. Additionally, extending the model to include the hydraulic aspects of the network would provide a more complete optimization framework, which could allow for a higher energy saving potential.

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References

1. World Energy Outlook 2023, IEA, Paris (2023) <https://www.iea.org/reports/world-energy-outlook-2023>
2. Zuberi MJS, Narula K, Klinken S, Chambers J, Streicher KN, Patel MK (2021) Potential and costs of decentralized heat pumps and thermal networks in Swiss residential areas. *Int J Energy Res* 45(10):15245–15264. <https://doi.org/10.1002/er.6801>
3. Lund H, Østergaard PA, Nielsen TB, Werner S, Thorsen JE, Gudmundsson O, Arabkoohsar A, Mathiesen BV (2021) Perspectives on fourth and fifth generation district heating. *Energy* 227:120520. <https://doi.org/10.1016/j.energy.2021.120520>
4. Ghane S, Jacobs S, Casteels W, Brembilla C, Mercelis S, Latré S, Verhaert I, Hellinckx P (2021) Supply temperature control of a heating network with reinforcement learning. In: 2021 IEEE international smart cities conference (ISC2). IEEE, pp 1–7. <https://doi.org/10.1109/ISC253183.2021.9562966>
5. Boggetti R, Kämpf JH (2024) Verification of an open-source Python library for the simulation of district heating networks with complex topologies. *Energy* 290:130169. <https://doi.org/10.1016/j.energy.2023.130169>
6. Denarie A, Aprile M, Motta M (2019) Heat transmission over long pipes: new model for fast and accurate district heating simulations. *Energy* 166:267–276. <https://doi.org/10.1016/j.energy.2018.09.186>
7. Popiel CO, Wojtkowiak J (1998) Simple formulas for thermophysical properties of liquid water for heat transfer calculations (from 0 C to 150 C). *Heat Transf Eng* 19(3):87–101. <https://doi.org/10.1080/01457639808939929>
8. Virtanen P, Gommers R, Oliphant TE, Haberland M, Reddy T, Cournapeau D et al (2020) SciPy 1.0: fundamental algorithms for scientific computing in python. *Nat Methods* 17(3):261–272. <https://doi.org/10.1038/s41592-019-0686-2>

Energy Demand for Indoor Thermal Comfort in a Northern Archival Office



Giulia Boccacci , Francesca Frasca , Chiara Bertolin , Erlend Lund, Tonje Dahlin Sæter, and Anna Maria Siani

Abstract This study evaluates the energy demand for thermal comfort in the workspaces of the Dora Library, a repository for the Norwegian University of Science and Technology (NTNU) Library (“NTNU UB Fellesmagasin”), located in the Dora I WWII submarine bunker in Trondheim, Norway (Lat. 63.4°N Long. 10.4°E). This research analyses five years (2020–2024) of indoor temperature data collected in staff offices, and future outdoor temperature from Copernicus Climate Data Store (CDS). Using the intermediate Socio-economic Pathways future climate scenario (SSP2-4.5), the study assesses how heating energy demand varies throughout the year under different workplace usage patterns. Each pattern reflects a different frequency of occupancy by Dora Library employees (i.e., high and low frequency). Moreover, two alternative scenarios are explored with respect to the actual indoor thermal conditions for energy saving purposes. The outcomes offer insights into the energy implications of climate control in the office area of Dora Library.

Keywords Microclimate · Bunker · Thermo-hygrometric monitoring · Office building · Indoor comfort · Energy demand

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1 Introduction

Thermal comfort is defined as “*that condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation*” [1]. In the last decades, indoor thermal comfort in non-residential buildings has gained significant attention, especially in office buildings, which represent the second biggest category of this sector in Europe [2]. Despite their shorter occupancy periods, office buildings have heating and cooling conditions similar to residential buildings use and are of particular interest, as people spend about a third of their day in these spaces [3]. Increasing attention is being given to how comfort affects health, well-being and productivity, as well as to improving buildings’ energy consumption, without decreasing the occupants’ comfort [4].

Moreover, there is growing concern about the impact of climate change on the energy performance and indoor thermal comfort of office buildings, and it has been found that depending on the building envelope, overall energy demand may increase, remain stable or even decrease under changing climate conditions [5]. Additionally, occupancy patterns have been found to play a crucial role in a building’s energy performance and considering them can lead to a more efficient energy management [6].

In this context, this paper aims to evaluate the recent past and future energy demand for thermal comfort in a modern workplace subsequently connected to a historic building (i.e., WWII Dora bunker), by considering monitored and simulated climate conditions and varying occupancy patterns.

2 Methodology

The Dora Library offices, built in 2005, are located on the top floor of Dora I reinforced concrete bunker, a WWII construction built in Trondheim (Norway, Lat. 62.7°N and Long. 11.3°E) between 1941 and 1943. The massive structure (i.e., walls up to 3.5 m thick) was repurposed for civil uses and nowadays it houses several archival institutions, including the Norwegian University of Science and Technology (NTNU) Library, of which the Dora Library serves as a repository. The office (representing a new connection to the historic building) is equipped with large glass windows with a mechanical curtain for radiation shielding, oriented north toward the Trondheim fjord. The space covers approximately 160 m² with a ceiling at the height of 2.9 m, divided into single rooms and a common area (Fig. 1, right panel). A TinyTag-TGU-4500 sensor measures temperature (uncertainty = ± 0.5 °C) and relative humidity (uncertainty = $\pm 3.0\%$) every three hours (i.e., black dot in Fig. 1), as part of a microclimate monitoring system implemented to assess the hygrothermal behavior of the adjacent archive housing paper-based materials.

An active control system operates year-round to maintain a stable indoor air temperature, through the presence of radiators in single offices, as well as to guarantee

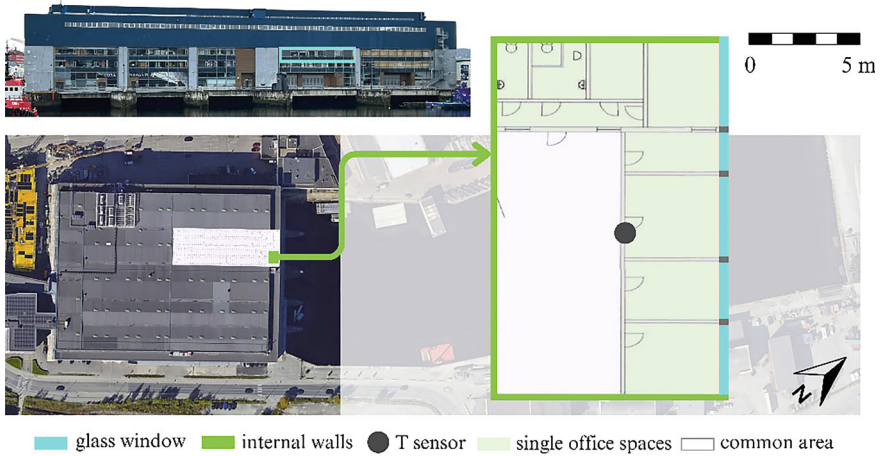


Fig. 1 Dora I bunker northwest façade (top left) with grey concrete elements representing the original structure of the historic building, and glass window indicating the modern addition. Satellite view of Dora I bunker (bottom left) and plan of Dora library workspaces with the datalogger location (right, black dot)

air exchange through a ventilation system. No cooling system is installed. In this analysis, multi-year mean (2020–2024) of indoor air T was computed and each year was then divided into 3 intervals based on the frequency of occupancy by the archive staff. By cross-referencing the NTNU academic calendar, which aligns with the work schedule of Dora Library employees, the following periods were identified:

- First high-frequency occupancy period (*High frequency I*) from January first to May 30th of each year, corresponding to NTNU's spring semester.
- Low-frequency occupancy period (*Low frequency*) from June first to July 31st of each year, corresponding to the summer holidays period.
- Second high-frequency occupancy period (*High frequency II*) from August first to December 31st of each year, corresponding to NTNU's autumn semester.

In Fig. 2, the occupancy load is presented as the percentage of office use (where “1” on the x-axis corresponds to hours of the day expressed as 12–1 am, and so on), for weekdays (full black line), Saturday (black dotted line) and Sunday (black dashed line). The data are adapted from [7] and adjusted to reflect NTNU's general working hours, regardless of Norwegian seasonal variations (i.e., in summer and winter schedule) and the reduced hours during Easter and Christmas.

Daily data of outdoor air temperature at Trondheim were also extracted from the Copernicus Climate Data Store (CDS) for the period 2020–2024 [8], and used to compute the heating energy demand (ED_{heat} in kWh m^{-3}) for each of the three occupancy period each year, through Eq. (1) [9, 10]:

$$ED_{\text{heat}} = \frac{A/V \cdot h \cdot U_{\text{value}} \cdot DD}{1000} \quad (1)$$

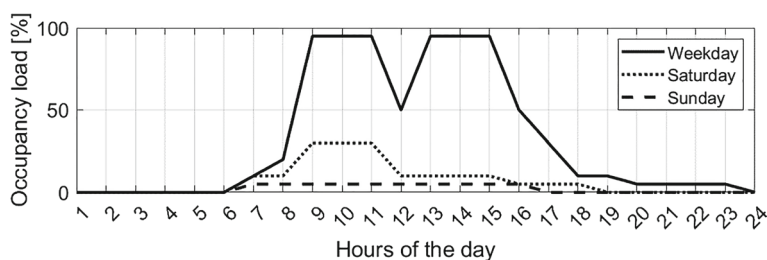


Fig. 2 Estimated occupancy load for office buildings in Norway (i.e., Dora Library workplace)

where A is the total surface area of the office space (i.e., common area and individual offices) [$\sim 160 \text{ m}^2$]; V is the total volume of the office space [$\sim 464 \text{ m}^3$] and h is equal to 24 h. U_{value} is the thermal transmittance of the building envelope, here considered to be $1.3 \text{ W m}^{-2} \text{ K}^{-1}$, computed as a weighted average between its glazed ($\sim 80\%$) and opaque ($\sim 20\%$) components. The U -values considered correspond to the minimum requirement for glass windows with frames ($1.6 \text{ W m}^{-2} \text{ K}^{-1}$), and for outer walls ($0.2 \text{ W m}^{-2} \text{ K}^{-1}$), as specified in the Technical Regulations under the Norwegian Planning and Building Act [11], which was applicable in 2005 when the office space was built. Finally DD represents the “degree-days” which gives the number of $^{\circ}\text{C}$ that the outdoor temperature (T_{out}) must (in this case) increase to reach a specific threshold value (T_{thresh}) equal to 21°C [12].

The same procedure was then applied to estimate the future ED_{heat} for the period 2071–2100 (i.e., far future), using air temperature data from the intermediate Socio-economic Pathways climate scenario (SSP2-4.5) [13], which represents the intermediate greenhouse gases emissions scenario (with a radiative forcing reaching 4.5 W m^{-2} by 2100). To this aim, a multi-year average (2071–2100) was computed by averaging daily air temperature values across the 30-years period, in order to characterize future conditions for heating energy demand calculations.

Finally, two alternative scenarios were explored—in respect to the actual indoor T conditions—for energy saving purposes, calculating the ED_{heat} over the 2020–2024 and 2071–2100 periods. In Scenario 1, the baseline temperature was lowered to 19°C on weekends while remaining at 21°C on weekdays. This was a hypothetical assumption based on 19°C being the standard winter setpoint for indoor thermal comfort in other European countries, and the fact that lower occupancy and reduced activity levels can justify a more energy-efficient setpoint without compromising thermal comfort. Scenario 2 extended this reduction to include an additional hypothetical “remote work” day (i.e., Wednesday), keeping 21°C for the other four weekdays.

3 Results

The upper panel of Fig. 3 shows the indoor air temperature (green line) collected within the office space. The low variability (~ 18 to ~ 24 °C) is due to active climate control on T, with peaks typically occurring between the end of June and the beginning of July during summer vacation. In the same figure, daylight duration for the city of Trondheim is reported in light blue for the same period, along with the subdivision of use/occupancy intervals into high frequency (I and II—black line) and low frequency (grey line). A delay between the peak of indoor air T and the maximum daylight duration is sometimes observed over the years (2021, 2023 and 2024). This shift likely reflects variations in office use during the summer period, depending on whether the staff is on holiday or actively occupying the space. The lower panel presents again the same indoor T series (green line) and its average (dashed red lines), considered as threshold temperatures for the DD calculation. The indoor series is here compared with the outdoor ones (for Trondheim)—to compute heating energy demand calculation—for the recent period 2020–2024 (grey line with variability ranging between ~ -20 and ~ 24 °C) and the projected values for the far future 2071–2100 period (black line with values ranging between ~ -2 and ~ 17 °C).

In Fig. 4 the heating degree days (HDD in upper panel) and the heating energy demand (ED_{heat} in lower panel) are represented by bars of different colors according to the three different occupancy intervals over the five considered years: spring semester at high frequency of occupancy (HF(I)), summer holidays at low frequency of occupancy (LF), and autumn semester at high frequency of occupancy (HF(II)). Filled bars represent the past period (i.e., monitored years from 2020 to 2024), while

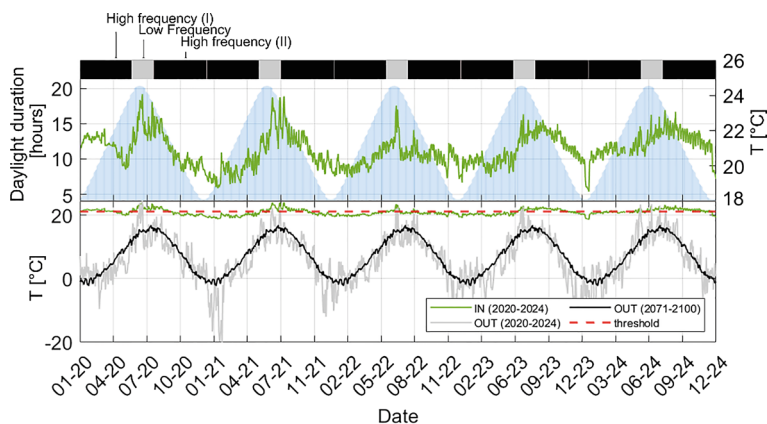


Fig. 3 Upper panel: indoor air T (green) in the office space and daylight duration in Trondheim (light blue) (2020–2024), with high frequency occupancy period I and II (black band) and a low-frequency occupancy period (grey band). Lower panel: indoor air T (green), threshold T (dashed red), and outdoor air T for 2020–2024 (grey) and for 2071–2100 average (black, graphically repeated five times for comparison)

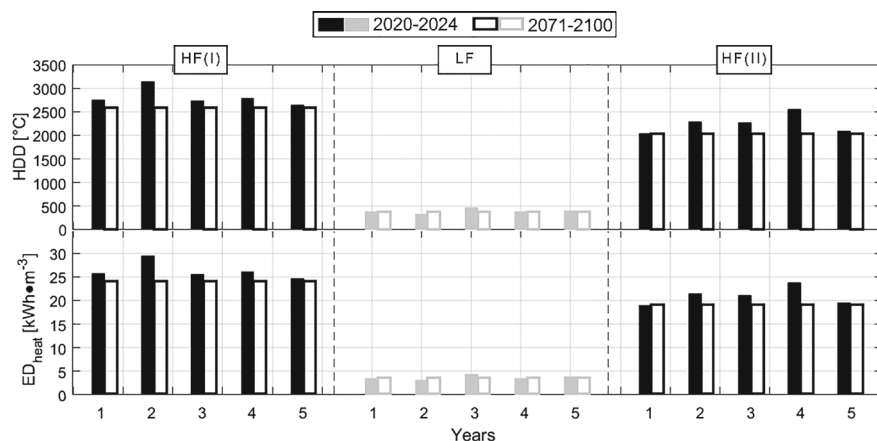


Fig. 4 Heating degree days (HDD—upper panel) and heating energy demand (ED_{heat} —lower panel) in colored filled (2020–2024) and empty (2071–2100) bars for the three different occupancy intervals: high frequency I and II (HF(I–II)—black) and low frequency (LF—grey), in recent present and far future

empty ones correspond to the future projection (i.e., climatological normal from 2071 to 2100).

For the period 2020–2024, the highest HDD and ED_{heat} are observed during the spring semester of NTNU (i.e., HF(I)). HDD values range between ~ 2600 and ~ 3200 °C, resulting in ED_{heat} values varying from ~ 25 to ~ 30 kWh m⁻³. Following this, the second most frequent period corresponding to the autumn semester (i.e., HF(II)), shows a lower energy demand ranging from ~ 19 to ~ 24 kWh m⁻³ with HDD values between ~ 2000 and ~ 2500 °C. Finally, the Low Frequency (LF) period, during the summer holidays (shades of gray), represents the least used period based on a two-month period rather than five, with lower HDD values ranging from ~ 330 to ~ 470 °C. Consequently, the ED_{heat} is also the lowest, ranging from ~ 3 to ~ 4 kWh m⁻³, as the summer months experience the smallest difference between the outdoor temperature and the threshold temperature indoors, further contributing to reduce the energy demand in this period.

For the projected far future 2071–2100 period under the intermediate SSP2-4.5 scenario, HDD and ED_{heat} values remain largely unchanged across the three occupancy stages. However, an exception occurs in HF(I) of Year 2 and in HF(II) of Year 4, where both HDD and ED_{heat} are significantly lower than their 2021 and 2023 counterparts. This is attributed to the absence of the sharp temperature drops (grey line in Fig. 1) observed during the winters of 2021 and 2023 in Trondheim, which had temporarily increased heating demand.

Finally, Fig. 5 reports the variation in heating energy demand, comparing the real indoor condition with two hypothetical alternatives. Scenario 1 assumes a 2 °C reduction in baseline temperature on weekends (full black bars), while Scenario 2 extends this reduction to include Wednesdays as smart working day (striped bars).

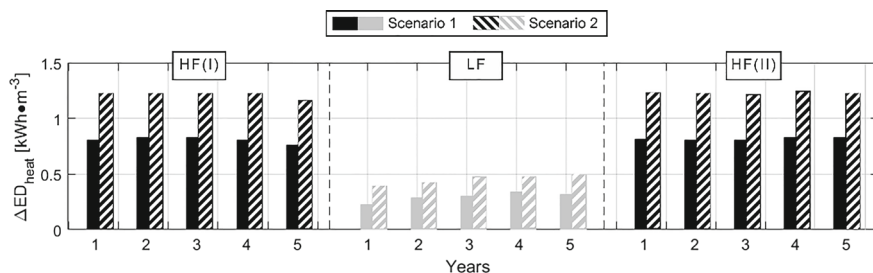


Fig. 5 Variation in heating energy demand (i.e., ΔED_{heat}) in scenario 1 (2 °C reduction in baseline T in weekends—solid bars) and scenario 2 (2 °C reduction in baseline T in weekends and on Wednesday—striped bars) with respect to the real case during the considered time intervals

The comparison is presented for each occupancy period (i.e., high and low frequency of occupancy) across the years 1–5, which refers to both the considered periods, as the analysis showed that reduction in ED presented in Fig. 5 would remain constant over time at the two considered scenarios (i.e., 1 and 2). A slight difference with respect to the real condition is observed in Scenario 1 (full black and gray bars in Fig. 5), with reduction in ED_{heat} (i.e., ΔED_{heat}) of approximately 0.8 kWh m⁻³ during high-frequency occupancy periods and around 0.3 kWh m⁻³ during low-frequency occupancy periods. In contrast, Scenario 2 (striped black and grey bars) results in greater reductions, reaching up to 1.2 kWh m⁻³ for HF(I)–(II) periods and up to 0.5 kWh m⁻³ for LF periods.

4 Conclusions

This study investigates energy demand for indoor climate control at the Dora Library offices over the very recent past 2020–2024 (monitored data) and the projected far future 2071–2100 (SSP2-4.5 scenario). For energy saving purposes, two alternative scenarios of indoor baseline temperature are evaluated for both periods. The results show that, at the actual status, the highest energy demand occurs during the university's spring semester (HF(I)), followed by the autumn semester (HF(II)), with the lowest demand during the summer holidays period (LF).

Projected far future data indicates little change in future energy demand, except for a significant peak in HDD and ED_{heat} during the 2021 and 2023 winters, in respect to the future milder forecast for Trondheim. These findings suggest that variations in energy demand may be driven more by occupancy conditions of the indoor space, rather than by unstable outdoor condition for the coming decades. However, other future socio-economic pathways scenarios could lead to further variations in energy demand for heating needs.

Moreover, lowering the baseline temperature to 19 °C on weekends—when occupancy is minimal or absent—has been shown to slightly reduce heating energy

demand. Extending this reduction to an additional weekday, particularly one with lower occupancy or encouraged remote work, can further decrease ED significantly by at most 4.5%.

In conclusion, implementing these scenarios, or even better, lowering the baseline temperature at night throughout the entire week, or both day and night, would contribute to energy saving, optimizing heating efficiency, and promoting more sustainable climate control strategies without compromising thermal comfort for workers.

References

1. ASHRAE (ed) (2017) ASHRAE Standard 55-2016. Thermal environmental conditions for human occupancy. ASHRAE, 2017
2. Laustsen J, Ruyssevelt P, Staniaszek D, Strong D (2011) Europe's buildings under the microscope: a country-by-country review of the energy performance of buildings
3. Antoniadou P, Papadopoulos AM (2017) Occupants' thermal comfort: state of the art and the prospects of personalized assessment in office buildings. *Energy Buildings* 153:136–149
4. Salimi S, Hammad A (2020) Optimizing energy consumption and occupants comfort in open-plan offices using local control based on occupancy dynamic data. *Build Environ* 176:106818
5. Berger T, Amann C, Formayer H, Korjenic A, Pospischal B, Neururer C, Smutny R (2014) Impacts of climate change upon cooling and heating energy demand of office buildings in Vienna, Austria. *Energy Build* 80:517–530
6. Capozzoli A, Piscitelli MS, Gorrino A, Ballarini I, Corrado V (2017) Data analytics for occupancy pattern learning to reduce the energy consumption of HVAC systems in office buildings. *Sustain Cities Soc* 35:191–208
7. ASHRAE (2011) American Society of Heating, Refrigerating and air-conditioning engineers. ASHRAE standard 90.1: energy standard for buildings except low-rise residential buildings (performance based compliance, section 11 and appendix G)
8. Copernicus Climate Change Service. <https://cds.climate.copernicus.eu/datasets/reanalysis-era5-single-levels?tab=overview>. Last accessed 19 Mar 2025
9. Frasca F, Bartolucci B, Parracha JL, Ogut O, Mendes MP, Siani AM, Tzortzi JN, Bertolin C, Flores-Colen I (2023) A quantitative comparison on the use of thermal insulation materials in three European countries through the TEnSE approach: challenges and opportunities. *Build Environ* 245:110973
10. Las-Heras-Casas J, López-Ochoa LM, López-González LM, Olasolo-Alonso P (2021) Energy renovation of residential buildings in hot and temperate Mediterranean zones using optimized thermal envelope insulation thicknesses: the case of Spain. *Appl Sci* 2021(1):370
11. TEK, FOR-1997-01-11 no. 33: Regulations on requirements for buildings and building products, (TEK) (1997) <http://www.lovdata.no/for/sf/kr/kr-19970122-0033.html>. Last accessed 19 Mar 2025
12. Frasca F, Siani AM, Bertolin C (2024) Energy demand for indoor climate control in museums: challenges and perspectives in time of a changing climate. *Procedia Struct Integr* 55:32–38
13. Lovato T, Peano D, Butenschön M, Materia S, Iovino D, Scoccimarro E, Fogli PG, Cherchi A, Bellucci A, Gualdi S, Masina S, Navarra A (2022) CMIP6 simulations with the CMCC Earth system model (CMCC-ESM2). *J Adv Model Earth Syst* 14:3, e2021MS002814

Water and Energy Consumptions in the Wine Production Industry: A Case Study in Portugal



Cristina Matos , Rita Teixeira , José Baptista , António Valente , and Ana Briga-Sá

Abstract The wine production, included in the primary sector is a great cultural and economic deal, both nationally and internationally matters. However, it is highly dependent on natural resources, and traditionally involves high energy and water consumption. Given the global climate change scenario and the need for efficient resource management, it is necessary to implement a sustainable plan for the wine sector to realize sustainable practices. Data from the International Organization of Vine and Wine (OIV), states that global wine production exceeded 260 million hectoliters, in 2022. These has resulted in significant water and energy consumption, with around 500–1200 m³ of water used per hectare for irrigation and 1.2 gigajoules per hectoliter of wine produced, concluding that more than 80% of total water consumption is associated with irrigation, while more than 90% of energy consumption, is associated with winery processes. In this context, the scarcity of water or the need to achieve carbon neutrality by 2050 makes it essential to adopt energy and water efficiency measures that allow for the sustainable management of resources without endangering the sector's viability. With this in mind, a case study applied to a Portuguese wine industry is presented, including data analysis from water and energy consumption. Also, efficiency metrics will be analyzed, proposing management and decision-support tools based on monitoring and sensor-based techniques. In fact, one example of these efficiency measures deals with the adoption of systems that provide real-time data on consumption patterns and resource availability in order to improve sustainability of the global process production.

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Keywords Water efficiency · Energy efficiency · Monitorization · Winery

1 Introduction

Energy and water efficiency in wine cellars has become a growing focus of attention, driven by the environmental and economic challenges currently facing the wine industry [1, 2]. This demands the adoption of more sustainable practices to ensure competitiveness in the global market [3–5]. In Portugal, the wine industry operates within a regulatory framework shaped by both national and European Union directives aimed at promoting environmental sustainability, such as the EU Green Deal [6], and the national decarbonization target by 2050 [7]. However, the sector still faces several barriers, such as a lack of awareness regarding water usage, limited access to funding for sustainable technologies, and the high initial cost of smart monitoring systems. Despite these challenges, there are growing incentives, including EU funding programs (e.g., RRP—Recovery and Resilience Plan [8]) and innovation grants, which support the implementation of energy and water efficiency technologies.

During the harvest season, wineries experience peaks in electricity consumption, with the cooling systems used to control fermentation being the main culprits [3]. To address these challenges, energy audits carried out in European wineries have identified various energy efficiency measures, including the implementation of energy management and control systems, which can have a significant impact on reducing consumption [2]. In turn, water consumption in wineries can vary widely from 1.41 to 4.35 liters per liter of wine produced, with the highest consumption recorded during bottling periods, and in some cases, it can range from 1.2 to 14.4 liters per liter of wine [9, 10]. However, a study of 18 Portuguese wineries revealed that more than 75% of wineries are unaware of their annual water consumption and the quality of their wastewater, highlighting the need for greater monitoring and innovation in the sector [1].

Therefore, the implementation of water and energy efficiency practices is therefore essential to ensure the sustainability of wine production, reducing dependence on natural resources and minimizing the environmental impacts associated with the intensive use of water and energy [11, 12]. The adoption of technologies and practices that promote the optimization of these resources and the reduction of environmental impacts is crucial for the long-term sustainability of wineries [13].

The use of meters and flowmeters in wineries is crucial for quality control and process optimization [14]. Smart meters have been essential for recording detailed consumption in different equipment and processes, while temperature and humidity sensors monitor the environmental conditions inside wineries, ensuring the quality of the wine [2]. On the other hand, water flow meters make it possible to monitor consumption at different stages of the production process, identifying waste and optimizing the use of water resources [15]. The integrated adoption of these strategies,

including real-time monitoring, appropriate operator training, and process automation, is essential for improving operational performance and ensuring environmental sustainability. This allows wineries to respond effectively to the demands of a market that is increasingly oriented towards sustainability and innovation. Therefore, this study presents an analysis of water and energy consumption of a Portuguese winery. The proposed methodology intends to analyze energy and water efficiency techniques, and to propose management and decision-support tools based on monitoring and sensor-based techniques. The novelty of the paper differs from previous works, due to the integration of a sensor-based system and the use of correlation analysis to relate water and energy consumption in Portuguese wineries.

2 Case Study

The winery under study is located in the Douro Region, in the Corgo subregion, as shown in Fig. 1. It is known for producing distinctive red and white wines, with an average of 534,037.60 l of wine, in the last five years. In addition to wine production, the site is also committed to wine tourism, offering visitors an immersive experience with guided tours, wine tastings, and stays in a guest house. In order to propose an efficient water and energy solution, it was important to characterize water and energy consumption, as well as, the efficiency metrics.

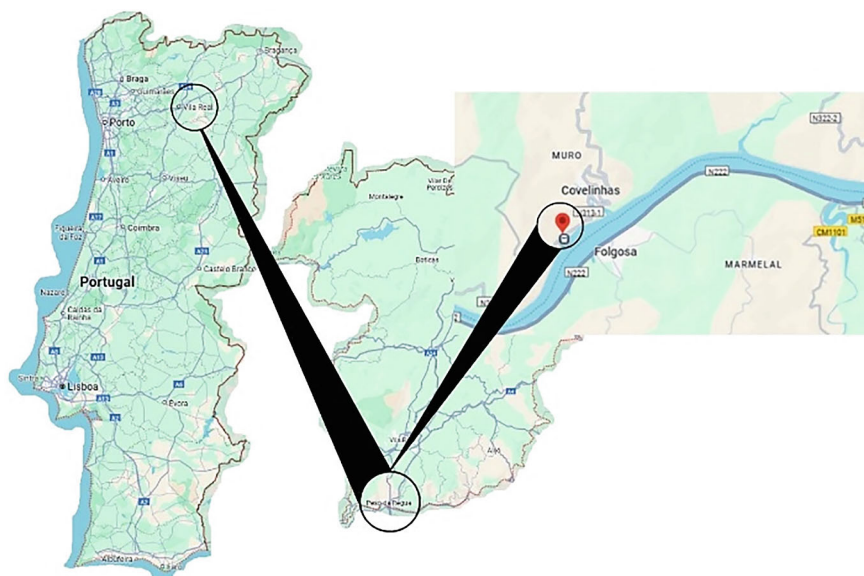


Fig. 1 Location of the winery under study on the map of Portugal

3 Methodology

The proposed methodology intends to analyze efficiency metrics based on water and energy consumption, and the wine produced. Based on the metrics obtained, it was proposed an example of a monitorization system that can be applied in the winery under study, to improve water and energy usage. In this phase no data collection procedure was implemented, only an analysis of the available data. The sensors proposed for the monitoring system are not yet specified.

3.1 *Water and Energy Consumption Characterization*

Water consumption in the winery was characterized on the basis of water consumption monitoring data provided by the winery. The water comes from the site's own catchment and is distributed throughout the site's various infrastructures. The water is collected by a pumping system, whose pump has a power of 2.2 kW and the flow rate is regulated by a variable speed drive.

In turn, the site's energy consumption was characterized on the basis of monthly bills between January and November 2024.

3.2 *Water-Energy Nexus*

The water-energy nexus refers to the interconnectedness between water and energy systems. Water is needed for energy production (e.g., hydropower, cooling power plants), while energy is required for water treatment, pumping, and distribution [15]. In fact, understanding the water-energy nexus is vital for developing sustainable water and energy policies.

To create a mathematical relation between water and energy consumption, it was calculated the correlation coefficient. Since water and energy consumption have different units, it was necessary to normalize the data first, reducing any bias introduced by the different range of values. The correlation coefficient measures the strength and direction of the linear relationship between two variables. A positive correlation means that both variables move in the same direction, i.e., as one variable increases, the other tends to increase, for example. In turn, a negative correlation means that the variables move in opposite direction, meaning that as one variable increases, the other tends to decrease. Also, the closer the coefficient is to 1 or -1 , the stronger the relationship.

3.3 Efficiency Metrics

Efficiency metrics can be described as quantifiable parameters used to assess water and energy consumption, for example [16]. They can provide objective data for evaluating the performance of water and energy systems, regarding their use, environmental impact, and operational costs.

In fact, efficiency metrics are crucial for: cost savings, by identifying areas of inefficiency and measures to minimize them; resource management, to manage water and energy use, minimizing their losses; environmental impact, by reducing water and energy consumption, mitigating greenhouse gas emissions (GEE), for example; and to guarantee service quality [17].

For this study, it was analyzed the specific water consumption (liter/liter), given by the ratio between the annual volume of water used (liters) and the annual wine produced (liters) [Eq. (1)].

$$\text{Specific water consumption (liter/liter)} = \frac{\text{Annual water used volume}}{\text{Annual wine produced}} \quad (1)$$

In terms of energy, it was calculated the specific electricity consumption (kWh/liters), given by the ratio between (the annual electricity consumption of the site (kWh) and by the annual wine produced (liters) [Eq. (2)].

$$\text{Specific GEE emissions (kg/liter)} = \frac{\text{Annual electricity consumption}}{\text{Annual wine produced}} \quad (2)$$

Finally, Eq. (3) gives the specific GEE emissions (kg/liter), based on the CO₂ emissions of electricity use (kg) and the annual wine produced (liter).

$$\text{Specific GEE emissions (kg/liter)} = \frac{\text{CO}_2 \text{ electricity emissions}}{\text{Annual wine produced}} \quad (3)$$

where CO₂ *electricity emissions* is given by Eq. (4), and it was obtained from the 2024 report of electricity emissions factor by APA [18]:

$$\text{CO}_2 \text{ electricity emissions} = 0.198 \left[\frac{\text{kgCO}_2}{\text{kWh}} \right] \text{electricity consumption[kWh]}. \quad (4)$$

3.4 Monitorization System

Given the awareness of the need to implement sustainable techniques to minimize the water and energy footprints of the winemaking process, efforts have been made to propose efficient solutions. Integrating advanced monitoring systems can facilitate

real-time data collection and analysis, enabling producers to identify inefficiencies, optimize resource use, and reduce operational costs.

With this in mind, this work proposes an example of monitorization system for water and energy use in a winery. Sensors are implemented to monitor water and energy consumption in the winery in real time, in order to sectorize the information. Through communication networks to analyze data in real time and to store and process historical data. Combined with the monitoring system, the measured data is used to implement models for managing and optimizing water and energy consumption, in order to predict consumption patterns and strategies for promoting water and energy efficiency.

This monitorization system can easily be used in different wineries, by making an initial assessment of water and energy consumption, identifying key patterns and problems; based on this data, the next step is installing water and energy meters, connected to a digital platform capable of real-time data visualization; and using historical and real-time data to model consumption patterns to predict and optimize the system, particularly during peak usage periods.

4 Results

4.1 *Water and Energy Consumption*

The data was directly collected from the winery reports. The analysis of the values revealed that the harvest season has significantly energy and water consumption compared to the rest of the year. This increase is attributed to the elevated operational demands for the winemaking process, such as, grape crushing, fermentation or refrigeration.

In the months of August to October the water use increases since it corresponds to the harvest period, in particular, in September, with an increase of around 1744% in comparison to the lowest months.

Figure 2 shows the water used in the winery and the wine produced, each year, and also the ratio between the amount of water that is used to produce a liter of wine. It is clear that when the water consumption is higher than the wine produced, the specific water consumption is higher, as it happened between 2019 and 2022. In turn, in 2023 and 2024, the amount of wine produced was higher than water consumption, minimizing the specific water consumed to produce a liter of wine.

Similarly, to water consumption, electricity consumption increased significantly in August and September, as this was the harvest period. In particular, in August consumption increased approximately 393% compared to the consumption billed in March.

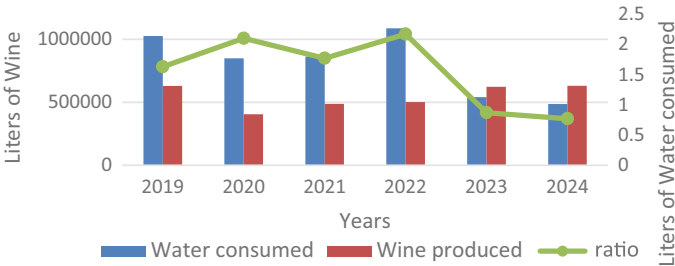


Fig. 2 Water consumed and wine produced from 2019 to 2024 in the winery under study

4.2 Water-Energy Nexus

Figure 3 shows the monthly water and energy consumption, in 2024, for the site, and it is clear that the peaks in both water and energy consumption often align during the harvest period, due to the intensive nature of winemaking operations.

Regarding water consumption, the first peak occurs in July, and it can be associated to the irrigation process. The second peak of water usage occurs in September, and corresponds to the harvest period, in particular, for cleaning and sanitation tasks for processing grapes. In terms of energy consumption, the peak occurred in August, and it can be associated with the operation of machinery and temperature control for wine production.

In this case, the correlation coefficient was 0.5441, which can be considered a moderate positive relationship, meaning that when water consumption increases, energy consumption also tends to increase, as it happens during the harvest period.

Based on this information, Table 1 displays the monthly water and energy consumption for the site in study, as well as, the respective efficiency metrics. In 2024, the total annual wine produced was 631,144 l. Equations (5–7) calculates the efficiency metrics regarding water and energy use in winemaking production.

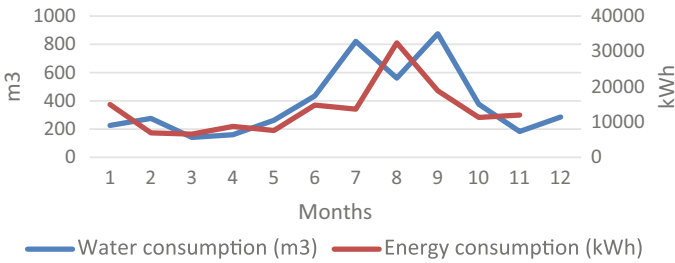


Fig. 3 Water and energy monthly consumption in 2024.Results

Table 1 Monthly and annual water and energy consumption

Months	Water consumption		Energy consumption (kWh)	CO ₂ emissions (kg)
	m ³	liters		
January	226	226,000	14,958	7,501,196.043
February	276	276,000	6947	3,483,807.476
March	141	141,000	6580	3,299,766.575
April	160	160,000	8765	4,395,499.911
May	263	263,000	7622	3,822,298.574
June	435	435,000	14,803	7,423,449.314
July	821	821,000	13,655	6,847,758.374
August	561	561,000	32,422	16,259,096.01
September	875	875,000	18,851	9,453,471.192
October	376	376,000	11,320	5,676,791.621
November	183	183,000	11,975	6,005,253.177
December	286	286,000	–	–
Annual	4603	4603,000	147,898	74,168,388.26

$$\text{Specific water consumption (liter/liter)} = \frac{4,603,000}{631,144} = 7.293 \text{ liter/liter} \quad (5)$$

$$\text{Specific electricity consumption (kWh/liter)} = \frac{147,898}{631,144} = 0.234 \text{ kWh/liter} \quad (6)$$

$$\text{Specific GEE emissions (kg/liter)} = \frac{74,168,388.26}{631,144} = 117.514 \text{ kg/liter} \quad (7)$$

5 Conclusion

The relationship between water and energy consumption in winemaking is critical to the industry's sustainability. As wine producers face increasing pressure to minimize their environmental impact, the adoption of monitoring and instrumentation techniques becomes vital. These tools allow wineries to continuously track water and energy usage and energy, offering the data needed to identify inefficiencies and implement better solutions.

In fact, monitoring water and energy consumption is important to identify patterns, to propose efficiency measures. By leveraging advanced technologies such as sensors and automated systems, winemakers can significantly reduce waste and optimize resource use throughout the production process. Combining these techniques with efficiency metrics can help to understand the resources use, so that producers can

implement targeted strategies to reduce waste, optimize resource management, and enhance operational sustainability.

Overall, integrating these specific measures into the winemaking process is essential for promoting environmental stewardship, operational efficiency, and long-term viability in a competitive market.

References

1. Lisboa S, Saraiva A, Dias I, Saraiva RS, Mamede H, Oliveira MOO (2020) Gestão sustentável da água em adegas nacionais – desafios atuais e futuros. *Revista da ui_ipsantarém*, vol 8, pp 157–169. <https://doi.org/10.25746/ruiips.v8.i3.21340>
2. Vela R, Mazarrón FR, Fuentes-Pila J, Baptista F, Silva LL, García JL (2017) Improved energy efficiency in wineries using data from audits. *Ciência e Técnica Vitivinícola* 32:62–71. <https://doi.org/10.1051/ctv/20173201062>
3. Correia J, Mourão A, Cavique M (2017) Energy evaluation at a winery: a case study at a Portuguese producer. In: Slătineanu L (eds) *MATEC web of conferences* 112: 10001. <https://doi.org/10.1051/mateconf/201711210001>
4. Lopez-Leyva JA (2022) Energy efficiency for wine companies: regional sustainability initiatives in the Guadalupe valley from a transdisciplinary perspective. *Clean Energy Syst* 2:100014. <https://doi.org/10.1016/j.cles.2022.100014>
5. Souza KL, do Carmo RD, Pereira MOA, de Macedo IYL, Casaroli L, Diniz DGA, Mulser H, de Souza Gil E (2024) Questões de ESG na cadeia de vinhos. *Cuadernos de Educación y Desarrollo* 16:868–897. <https://doi.org/10.55905/cuadv16n1-047>
6. The European Green Deal: A growth strategy that protects the climate (2019)
7. RNC 2050 (2018) RNC2050
8. Plano de Recuperação e Resiliência-Recuperar Portugal (2025) Plano de Recuperação e Resiliência-Recuperar Portugal. <https://recuperarportugal.gov.pt/>. Accessed 2 May
9. Saraiva A, Presumido P, Silvestre J, Feliciano M, Rodrigues G, Silva POE, Damásio M et al (2020) Water footprint sustainability as a tool to address climate change in the wine sector: a methodological approach applied to a Portuguese case study. *Atmosphere* 11. Multidisciplinary Digital Publishing Institute: 934. <https://doi.org/10.3390/atmos11090934>
10. Vieira FR (2022) Contributo para a sustentabilidade ambiental na adega: uso eficiente da água. masterThesis, s.n
11. Costa JM, Carlos Lopes L, Santos MC, Mira L (2020) Demonstração e inovação em viticultura focada no uso eficiente da água no Alentejo: “cross-visit” do projeto NEFERTITI. *Revista da Associação Portuguesa de Horticultura*
12. Gonçalves RAV (2018) Bases para um projeto de eco-adega na Região do Algarve. masterThesis, ISA/UL
13. Correia, da Costa Malato JML (2016) Avaliação Energética dos Sistemas de Refrigeração na Indústria Vinícola Caso de uma Aplicação na Adega da Ervideira. masterThesis
14. Abreu A, Requeijo JG, Calado J (2018) Implementation of statistical process control in a bottling line in winery industry. *Millenium-J Educ Technol Health*:23–37. <https://doi.org/10.29352/mill0207.02.00180>
15. de Almeida Baêta SA (2016) Promoção do uso eficiente de água e energia em unidades de produção vitivinícola: estudos de caso da Adega Mayor e Granacer. masterThesis
16. Jorge C, do Céu Almeida M, Covas D (2021) Performance Assessment System for Energy Efficiency in Wastewater Systems. *Water* 13:1807. <https://doi.org/10.3390/w13131807>
17. da Silveira A, Pereira P, Mata-Lima H (2021) Assessing energy efficiency in water utilities using long-term data analysis. *Water Resour Manag* 35:2763–2779. <https://doi.org/10.1007/s11269-021-02866-8>

18. Fator de Emissão de Gases de Efeito de Estufa para a Eletricidade Produzida em Portugal | Agência Portuguesa do Ambiente (2025) <https://apambiente.pt/clima/fator-de-emissao-de-gases-de-efeito-de-estufa-para-eletricidade-produzida-em-portugal>. Accessed 2 May

Dynamic Ventilated Façades for Lightweight Buildings: A Strategy for Mitigating Overheating



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and Victor Miguel Carneiro Sousa Ferreira 

Abstract In the building industry, which is a major contributor to carbon emissions, there is an increasing need for strategies that minimize environmental impacts and enhance energy efficiency. Among other possibilities, the focus on construction components with dynamic performance, particularly in the external envelope (opaque and translucent), is a promising trend namely in the scope of a growing sector of prefabrication. This study explores the application of dynamic ventilated façades in low thermal inertia Light Steel Frame (LSF) construction systems, aiming to mitigate overheating and enhance the thermal and energy efficiency of buildings. To achieve these objectives, a ventilated façade was developed that integrates the geometric optimization of air passage openings (slits) to maximize natural ventilation and reduce recirculation zones and thermal bridges. The evaluation of thermal performance was carried out through Conjugate Heat Transfer (CHT) numerical simulations, comparing the proposed solution with a conventional ventilated façade configuration. The results demonstrated that the proposed dynamic ventilated façade provided an internal temperature reduction of up to 2–3 °C, maintaining the environment below 26 °C, while the conventional system stabilized the temperature around 28 °C. These findings highlight the potential of the strategy to improve thermal comfort and energy efficiency in low inertia buildings, contributing to more sustainable developments in the construction industry.

Keywords Dynamic ventilated façade · Energy efficiency · Conjugate Heat Transfer (CHT) · Overheating · Light steel frame

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1 Introduction

Indoor heating and cooling remain key drivers for energy consumption in buildings, accounting for a share of about 80% [3, 6, 7]. Following the international standards that require the reduction of energy consumption in the building sector and, at the same time, raising quality standards and improving indoor thermal comfort conditions, industrialized lightweight systems have become a promising, efficient and sustainable design choice [4, 5, 8]. Among the lightweight systems, Light Steel Frame (LSF) offers several advantages in comparison to traditional construction techniques: reduced weight which facilitates transportation and handling, faster construction on site, lower cost, reduced waste production and use of water, high quality control due to prefabrication and relevant adaptability [10]. However, due to its low thermal mass and consequent reduced thermal inertia, lightweight construction may be subject to increased difficulties in the indoor thermal regulation, which may compromise indoor thermal comfort and reduce energy efficiency as consequence [8, 11]. Considerable indoor temperature fluctuations and overheating are challenges often reported in lightweight buildings [4].

The role of the external building envelope is very significant when it comes to indoor thermal comfort and thermal regulation. In fact, the relevance of dynamic ventilated façades has been gaining interest in the scientific literature due to its promising results.

A ventilated façade can be defined as an exterior cladding system set away from the building's structural wall in order to form a naturally ventilated air cavity that expels heat and moisture via stack and wind effects. A dynamic ventilated façade contributes to the active control of the building, monitoring environmental factors (e.g. temperature, solar radiation and humidity) and/or accepting commands to alter its physical or energy-transmission properties, thereby adjusting light, thermal resistance or airflow in real time. Consequently, the conventional system is characterised by a fixed, passive design, whereas the dynamic version exhibits a capacity for continual adaptation in order to achieve optimal performance.

Yang et al. [13] proposed a double-skin ventilated glazing façade integrating Phase Change Materials (PCM) to damp indoor temperature fluctuations, prevent overheating, and promote energy-saving potential in buildings. Abdollahi Rizi et al. [1] used numerical simulation and computational fluid dynamics (CFD) to study an innovative approach to adaptive building-envelope design aiming to achieve improved levels of indoor comfort. The authors report that the optimized façade configuration improved daylight performance, consistently maintaining indoor air temperature and velocity within comfortable limits. Soudian and Berardi [9, 12] proposed a multi-functional, climate-responsive ventilated building façade, designed to regulate the flow of heat, air and moisture into buildings, numerically optimizing the solution and evaluating its performance through experimental tests.

This study proposes and evaluates a dynamic ventilated façade for the envelope of LSF systems, aiming to reduce overheating and improve thermal comfort. Different configurations of air-passage grooves in the insulation were evaluated using

numerical simulation with Conjugate Heat Transfer (CHT) analysis, in addition to comparing the efficiency of the proposed façade with that of a conventional ventilated façade solution.

1.1 Objective

This study aims to investigate the application of dynamic ventilated facades in Light Steel Frame (LSF) construction systems to mitigate overheating and improve thermal efficiency in low thermal mass buildings. To achieve this objective, it is proposed to develop a ventilated facade using materials commonly employed in LSF systems, in order to promote natural ventilation and ensure internal thermal comfort. In addition, a parametric study of the geometry of the openings (friezes) for air passage will be carried out, aiming to minimize thermal bridging and reduce recirculation zones, ensuring a continuous and efficient airflow. Finally, the thermal performance of the proposed facade will be evaluated through numerical simulations with Conjugate Heat Transfer (CHT) analysis, compared with a conventional solution.

2 Methodology

The methodological approach of this study is structured into two interdependent stages. The first stage involves the optimization of the ventilated façade design through parametric studies exploring various geometric configurations of air passage through the grooves aiming to maximize the efficiency of natural ventilation and minimize recirculation zones. The second stage comprises evaluating the thermal efficiency of the system using numerical simulations performed in an environment replicating a test cell. This test cell will later serve as a basis for full-scale analysis, enabling the validation of results and the adjustment of the façade performance.

2.1 Description of the Ventilated Façade System

The proposed ventilated façade adapts the traditional concept to the specific characteristics of Light Steel Frame (LSF) construction, which is marked by low thermal inertia. The system is designed to compensate for the lack of thermal mass and its stabilizing effect through dynamic natural ventilation, thus ensuring improved indoor thermal comfort.

Key components of the system include:

- LSF steel studs: Arranged in a grid with dimensions of 100×45 mm and spaced at 600 mm intervals.

- **Internal finishing layer:** Provided by plasterboard, ensuring a uniform inner finish.
- **Thermal Insulation:** A trapezoidal insulation panel made of glass wool, coated with an impermeable material, facilitates application/execution and cleanliness and contributes to overall thermal performance.
- **Air Cavities:** Two main air chambers (to the external and internal sides) are separated by the thermal insulation element. The external chamber is divided by an airflow barrier (insulation), separating the air intake zone from the non-intake zone. Air is drawn into the external chamber side through a lower positioned grille, directed via grooves distributed along the insulation, and released at the top through an upper grille. Simultaneously, the internal chamber side supplies air to the building's interior, promoting continuous air renewal and effective free cooling.

This integrated design not only controls the external thermal loads but also actively conditions the indoor environment through strategic air circulation.

2.2 Optimization of Ventilated Façade Air Passage

To enhance the natural ventilation efficiency, a parametric study was conducted focusing on the geometry of the air passages, this is grooves in the thermal insulation that connects the external and internal air chambers. The objectives of the optimization were:

- **Minimization of the Recirculation Zones:** A physical barrier was introduced to separate the direct air intake area from the non-intake area, reducing thermal bridging.
- **Assurance of Adequate Airflow:** Various groove dimensions were tested (40, 20, 10, and 5 mm widths) while maintaining an equivalent total area for air passage through the lower insulation level.

A schematic diagram of the proposed façade and the tested groove configurations is provided in Fig. 1. This optimization aims to achieve a balance between maximizing airflow and minimizing thermal flux across the façade.

2.3 Thermal Efficiency Evaluation

The thermal performance of the ventilated façade was evaluated through comparative numerical simulations, analyzing two configurations: the proposed dynamic ventilated façade, which incorporates the optimized air passages (groove configuration) and a conventional ventilated façade for the sake of comparison, as the reference system. The test environment was established for a cell with a total volume

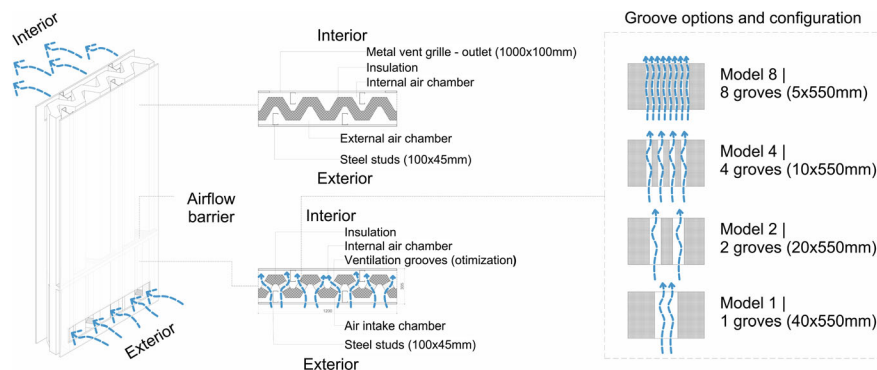


Fig. 1 Schematic diagram of the proposed ventilated façade and tested groove configurations

of 10.80 m^3 of (dimensions $2000 \times 2000 \times 2700 \text{ mm}$) under specific initial conditions. The cell was set to an initial overheating condition, with an initial internal temperature of 26°C influenced by steel studs walls that exhibit an external surface temperature of 30°C . Additionally, for the conventional system, an air exchange rate of $0.6 \text{ m}^3/\text{h}$ was imposed to simulate typical ventilation conditions. These parameters provide a baseline for assessing the cooling potential and overall energy efficiency improvement introduced by the proposed façade system.

2.4 Numerical Model

In this section is presented the geometry of the numerical models used to assess the thermal performance of both the conventional ventilated façade and the test cell volume attached to it (see Fig. 2). Two sets of simulations were conducted: i) one focused solely on optimizing the air grooves in the lower positioned insulation layer in the area of the intake air grille under ideal conditions and a steady-state regime, ii) another comparing the proposed ventilated façade (with optimized groove geometry) to a conventional ventilated façade, both integrated into the test cell under a transient regime.

In the simulation of the ventilated façade panel, ideal conditions were adopted to optimize the air passage. A temperature difference (ΔT) of 10°C was considered, with the internal surface set at 20°C and the external surface at 30°C , while the domain's lateral boundaries were defined as adiabatic, and solids and fluids starting temperature was set to 25°C . The thermophysical properties of the materials used are provided in Table 1. In all studies, the k- ω turbulence model and the Surface-to-Surface (S2S) radiation model were employed. The computational mesh was generated with a minimum orthogonal quality of 0.20, ensuring accuracy and stability in the numerical solution. Under these conditions, it was possible to identify the groove configuration that maximized thermal performance.

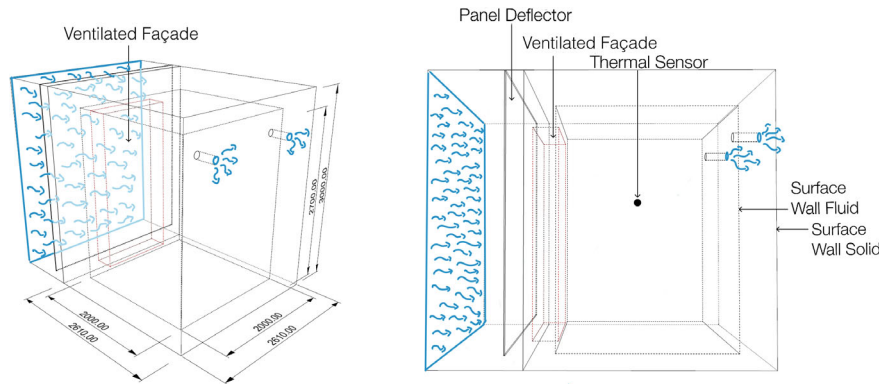


Fig. 2 Input conditions for the numerical model configuration of the test cell (dimensions in mm)

Table 1 Thermo-physical properties of the materials

Material (supplier data)	Thickness (mm)	Density (kg/m ³)	Thermal conductivity (W/m K)	Specific heat J/(kg K)
Glass wool	80	115	0.034	840
Glass fiber reinforced gypsum board	12.5	872	0.186	840
Gypsum plasterboard	12.5	944	0.250	950
Cold-formed C 1.5 mm	1.5	7850	60.50	434

For the comparative evaluation in the test cell, the façades were coupled to a domain, with a 11 m³ volume (2000 × 2000 × 2700 mm). In this transient simulation, an inflow velocity of 0.275 m/s at 20 °C was considered. The external walls of the cell underwent convective heat exchange, set at 30 °C with a convective coefficient of 10 W/m² K, and the boundary wall was assigned geometric (thickness) features and a thermal transmittance ($U = 0.34$ W/m² K) representative of a conventional LSF system. The indoor thermal environment was monitored at intervals over 24 h, allowing an assessment of the system’s response and its ability to mitigate overheating under real operating conditions. As in the case of the façade simulation, the k-omega turbulence model, the S2S radiation model, and a mesh with a minimum quality of 0.20 were used.

3 Results

This section presents the results obtained from the numerical analysis, according to the methodology described in Sect. 2.

Table 2 Optimization results of groove configurations for thermal performance

Numerical model	Number of grooves	Dimension grooves	Heat flux (W/m ²)
Model Ref.	1	130 × 170 mm	5.18
Model 1	1	40 × 550 mm	5.15
Model 2	2	20 × 550 mm	4.74
Model 4	4	10 × 550 mm	4.50
Model 8	8	5 × 550 mm	4.20

3.1 Results of Ventilated Façade Air Passage Optimization

The first stage focused on assessing the impact of the groove geometry on thermal flux through the analysis of different models. As presented in Table 2, configurations with groove widths of 20, 10, and 5 mm were tested while maintaining an equivalent total air passage area. It was observed that, as the groove width decreases, there is a progressive reduction in thermal flux. In particular, Models 4 and 8 demonstrated superior performance: Model 4 showed a 13% reduction in thermal flux, while Model 8 reduced it by 19% compared to the reference model (one single equivalent opening). These results highlight the importance of optimizing the air passage channels to minimize recirculation zones and thermal bridges, thereby contributing to improved energy efficiency of the façade, in line with the study’s objectives (see Sect. 2.4).

3.2 Thermal Performance Results

In the second stage, a comparison was conducted between the proposed ventilated façade and a conventional configuration, using Conjugate Heat Transfer (CHT) simulations as described in Sect. 2.3. Figure 3 illustrates the evolution of the internal temperature over a 24-hour period. It was observed that the proposed façade was able to reduce the internal temperature to approximately 25 °C, while the conventional façade—operating with an air renewal rate of 0.6 m³/h—stabilized the temperature between 27.8 and 28 °C after 10 h.

Additionally, the analysis of Fig. 4 reinforces that the dynamic ventilation strategy adopted in the proposed solution based on the flow of cooler outside air from the ventilated façade enables more effective cooling by maintaining temperatures below 26 °C and within the adaptive comfort range defined by ASHRAE Standard 55-2023 [2]. This improvement in thermal performance not only demonstrates the potential to mitigate overheating in low-inertia LSF buildings but also highlights the practical viability of the solution to reduce thermal loads and enhance indoor comfort conditions.

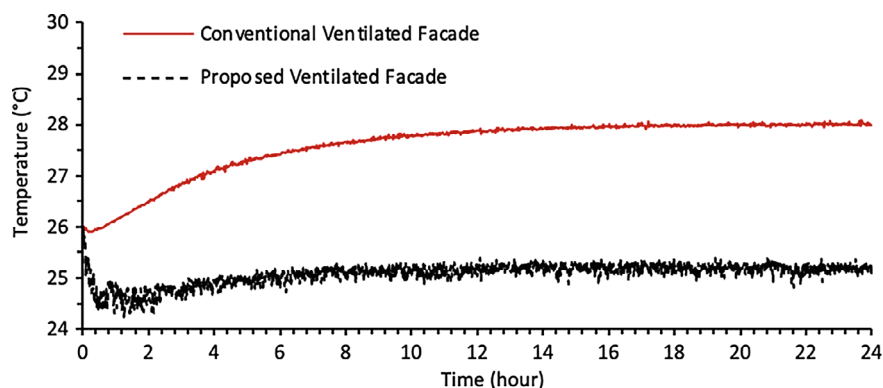


Fig. 3 Hour indoor temperature evolution—conventional versus proposed ventilated

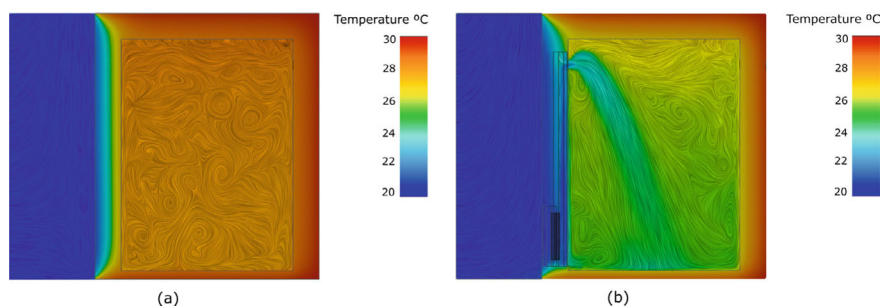


Fig. 4 Cooling performance comparison of ventilated façade systems after 24 h: **a** conventional versus **b** proposed

4 Conclusions

This study demonstrated that the geometric optimization of the air grooves for air passage through the insulation layer, combined with dynamic ventilation, is promising in terms of thermal efficiency. Results indicated an internal temperature reduction of up to 2–3 °C with the proposed ventilated façade compared to conventional solution, aiding in mitigating overheating. Thus, the proposal reveals its potential to increase energy efficiency and provide better indoor comfort, emerging as a promising solution for lightweight, low thermal inertia construction systems.

The study did not consider thermal gains from solar radiation, meaning that the reported 10 °C difference relates solely to air temperature and characterises the milder external thermal conditions typically encountered at night; the inclusion of radiation-induced thermal gains has therefore been proposed for future research. Additionally, the impact of humidity and condensation was not evaluated although solutions to address these effects have already been suggested, they still need to be incorporated into the prototype's experimental studies.

References

1. Abdollahi Rizi R et al (2023) Optimising daylight and ventilation performance: a building envelope design methodology. *Buildings* 13(11):2840. <https://doi.org/10.3390/buildings13112840>
2. ASHRAE: ANSI/ASHRAE Standard 55-2023 (2023) Thermal environmental conditions for human occupancy, Atlanta
3. Cornette JFP, Blondeau J (2024) Operational greenhouse gas emissions of various energy carriers for building heating. *Clean Energy Syst* 9:100148. <https://doi.org/10.1016/j.cles.2024.100148>
4. Figueiredo A et al (2024) Impact of heating strategies towards energy-efficient buildings. *Energy Build* 315:114287. <https://doi.org/10.1016/j.enbuild.2024.114287>
5. Gonçalves M et al (2024) Thermal performance evaluation of a light steel framing building with macroencapsulated phase change materials in a Mediterranean climate. *Energy Build* 323:114837. <https://doi.org/10.1016/j.enbuild.2024.114837>
6. González-Torres M et al (2022) A review on buildings energy information: trends, end-uses, fuels and drivers. *Energy Rep* 8:626–637. <https://doi.org/10.1016/J.EGYR.2021.11.280>
7. Lin T-Y et al (2025) Renewable energy consumption efficiency, greenhouse gas emission efficiency, and climate change in Europe. *Geoenergy Sci Eng* 247:213665. <https://doi.org/10.1016/j.geoen.2025.213665>
8. Roque E et al (2021) Opportunities of light steel framing towards thermal comfort in southern European climates: long-term monitoring and comparison with the heavyweight construction. *Build Environ* 200:107937. <https://doi.org/10.1016/j.buildenv.2021.107937>
9. Shahrzad S, Umberto B (2022) Parametric optimization of multifunctional integrated climate-responsive opaque and ventilated façades using CFD simulations. *Appl Therm Eng* 204:117923. <https://doi.org/10.1016/j.applthermaleng.2021.117923>
10. Soares N et al (2017) Energy efficiency and thermal performance of lightweight steel-framed (LSF) construction: a review. *Renew Sust Energy Rev* 78:194–209. <https://doi.org/10.1016/j.rser.2017.04.066>
11. Soares N et al (2014) Multi-dimensional optimization of the incorporation of PCM-drywalls in lightweight steel-framed residential buildings in different climates. *Energy Build* 70. <https://doi.org/10.1016/j.enbuild.2013.11.072>
12. Soudian S, Berardi U (2022) Experimental performance evaluation of a climate-responsive ventilated building façade. *J Build Eng* 61:105233. <https://doi.org/10.1016/j.jobee.2022.105233>
13. Yang R et al (2023) Thermal performance of an innovative double-skin ventilated façade with multistep-encapsulated PCM integration. *J Energy Storage* 73:109121. <https://doi.org/10.1016/j.est.2023.109121>

Development and Validation of a Numerical Model for Packed Bed PCM Thermal Energy Storage Systems



Pasquale Mollo , Aminhossein Jahanbin , and Umberto Berardi 

Abstract Thermal energy storage systems (TESS) play a crucial role in addressing climate and energy challenges, particularly by improving energy efficiency and enabling the integration of renewable energy in the building sector. This study aims to develop and validate a numerical model of a packed bed latent thermal energy storage (PB-LTES) system that incorporates encapsulated phase change materials (PCM). The proposed model offers a robust and computationally efficient framework for evaluating the energy performance of LTES systems integrated into various renewable energy-based plant configurations. Developed in MATLAB, the PB-LTES model employs a one-dimensional total enthalpy approach, striking a balance between computational cost and simulation accuracy to deliver reliable results with minimal errors and reduced calculation time. The numerical model is validated using experimental data to ensure consistency with the actual thermal behavior of the LTES system. Key validation metrics include the temperature profiles of the PCM and the heat transfer fluid, which are essential indicators of system performance. In addition, the model's performance is evaluated for a hot water application during both charging and discharging phases to demonstrate its practical applicability. This research advances the development of TESS by delivering a validated, dynamic simulation tool that supports the deployment of sustainable energy solutions in real-world applications.

Keywords Energy storage · Latent thermal storage · Encapsulated-PCM · Dynamic simulation

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1 Introduction

The growing integration of renewable energy sources is a key strategy for reducing the environmental impact of human activities. However, a major limitation of these systems lies in the intermittent and non-dispatchable nature of renewable energy, which leads to mismatches between energy supply and demand. As a result, future energy systems will increasingly require energy storage solutions (ESS) to enhance flexibility and ensure a reliable energy balance [1]. Integrated renewable energy systems combined with ESS provide a promising pathway for decarbonization in the context of sustainable development [2].

Among the various ESS technologies, thermal energy storage (TES) has emerged as a widely adopted option, enabling the storage of heat in dedicated tanks for later use. TES systems are generally categorized into three main types: sensible heat storage, latent heat storage (LHS), and thermochemical storage, each distinguished by the storage mechanism and material characteristics.

Sensible heat storage involves the accumulation of thermal energy by increasing the temperature of a solid or liquid medium, typically water, molten salts, or rocks, without inducing a phase transition [3]. LHS systems, in contrast, utilize PCMs that absorb or release significant amounts of thermal energy during phase transitions, most commonly from solid to liquid and vice versa [4]. This mechanism allows for high energy storage densities at nearly constant temperatures, making it advantageous for applications requiring stable thermal outputs. Thermochemical storage is based on reversible chemical reactions, where thermal energy is stored through an endothermic reaction and released via the corresponding exothermic reaction [5].

LHS offers significant advantages over sensible heat storage, particularly in terms of energy storage density, and represents a relatively mature technology that is already commercially available. However, one of the main limitations of this approach is the inherently low thermal conductivity of most PCMs, which hinders effective heat transfer and results in prolonged charging and discharging times.

To enhance the heat transfer performance of PCMs, a widely adopted strategy involves increasing the heat transfer surface area through encapsulation of the storage material [6]. The encapsulation technique typically consists in enclosing the PCM—often in its molten state—within metal capsules, which serve to stabilize the heat exchange interface even when the PCM is fully liquefied [7]. When multiple capsules are packed into a container, they form a packed bed latent TES system [8].

Scientific literature reports extensive investigations on both numerical and experimental modeling of encapsulated latent TES systems. Given the technological importance of these systems, particularly for renewable integration and load-shifting applications, the development of robust and computationally efficient models is essential. These models are critical for understanding system behavior and for facilitating their integration into larger-scale simulation frameworks.

Despite this, a clear gap exists about the availability of streamlined and adaptable models that are suitable for their implementation in dynamic simulation environments. This gap is particularly evident for PB-LHTES systems, where many existing

models are either too computationally intensive for iterative system-level simulations or tailored to highly specific configurations.

The present study proposes a numerically efficient and modular model developed in MATLAB for the simulation of PB-LHTES systems. The model is validated against experimental data and is structured to allow easy integration into dynamic simulation tools such as TRNSYS, enabling more comprehensive technical and operational analyses of these systems within energy networks. A particular emphasis is placed on demonstrating how this technology can enhance energy storage efficiency while significantly reducing the storage mass and volume compared to conventional water-based TES systems. By enabling higher energy density storage through latent heat and improved heat transfer via encapsulation, the model supports the design and optimization of compact, high-performance TES solutions that offer substantial size and weight reductions without compromising hot water supply quality, thus facilitating more practical and sustainable DHW production in buildings.

2 Model Development

In literature, several studies have developed models for PB-LHTES systems. Generally, these models can be divided into two main groups: single-phase models and two-phase models. The single-phase model is a simplified approach that assumes the solid phase and the heat transfer fluid (HTF) share the same instantaneous temperature. In contrast, two-phase models treat the solid and fluid phases separately [9]. The interaction between the two-phase boundaries is typically described using a Nusselt number correlation. There are three main types of two-phase models: the concentric dispersion model, the continuous solid phase model, and Schumann's model [10].

In this study, the concentric dispersion model is adopted to simulate the PB-LHTES system, as it offers a balanced compromise between computational efficiency and accuracy in representing the thermal behavior of the PCM. The concentric dispersion model treats the packed bed as an isotropic porous medium, this approach allows for the calculation of the thermal distribution within the solid capsules. However, it is a one-dimensional (1D) model, meaning it can only assess the thermal gradient in the axial direction, not in the radial one. This modeling approach enables an effective analysis of the PCM dynamic response while maintaining good agreement with experimental observations, and it is computationally less demanding than more complex two-dimensional models.

The concentric dispersion model formulates the thermal behavior of the system using a set of coupled equations: one governing the HTF and two describing the PCM. Specifically, the PCM is characterized by separate equations, one capturing the heat exchange at the capsule boundary and another accounting for the internal thermal distribution within the capsule [11].

The governing equation for the HTF phase is:

$$\varepsilon \cdot C_{P,f} \cdot \rho_f \cdot \left(\frac{\partial T_f}{\partial t} + u \frac{\partial T_f}{\partial y} \right) = \varepsilon \cdot k_f \frac{\partial^2 T}{\partial y^2} + h_{PCM-HTF} (T_{PCM} - T_f) - U_L (T_f - T_{ENV}) \quad (1)$$

where ε is the porosity of the PB system, $C_{P,f}$ is HTF specific heat, ρ_f is the density, u is the velocity in the axial direction of the fluid, k_f is the thermal conductivity of the fluid, $h_{PCM-HTF}$ is the heat transfer coefficient between the PCM and HTF calculated with the common Nusselt's correlations and U_L is the thermal transmittance of the storage wall. The term on the left-hand side represents the heat accumulation of HTF. On the right-hand side, the first term accounts for axial heat conduction, the second represents the heat exchanged between the PCM and the HTF, and the third term accounts for heat losses to the environment.

For the PCM at the boundary, the following equation is used:

$$(1 - \varepsilon) \cdot \rho_{PCM} \cdot \frac{\partial H}{\partial t} = \varepsilon \cdot k_{PCM} \frac{\partial^2 T}{\partial y^2} + h_{PCM-HTF} (T_f - T_{PCM}) \quad (2)$$

where ρ_{PCM} is the PCM density and k_{PCM} is the thermal conductivity of the PCM. This formulation exploits the total enthalpy approach which includes both sensible and latent heat contributions. The right-hand side includes two terms: the first represents axial heat conduction, while the second describes the heat exchange between the PCM and the HTF.

To analyze the inner part of the PCM capsules, a third equation is introduced:

$$\rho_{PCM} \cdot \frac{\partial H}{\partial t} = \frac{1}{r^2} \cdot \frac{\partial}{\partial r} \left(k_{PCM} \cdot r^2 \cdot \frac{\partial T}{\partial r} \right) \quad (3)$$

This equation captures the thermal and enthalpy gradients in the radial direction within the spherical capsule, allowing for a more detailed analysis of the internal PCM behaviour. In the concentric dispersion model, the storage tank is divided into multiple layers, each assumed to have uniform temperature and thermodynamic properties.

The computational domain is discretized using the finite difference method by dividing the height of the reservoir into several calculation nodes. Since the governing equations are differential in nature, a time discretization scheme is also required. The implicit Euler method is selected due to its ease of implementation and low computational cost. The equations were then implemented within the MATLAB software and are solved using the matrix method. The following equations show the discretised models of the HTF and both the PCM equations.

$$\varepsilon \rho_f C_{P,f} \left(\frac{T_f^{(t+1,i)} - T_f^{(t,i)}}{\Delta t} + u \frac{T_f^{(t,i)} - T_f^{(t,i-1)}}{\Delta x} \right) = \varepsilon k_f \frac{T_f^{(t,i+1)} - 2T_f^{(t,i)} + T_f^{(t,i-1)}}{\Delta x^2}$$

$$\begin{aligned}
& + h_{PCM-HTF} \left(T_s^{(t,i)} - T_f^{(t,i)} \right) \\
& + U_L \left(T_f^{(t,i)} - T_{ENV}^{(t,i)} \right). \quad (4)
\end{aligned}$$

$$\begin{aligned}
(1 - \varepsilon) \cdot \rho_{PCM} \cdot \frac{H^{(t+1,i)} - H^{(t,i)}}{\Delta t} &= \varepsilon \cdot k_{PCM} \frac{T_s^{(t,i+1)} - 2 \cdot T_s^{(t,i)} + T_s^{(t,i-1)}}{\Delta y^2} \\
&+ h_{PCM-HTF} \left(T_f^{(t,i)} - T_s^{(t,i)} \right) \quad (5)
\end{aligned}$$

$$\rho_{PCM} \cdot \frac{H^{(t+1,r)} - H^{(t,r)}}{\Delta t} = \frac{k_{PCM}}{r} \cdot \frac{T_s^{(t,r+\Delta r)} - 2 \cdot T_s^{(t,r)} + T_s^{(t,r-\Delta r)}}{\Delta r^2} \quad (6)$$

By expressing the term at time step $t + 1$ using Euler's method, the temperature and enthalpy of both the PCM and HTF can be calculated for each time step and for each node.

3 Reference TES System

The configuration adopted in this study is based on the experimental setup developed by Raul et al. [12], in which a PB-LHTES system designed for solar thermal applications is analysed. The LHTES tank consists of a cylindrical packed-bed system, along with essential auxiliary components such as a circulation pump for the HTF, heat exchangers, control valves, and electric heaters. Figure 1 shows the diagram of the experimental setup of the PB-LHTES under study.

For this application, A164, a commercial PCM with a melting temperature of 168.7 °C, is selected as the storage medium. In the reference study, Hytherm 600 is used as the HTF, while the PCM capsules are enclosed in shells made of stainless steel SS316. The thermal properties of used materials in the simulations can be find in the reference article [12],

From a geometrical point of view, a lab-scale tank with a height of 360 mm was developed and filled with a packed bed consisting of 209 capsules, each containing 95% PCM by volume. The simulation is evaluated in similitude to all the geometrical parameters used in the reference system.

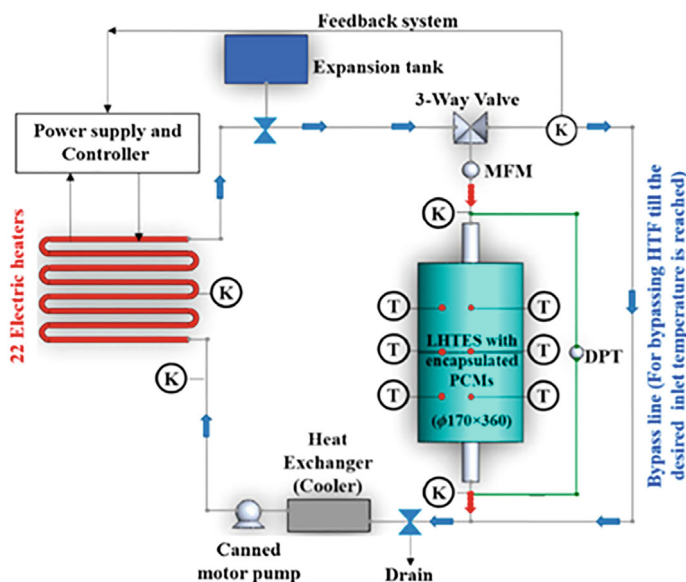


Fig. 1 Experimental configuration of the PB-LHTES under examination [12]

4 Results

4.1 Model Validation

In the following section, the results obtained from the developed numerical model are presented and compared with the experimental data reported in the reference study [12]. For the model validation phase, the same input parameters as in the experimental setup were adopted, specifically the inlet temperature and mass flow rate of the HTF. The key outputs selected for benchmarking the model against the experimental results are the outlet temperature of the HTF and the PCM temperature at the central nodes, as these are critical indicators for the performance evaluation of TES technologies.

The first comparison focuses on the HTF outlet temperature from the storage tank, a crucial parameter that directly reflects the thermal energy delivered to downstream thermal loads in the PB-LHTES system. As illustrated in Fig. 2, the numerical results exhibit good agreement with the experimental data. To quantitatively assess the model's accuracy, the Root Mean Square Error (RMSE) is calculated. For the HTF outlet temperature, the RMSE is found to be 4.46%, indicating a satisfactory level of accuracy and supporting the validity of the model.

Fig. 2 Comparison between the simulated and experimental HTF temperature

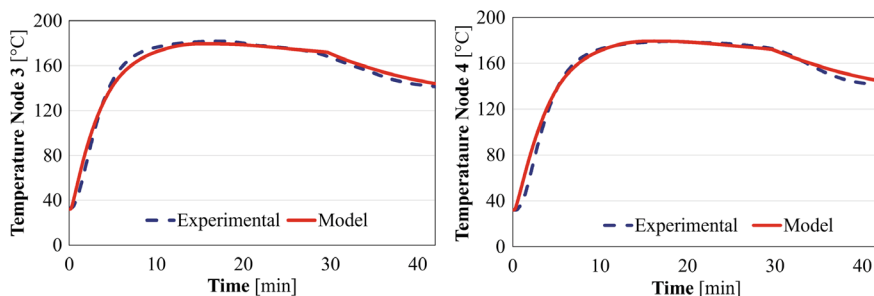
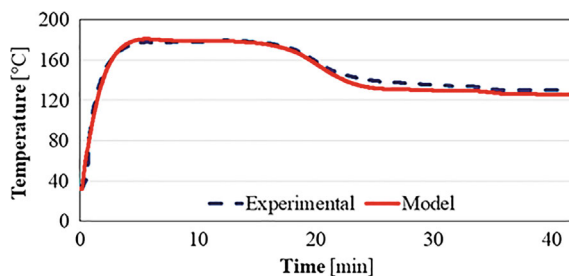


Fig. 3 Comparison between experimental and simulated PCM temperature at central nodes

The second validation parameter is the PCM temperature at the central nodes, which is considered representative of the actual thermal response of the encapsulated PCM within the storage system. The comparison, shown in Fig. 3, demonstrates very good alignment between simulated and experimental results. This is further confirmed by an RMSE value of 4.15%, which falls within an acceptable range for model validation and reinforces the reliability of the simulation for future performance assessments.

4.2 Performance Evaluation

The model's performance is evaluated for a hot water application during both charging and discharging phases to demonstrate its practical applicability. For this application, the commercial PCM RT 70 HC—produced by Rubitherm and characterized by a phase transition temperature between 69 °C and 73 °C and a latent heat of fusion of 260 kJ/kg—is utilized [13]. Based on the thermal storage capacity of the selected PCM, a cylindrical storage tank with a height of 1 m and a diameter of 0.5 m, containing approximately 102.5 kg of PCM, is considered.

The temperature profiles of the HTF at the inlet and outlet, as well as the PCM temperature throughout the process, are presented in Fig. 4.

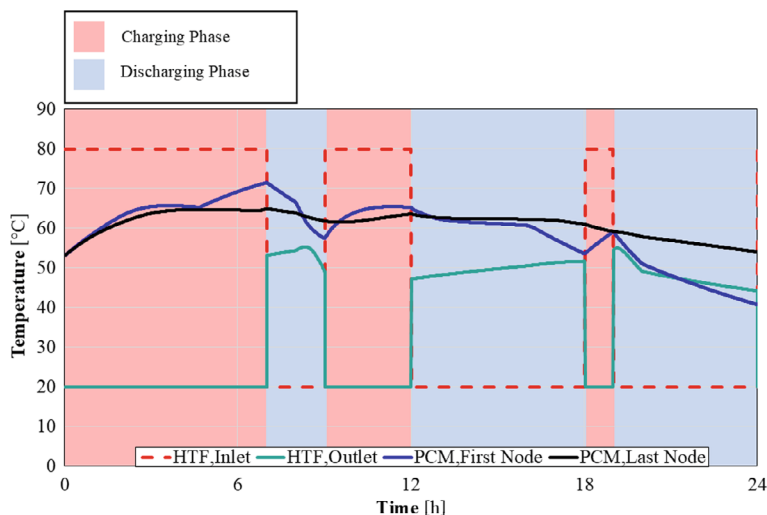


Fig. 4 Temperature trend of HTF and PCM at the inlet and outlet node of the tank

During the charging phase, the water temperature is maintained at 80 °C, while in the discharging phase, it is reduced to 20 °C. The outlet temperature of the HTF follows the thermal behavior of the PCM in the final node of the packed bed. The PCM at the last node shows a smaller temperature variation compared to that at the first node. This behavior is due to the phase transition occurring within the operational temperature range, which allows thermal energy to be stored at a temperature suitable for end-use applications. Furthermore, the average outlet water temperature is approximately 58.1 °C, which is adequate for domestic hot water production.

When compared to a conventional water-based storage system, the required storage mass for this type of TES is approximately 212 kg, underscoring a notable reduction in both weight and system volume achieved with the proposed solution. Additionally, the estimated efficiency of the PB-LTES tank is 90.79%, demonstrating its potential as energy-efficient and compact thermal storage technology.

5 Conclusions

This study presented the development and validation of a numerical model for a PB-LHTES system employing encapsulated PCMs. The model, based on the concentric dispersion approach and implemented in MATLAB, balanced computational efficiency with accuracy, making it suitable for integration into dynamic building energy simulations. Validation against experimental data from a reference system demonstrated strong agreement in both the outlet HTF temperatures and the internal PCM node temperatures, with RMSE values consistently below 4.5%.

Furthermore, the system's performance was evaluated as a domestic hot water application during both the charging and discharging phases. The results showed a notable reduction in both system weight and volume compared to conventional hot water storage solutions, while providing hot water with a mean daily temperature of 58.1 °C and achieving an efficiency of 90.79%. Such improvements pave the way for downsizing conventional TES systems, making them more practical and sustainable for integration with renewable energy sources in building applications. These findings confirmed the reliability of the proposed model and its applicability for the analysis and design of PB-LHTES systems integrated with renewable energy sources in the building sector.

References

1. Brosa Planella F (2025) A simple model for latent thermal energy storage systems with encapsulated phase-change material. *Int J Heat Mass Transf* 239:126533
2. Jahanbin A, Abdolmaleki L, Berardi U (2025) Cross-climate analysis of techno-economic metrics in bi-level electrical and hydrogen storage systems for off-grid electrification of buildings. *J Energy Storage* 107:114938
3. Furbo S (2015) 2—Using water for heat storage in thermal energy storage (TES) systems. In: Cabeza LF (ed) *Advances in thermal energy storage systems*. Woodhead Publishing, p 31–47
4. Jouhara H, Żabnieńska-Góra A, Khordehgah N, Ahmad D, Lipinski T (2020) Latent thermal energy storage technologies and applications: a review. *Int J Thermofluids* 5–6:100039
5. Abedin AH, Rosen M (2011) A critical review of thermochemical energy storage systems. *Open Renew Energy J* 4(1):42–46
6. Zhang H, Baeyens J, Cáceres G, Degrève J, Lv Y (2016) Thermal energy storage: recent developments and practical aspects. *Prog Energy Combust Sci* 53:1–40
7. Mohaghegh MR, Alomair Y, Alomair M, Tasnim SH, Mahmud S, Abdullah H (2021) Melting of PCM inside a novel encapsulation design for thermal energy storage system. *Energy Convers Manag*: X 11:100098
8. Felix Regin A, Solanki SC, Saini JS (2009) An analysis of a packed bed latent heat thermal energy storage system using PCM capsules: Numerical investigation. *Renew Energy* 34(7):1765–1773
9. Farid MM, Khudhair AM, Razack SAK, Al-Hallaj S (2004) A review on phase change energy storage: materials and applications. *Energy Convers Manag* 45(9):1597–1615
10. Zalba B, Marín JM, Cabeza LF, Mehling H (2003) Review on thermal energy storage with phase change: materials, heat transfer analysis and applications. *Appl Therm Eng* 23(3):251–283
11. de Gracia A, Cabeza LF (2017) Numerical simulation of a PCM packed bed system: a review. *Renew Sustain Energy Rev* 69:1055–1063
12. Raul A, Jain M, Gaikwad S, Saha SK (2018) Modelling and experimental study of latent heat thermal energy storage with encapsulated PCMs for solar thermal applications. *Appl Therm Eng* 143:415–428
13. Khan Z, Khan Z, Ghafoor A (2016) A review of performance enhancement of PCM based latent heat storage system within the context of materials, thermal stability and compatibility. *Energy Convers Manag* 115:132–158

A Methodology Based on Equivalent Models for Multilayer Walls for the Energy Retrofit of Existing Buildings



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Abstract The energy performance of building elements is typically assessed using thermal resistance that depends on the detailed knowledge of the wall assembly. Unfortunately, such information is often unavailable, as technical data may have been lost over time, and aging or weathering processes can alter the thermal behavior of building envelopes. This issue is especially relevant for the Italian building heritage. To address the lack of information, equivalent models for multilayer walls were developed to replicate the thermal behavior of actual structures. These equivalent configurations enable the evaluation of energy efficiency improvements while overcoming data limitations. This paper presents a case-study focused on the development of a methodological procedure for identifying equivalent thermo-physical properties of walls in the context of an energy retrofit intervention on a listed heritage building. Numerical simulations were conducted using COMSOL Multiphysics and equivalent configurations were tested to assess their ability to replicate the thermal behavior of the original multilayer structures. To ensure a robust validation of the proposed methodology, numerical results were compared with measurements taken in two distinct scenarios: the first prior to retrofitting, and the second after the application of thermal insulation. The results demonstrate that equivalent wall models can provide a satisfactory representation of the thermal behavior of both uninsulated and insulated multilayer walls, offering a practical approach for thermal performance assessment in scenarios where detailed stratigraphic information is unavailable.

Keywords Simulation · Thermo-physical properties · Retrofit · Building · Sustainable materials

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1 Introduction

Significant overall energy saving can be achieved in the civil sector through the energy retrofit of buildings [1]. A significant portion of energy savings can be achieved by improving the thermal insulation of building envelope components, thereby reducing the amount of energy required for heating and cooling indoor environments. A performance indicator that allows us to characterize the thermal properties of a building envelope component is the thermal transmittance, which represents the material's tendency to be traversed by heat flux.

The starting point for any energy improvement action is the knowledge of the thermophysical properties of all the elements that make up the building [2]. But it is often the case that there is lack about the stratigraphy of opaque elements, especially in the case of historic buildings [3]. Technical data of building elements may be lost or may deviate from reality due to ageing materials. Invasive or non-invasive on-site surveys can be used to solve the problem [4]. Invasive tests involve the removal of samples into the wall. Conversely, non-invasive tests involve the use of measuring instruments without removing any samples and allow for the estimation of the thermal resistance value of the wall. However, this approach enables merely the steady-state description of heat transfer through the wall not taking into account the dynamic thermal behavior. The thermal inertia, related to thermal capacitance, must be considered to account for dynamic thermal characteristics of the walls. To study the dynamic behavior of a wall, without invasive methods, some studies have focused on its equivalent representation, that is, they have investigated whether a single-layer equivalent homogeneous wall can be used to approximate any given physical wall under the same thermal boundary conditions [5]. A perfect equivalence is achieved only when the effusivities of both materials are identical, but an approximate model may be employed to obtain the dynamic thermal properties of unknown multilayer walls [6]. Various representations were tested and the results indicate that these representations can indeed provide satisfactory equivalence. The equivalent models have already been developed based on experimental data but not on real retrofit intervention.

Starting from this, the focus of this study is to develop a methodological procedure for identifying equivalent dynamic thermo-physical properties of walls in the context of a real energy retrofit intervention.

2 Material and Methods

2.1 Case study and experimental setup

The case study involves an energy retrofit intervention of a historic building, known as Villa Rossi, located in the municipality of Banchette di Ivrea (TO). The building was designed between 1959 and 1961 by Emilio Aventino Tarpino and is subject

to historical preservation restrictions imposed by the Superintendence of Fine Arts [7]. Measurements were carried out using the heat flow meter method as outlined in the UNI ISO 9869 part 1 standard of 2015 [8]. This standard describes the heat flow meter method to measure the thermal transmission properties of flat building components, the equipment to be used, the calibration procedure, installation and measurement procedures, data analysis, including systematic error correction.

The wall examined before and after an energy efficiency intervention is typical cavity wall. The efficiency intervention involved blown-in of cork granules inside the empty cavity of the walls, combined with an internal insulation of 2 cm cork board, a water vapour retardant membrane, and a gypsum plasterboard sheet finished with smoothing. The stratigraphy is reported in Table 1.

The theoretical thermal resistances (R) (not considering the internal and external surface resistances) are equal to $0.904 \text{ m}^2\text{K/W}$ and $2.96 \text{ m}^2\text{K/W}$ respectively for pre-retrofit and post-retrofit walls.

Heat flow meter sensors were installed on the internal side of the walls. Surface temperature probes were inserted on the internal and external side of the walls. The schematic representation of the experimental setup is shown in Fig. 1.

The measurement campaign was conducted during the winter. Inside the room where the measurements were taken, an electric oil heater connected to a thermostat set at 19°C was installed to maintain a constant and controlled indoor temperature.

2.2 Methodological Approach

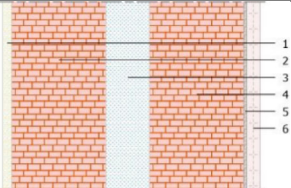
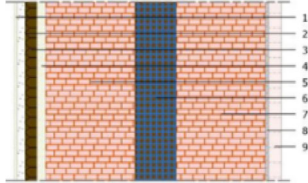
The methodological approach is characterized by the following steps:

- (1) As the data processing method for the measurements collected during the monitoring campaign, the progressive averaging method, as outlined in UNI ISO 6989 Part 1:2015, was selected and employed. The chosen method uses average values calculated over preceding time intervals instead of relying on instantaneous values of heat flux and temperature. The average values are collected in both tabular and graphical form instant by instant. An approximate value of resistance “ R ” can be derived from the following formula:

$$R_{wall-exp} = \frac{\sum_i (T_{si} - T_{se})_i}{\sum_i q_i} \quad (1)$$

where q_i is the heat flow density and T_{si} and T_{se} are the internal and external surface temperatures. Thus, it was compared the theoretical wall thermal resistances and the experimental ones where the equivalent thermal conductivities λ_{eq} was obtained through the equation $\lambda_{eq} = s/R$, where s is the thickness of the wall.

Table 1 Walls stratigraphy and thermophysical properties

Layer	Thickness [m]	Thermal conductivity [W/(mK)]	Specific heat capacity [J/(kgK)]	Mass density [kg/m ³]	Thermal resistance [m ² K/W]	
<i>Pre-retrofit wall</i>						
	1. Plaster	0.01	0.21	950	1600	0.048
	2.Hollow brick	0.12	0.600	840	1200	0.200
	3. Air gap	0.07	0.18	1000	1.2	0.389
	4.Hollow brick	0.12	0.600	840	1200	0.200
	5. Plaster	0.01	0.21	950	1600	0.048
	6. Klinker	0.02	1	1100	2000	0.020
Total	0.35				0.904	
<i>Post-retrofit wall</i>						
	1–2. Plasterboard	0.01	0.21	1000	900	0.048
	3. Cork panel	0.02	0.04	1674	150	0.488
	4. Plaster	0.01	0.04	950	1600	0.250
	5.Hollow brick	0.12	0.600	840	1200	0.200
	6. Cork grit	0.07	0.041	1674	150	1.707
	7.Hollow brick	0.12	0.600	840	1200	0.200
	8. Plaster	0.01	0.21	950	1600	0.048
	9. Klinker	0.02	1	1100	2000	0.020
Total	0.38				2.96	

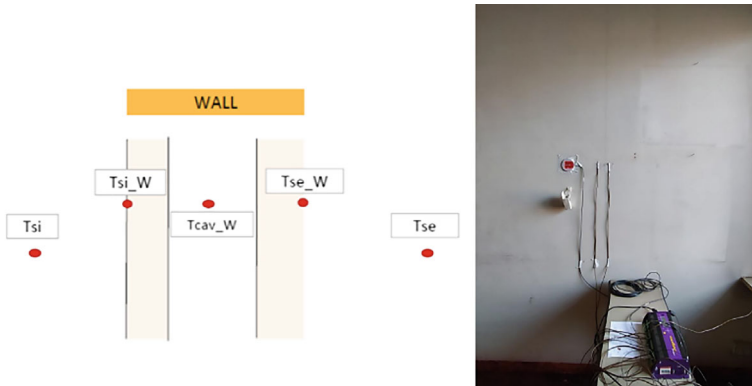


Fig. 1 (Left) Temperature sensors position; (right) Heat-flow meter sensor and surface temperature probes

- (2) To assess the ability to replicate the thermal behavior of the original multilayer structures, the equivalent configurations were tested using COMSOL Multiphysics. The *Heat Transfer Module in Solids* module was utilized to study the heat transfer according to the following formula:

$$\rho c \frac{\partial T}{\partial t} \nabla \cdot \mathbf{q} = Q \quad (2)$$

where Q is the heat flux, ρ is the material mass density and c is the specific heat capacity. The heat transfer through the wall was modeled as a one-dimensional problem: to ensure no heat transfer across the boundary, adiabatic boundary conditions were implemented on the top and bottom sides of the wall models. Both walls were replicated as single-layer walls. Boundary conditions were therefore reproduced. Thermal inputs equal to the external surface temperatures (T_{se}) and internal surface temperatures (T_{si}) were set in the models.

- (3) After recreating the walls as equivalent homogeneous layers with thicknesses matching the original walls, the accuracy of the approximation was evaluated using the EF index, defined as follows:

$$EF = \frac{\sum_{i=1}^N (m_i - \bar{m})^2 - \sum_{i=1}^N (s_i - m_i)^2}{\sum_{i=1}^N (m_i - \bar{m})^2} \quad (3)$$

where m_i is the measured value at time t_i , $\bar{m}$ is the mean measured value, s_i is the simulated value and N is the total number of measurements $\bar{m}$ is the mean value among the measured ones. The EF index (Efficiency Index) is a statistical indicator used to assess the agreement between measured and simulated data. A value close to 1 indicates a good match between the two datasets.

The thermal dynamic response of walls is linked to density (ρ) and specific heat capacity (c). Utilizing the equivalent thermal conductivity λ_{eq} , the equivalent density (ρ_{eq}) and specific heat capacity (c_{eq}) were determined through an iterative procedure aimed at maximizing the EF index. This approach enabled the closest approximation of the wall’s actual dynamic thermal characteristics, specifically regarding heat flux. A constant value of c_{eq} , fixed at 900 J/kg·K, to reflect typical construction material properties, was adopted. Meanwhile, the equivalent density ρ_{eq} was adjusted iteratively to satisfy the defined criteria.

3 Results and Discussion

The experimental data were initially used to determine the thermal resistance of the wall. Figure 2 shows the measured heat fluxes and internal and external surface temperatures. The progressive average method was utilized to calculate the experimental thermal resistances of the walls, which are detailed and compared with the theoretical thermal resistance in Table 2.

The equivalent wall model was developed using COMSOL. Specifically, for the single layer, the original thickness of the reference wall and the equivalent thermal conductivities λ_{eq} were used. The equivalent specific heat capacity c_{eq} was set equal to 900 J/kgK and the equivalent mass density ρ_{eq} was adjusted incrementally to achieve optimal alignment with the experimental heat flow. Figure 3 shows the ability to reproduce the experimental heat fluxes: the red lines refer to the experimental values, the black lines refer to the equivalent wall characterized by the experimental λ_{eq} . The

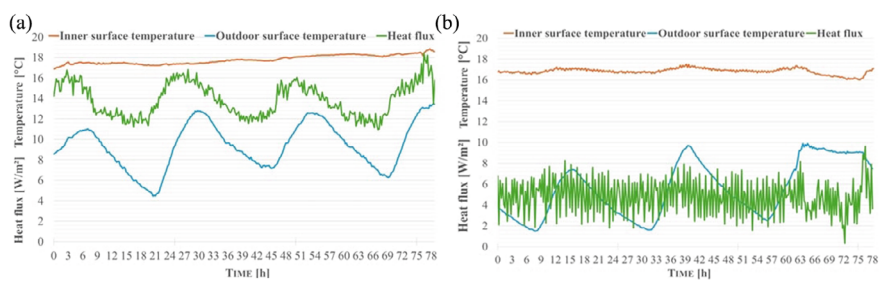


Fig. 2 Measured heat flow density and internal and external surface temperatures pre-retrofit **a** and post-retrofit **b** walls

Table 2 Theoretical and experimental thermal resistances of walls

Wall	Theoretical R [(m² K)/W]	Experimental R [(m² K)/W]	Theoretical λ_{eq} [W/(m K)]	Experimental λ_{eq} [W/(m K)]
Pre-retrofit	0.904	0.619	0.387	0.565
Post-retrofit	2.960	2.632	0.128	0.144

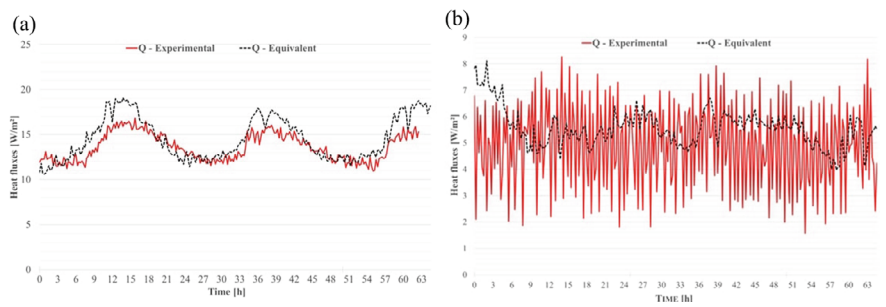


Fig. 3 Heat fluxes comparison between original walls and equivalent pre-retrofit (a) and post-retrofit (b) walls

Table 3 Equivalent thermophysical properties and EF indexes for the equivalent walls

Wall	λ_{eq} [W/(m K)]	$\rho_{eq} * c_{eq}$ [J/(m ³ K)]	EF
Pre-retrofit	0.565	1440 * 900	0.96
Post-retrofit	0.144	1690 * 900	0.98

most accurate equivalent wall representations were determined for values listed in Table 3.

The results showed that the proposed method can effectively be utilized to achieve satisfactory outcomes in dynamic thermo-physical parameters within real-world boundary conditions. The EF values were equal to 0.96 and 0.98 respectively for pre-retrofit and post-retrofit walls. Thus, the proposed approach seeks to address uncertainties in defining masonry stratigraphy by offering a methodology capable of identifying equivalent thermo-physical properties that are valuable for energy software used in buildings.

4 Conclusions

The aim of this study was to verify whether a multilayer wall can be accurately approximated by an equivalent homogeneous wall to analyze its dynamic thermal behavior in cases where the wall’s stratigraphy is unknown. Starting from a case study of an energy retrofit in a historic building, the wall was modeled using finite-element software under dynamic thermal boundary conditions. Then, experimental data collected were utilized to create an equivalent model under real boundary conditions. The goodness-of-fit was evaluated using EF, with values reaching up to 0.98 and 0.95 respectively for pre-retrofit and post-retrofit wall. The results demonstrate that equivalent wall models can provide a satisfactory representation of multilayer walls for the energy retrofit of existing buildings.

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References

1. Ma'bdeh SN, Ghani YA, Obeidat L, Alosan M (2023) Affordability assessment of passive retrofitting measures for residential buildings using life cycle assessment. *Heliyon* 9:e13574
2. Sassine E, Cherif Y, Antczak E (2019) Parametric identification of thermophysical properties in masonry walls of buildings. *J Build Eng* 25:100801
3. Ficco G, Iannetta F, Ianniello E, D'Ambrosio Alfano FR, Dell'Isola M (2015) U-value in situ measurement for energy diagnosis of existing buildings. *Energy Build* 104:108–121
4. Domazetović M, Krstić H, Kosiński P (2019) Review and comparison of current experimental approaches for in-situ measurements of building walls thermal transmittance. *Energy Build* 109417
5. Evangelisti L, Guattari C, Gori P, Asdrubali F (2018) Assessment of equivalent thermal properties of multilayer building walls coupling simulations and experimental measurements. *Build Environ* 127:77–85
6. Evangelisti L, De Lieto Vollaro R, Asdrubali F (2022) On the equivalent thermo-physical properties for modeling building walls with unknown stratigraphy. *Energy* 238:121679
7. Giapopelli E (2021) Four villas of the homes consultancy office for Olivetti employees. Between architecture and industrial product. *Soc Eng Arch Turin (SIAT)*. *Atti e rassegna tecnica* 154(2):9–20. ISSN: 0004-7287
8. Bienvenido-Huertas D, Moyano J, Marín D, Fresco-Contreras R (2019) Review of in situ methods for assessing the thermal transmittance of walls. *Renew Sustain Energy Rev* 102:356–371

A GIS and Bottom-Up Simulation-Based Framework to Assess the Role of Zero-Emission Building Standards in Achieving Low-Carbon Goals: Insights from a Case Study for China



Sadik Yigit , Juan Mahecha Zambrano , and Luca Baldini 

Abstract The transition to zero-emission buildings is crucial for improving energy performance and achieving global low-carbon goals. This study introduces a GIS and simulation-based methodology to assess the impact of zero-emission building standards on carbon reduction targets, applicable across various urban settings. Using China as a case study, the research examines four climate zones: Shenzhen (hot summer, warm winter), Harbin (extremely cold), Beijing (cold), and Shanghai (hot summer, cold winter). Residential buildings are categorized into archetypes based on height and age. Simulations of baseline energy demands for heating and cooling use archetype-specific configurations and schedules from a public database. The methodology evaluates carbon reduction measures at the building level, assessing their effectiveness across different archetypes and climates. Passive measures enable most buildings in Beijing, Harbin, and Shanghai to achieve nearly zero carbon emission thresholds, except for terraced houses in Harbin and Shanghai. In Shenzhen, active measures like PV panels and HVAC upgrades are required for most building types. The results demonstrate the potential of zero-carbon building standards to reduce energy use and carbon emissions. Insights from this case study highlight effective retrofit strategies for various archetypes and climates, providing a foundation for future upscaling efforts. This scalable approach offers a robust framework for designers and urban planners to implement zero-carbon building standards globally, using China as a proof-of-concept.

Keywords Zero-emission buildings · Carbon reduction · GIS methodology · Bottom-up modelling · Building archetypes · Retrofit strategies

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1 Introduction

China, the world's largest CO₂ emitter, aims to peak carbon emissions by 2030 and achieve carbon neutrality by 2060 [1]. Building energy consumption, influenced by factors like floor space, income, and population, accounts for about a third of China's total energy demand. Transitioning to zero-carbon buildings is crucial for climate change mitigation, especially in urbanizing regions. Large-scale adoption of zero-emission buildings (ZEBs) is necessary, with energy demand managed through various measures and technological advancements. Improving building energy performance through retrofits and stricter standards is key to aligning urban development with national climate targets.

Research highlights the importance of building energy efficiency in reducing emissions. For example, studies on Shenzhen show that operational emissions from buildings nearly doubled between 2005 and 2019 [1]. Strict energy efficiency policies and renewable energy integration could help the building sector peak emissions by 2025, ahead of the national target. Enhanced policy frameworks, financial incentives, and technological advancements are needed to support these efforts [2].

Energy conservation measures like envelope upgrades, daylight optimization, and photovoltaic system integration have been explored to reduce carbon emissions [3]. Advanced energy modeling tools developed to simulate energy demand and evaluate retrofit strategies. Effective measures include efficient thermal insulation, high-performance windows, and fresh air heat recovery systems. Large-scale photovoltaic deployment and its impact on distribution grids have also been studied, highlighting technical and regulatory challenges [4].

On-site electricity generation is crucial for achieving carbon neutrality. Integrating heat pumps and combined heat and power systems with renewable energy sources like solar and geothermal is essential [5]. Urban-scale energy modeling supports city-wide energy efficiency strategies, and various methodologies estimate and project China's building energy demand [6]. Research on zero-energy buildings provides a foundation for representative building stock analysis [7].

This study introduces a GIS and simulation-based framework to assess the role of the new ZEB standard [8] in achieving low-carbon goals. Using China as a case study, it evaluates retrofitting and active energy generation measures at the building level across four climate zones: Shenzhen, Harbin, Beijing, and Shanghai. By categorizing residential buildings into archetypes, the study simulates baseline energy demands and evaluates zero-carbon strategies, providing insights for scalable urban energy planning. The presented analysis is part of a newly developed methodology and framework for the analysis of the impact of new building standards on the carbon emissions of larger urban areas.

1.1 Objectives of the Study

This study aims to:

- Present a GIS-based bottom-up simulation-based methodology to assess the role of ZEB standards in achieving low-carbon goals.
- Assess the impact of ZEB standards on energy demand and carbon reduction at the building level.
- Identify the most effective decarbonization strategies for residential buildings for different building types and climates (Shenzhen, Harbin, Beijing, and Shanghai).
- Provide insights for policymakers, urban planners, and designers to support the transition to low-carbon urban development.

2 Methodology

2.1 Overview of the Framework

The methodology presented in Fig. 1 follows a bottom-up approach, beginning with a detailed building-level analysis before scaling up to the superblock level to estimate carbon emissions across larger urban areas. This structured framework integrates energy simulation, GIS-based spatial analysis, and clustering techniques to assess the role of ZEB standards in achieving low-carbon goals.

At the building level, the analysis starts with the classification of residential buildings into archetypes (terraced-house, low-rise apartment, high-rise slab, high-rise tower) based on key parameters such as height, age, and climate zone [7]. A Python-based workflow extracts detailed information, including size, construction materials,

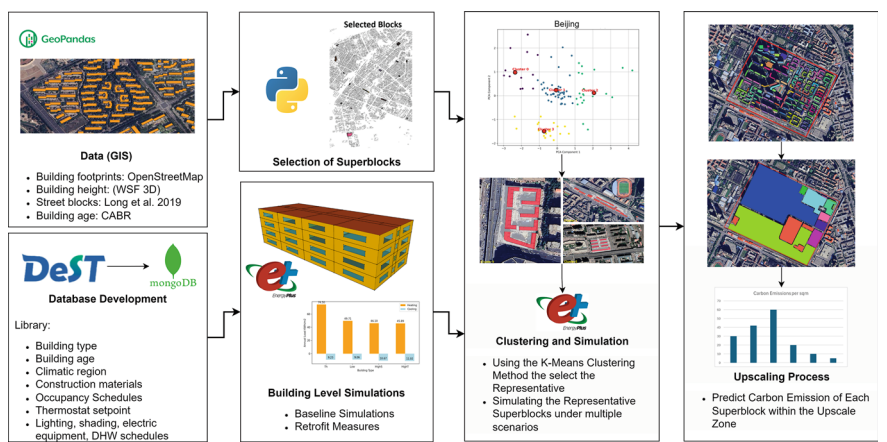


Fig. 1 The general framework of the study

insulation levels, climatic conditions, and usage patterns, to accurately model their energy performance using the DeST prototype building database. This database hosts building construction and performance data compliant with building standards and codes valid for a certain construction period. Additionally, building operation characteristics, such as occupancy schedules, electricity consumption, domestic hot water (DHW) usage, temperature settings, and equipment use, are incorporated based on the NZEB standard [9] and research findings [7] to ensure realistic energy demand profiles.

These archetypes are then simulated using Cesar-p (an EnergyPlus-based engine) to establish baseline energy consumption for heating and cooling, as well as to evaluate decarbonization strategies [10]. Various retrofit measures are tested to assess improvements in energy performance. Passive strategies, such as improved insulation, window replacement, and window shading systems, are tested first, followed by active measures such as photovoltaic (PV) integration and HVAC system upgrades to assess their effectiveness in achieving zero-emission goals.

The results from the building-level simulations are then used to inform the superblock-level analysis. Superblocks are synonymous with street blocks and most of the time represent a real-estate area developed at the same time. In Chinese cities, the superblocks form a predominant urban pattern [11] and are thus seen to be an appropriate unitary base for urban energy performance analysis and upscaling. At the superblock level, buildings are grouped into categories using a k-means clustering algorithm to identify common patterns based on factors such as density, overall U-factor, and shape factor. Representative superblocks are selected from each cluster and tested under different conditions, including future climate scenarios, to evaluate their energy performance.

Finally, the results from the superblock level are upscaled to larger areas in selected cities. This upscaling allows for a broader assessment of urban-scale decarbonization scenarios, helping to understand and improve energy use at different scales, from individual buildings to broader urban areas. While the broader framework incorporates GIS for large-scale spatial analysis, this paper primarily presents results at the building level, where GIS does not play a direct role. However, the insights gained from building-level simulations remain crucial for informing the GIS-based superblock clustering and urban-scale upscaling, ensuring a coherent approach to achieving low-carbon urban development.

2.2 Building-Level Simulation Approach

The baseline for the building archetypes was established based on a study conducted by [7]. Buildings are classified into four archetypes: Terraced House, Low-rise, High-rise Slab, and High-rise Tower. A prototype from each archetype was developed using the DeST software. The geometrical information of the archetype buildings is presented in Table 1.

Table 1 The geometrical information and natural ventilation rates for building archetypes

	Air conditioned area	Number of floors	Shape factor	WWR	Natural ventilation (ACH)
Terraced H.	930	2	0.48	0.27	0.5–5
Low-rise	1703	4	0.36	0.26	0.5–5
High-rise S.	3947	9	0.31	0.26	0.5–5
High-rise T.	10,261	24	0.30	0.25	0.5–5

Data obtained from the DeST database is organized by city (Beijing, Harbin, Shanghai, and Shenzhen), archetype (Terraced House, Low-rise, High-rise Slab, and High-rise Tower), and building age, based on the energy standard in effect at the time. A total of 48 building archetypes are defined. The stored building properties include construction and material details for surfaces such as walls, floors, and roofs. Additionally, activity schedules—including occupancy, lighting, and appliance usage—are sourced from DeST models and a published article [7].

2.3 Carbon Reduction Pathways

The transition to low-carbon buildings requires a mix of passive and active strategies to improve energy efficiency and reduce emissions. The decarbonization pathways begin with insulation and window upgrades, followed by HVAC improvements, shading, and on-site renewable energy integration. Insulation and window upgrades follow China’s GB/T 51350–2019 Near-Zero Energy Buildings Standard, with climate-specific U-values: windows range from 1.0 W/m²K in Harbin to 2.5 W/m²K in Shenzhen, while wall insulation varies from 0.15 W/m²K in Harbin to 0.80 W/m²K in Shenzhen [9]. Roof and ground floor insulation also follow climate-adapted values, ensuring optimal thermal performance.

The current and proposed HVAC systems are presented in Table 2. HVAC efficiency is improved by replacing conventional systems with energy-efficient alternatives, significantly reducing operational emissions. A rated COP of 4.5 for heating and 3.5 for cooling was used under standard conditions. Solar panels are added in later stages to produce clean electricity directly at the building, reducing dependence on the power grid. Based on the new standard we assume 20% panel efficiency and 75% roof coverage, a best-case scenario showing full solar potential [8]. Shading elements are introduced in some scenarios to limit solar heat gains, particularly in cooling-dominated climates, reducing cooling demand.

The retrofiting pathways presented in Table 3 follow a stepwise approach, starting with basic upgrades and progressively adding advanced strategies. The updated ZEB standard assesses building performance based on carbon emission intensity per square meter of floor area, with residential building carbon emission thresholds outlined in Table 4.

Table 2 HVAC systems for the current and retrofitted design of the buildings

	Existing building	Retrofit option
<i>Heating dominated climate (Harbin, Beijing)</i>		
Heating	Centralized gas heater	Centralized air-source hp
DHW	Centralized gas heater	Centralized air-source hp
Cooling	Decentralized split unit (air-air hp)	Decentralized split unit (air-air hp)
<i>Cooling dominated climate (Shanghai, Shenzhen)</i>		
Heating	Decentralized split unit (air-air hp)	Decentralized split unit (air-air hp)
DHW	Decentralized gas heater	hp water heater
Cooling	Decentralized split unit (air-air hp)	Decentralized split unit (air-air hp)

Table 3 Decarbonization pathways determined for energy performance improvement

Measure	Ground floor insulation	Roof insulation	Wall insulation	Windows upgrade	HVAC improvement	PV panels	Shading elements
1	+	+		+			+
2	+	+	+	+			+
3	+	+		+	+		+
4	+	+	+	+	+		+
5	+	+		+	+	+	+
6	+	+	+	+	+	+	+

Table 4 CO₂ emission intensity (kgCO₂e/m²a) thresholds for nearly zero carbon residential buildings according to the new zero-carbon standard [8]

Solar irradiance rating	Extremely cold zone	Cold zone	Hot summer and cold winter zone	Hot summer and warm winter zone	Temperate zone
I	14	13	/	/	/
II	15	14	/	16	12
III	16	16	16	17	13
IV	/	/	/	17	14

To determine the impact of the new regulation, simulation results must be converted into carbon emission values. Consequently, we gathered data on the carbon emission intensity of electricity and natural gas, the primary energy sources for HVAC and DHW systems in buildings. Recent research indicates that China’s overall electricity carbon footprint is 683.5 kgCO₂e/MWh [12]. The carbon emission intensity of natural gas, from extraction to delivery, varies between 0.022 and 0.156 kgCO₂e/kWh across 104 fields in China, with a weighted average of 0.078 kgCO₂e/kWh [13]. For combustion alone, the emission intensity ranges from 0.180 to 0.216 kgCO₂e/

kWh, averaging 0.198 kgCO₂e/kWh [14]. In our calculations, we adopted a combined emission factor of 0.276 kgCO₂e/kWh, accounting for both combustion and delivery emissions.

3 Case Study-Results and Discussions

Beijing, Harbin, Shenzhen, and Shanghai were chosen as case study cities for their distinct characteristics, climate variations, and relevance to China's low-carbon policy initiatives. Beijing (cold winters, hot summers), Shenzhen (tropical climate), and Shanghai (subtropical climate) are key participants in China's low-carbon city pilot program, with Shenzhen leading green innovation since 2010, while Beijing and Shanghai, added in 2012, focus on energy-efficient buildings, public transport, and carbon trading [14]. Although Harbin is not part of this initiative, its cold climate provides valuable insights into zero-carbon transitions in colder regions.

This study provides insights into the effectiveness of ZEB standards and retrofitting strategies across different climate zones and residential building archetypes in China. A total of 336 simulations were conducted, with results visualized in a heat map matrix in Fig. 2, categorizing buildings by carbon emission levels for HVAC and DHW. None of the baseline buildings except for the 2018 high-rise tower in Beijing met the new ZEB standard even though we have not considered other loads such as lighting and electric appliances. Terraced houses performed the poorest due to their shape factor, requiring photovoltaic (PV) panels to comply, while other archetypes, except those in Shenzhen, met the standards with simple envelope improvements such as insulation and window upgrades.

The effectiveness of decarbonization measures varied by climate zone. In Beijing and Harbin, passive strategies such as improved insulation and high-performance windows effectively reduced heating demands, but terraced houses required PV panels. Shanghai exhibited similar trends, with most buildings meeting the threshold through passive measures alone. Shenzhen, a cooling-dominated climate, relied heavily on active measures, including PV panels and HVAC upgrades. Shading played a crucial role in reducing cooling loads, making it necessary for achieving performance targets.

4 Conclusions

This study presents a comprehensive GIS and simulation-based framework to assess the role of ZEB standards in achieving low-carbon goals, using China as a case study. By focusing on four distinct climate zones—Shenzhen, Harbin, Beijing, and Shanghai—the research evaluates the effectiveness of various decarbonization strategies for residential buildings, categorized into archetypes based on height, age, and

Year	Archetype	Location	Baseline			Measure 1			Measure 2			Measure 3			Measure 4			Measure 5			Measure 6
			1986	1986	1986	1986	1986	1986	1986	1986	1986	1986	1986	1986	1986	1986	1986	1986	1986		
1986	HighS	Beijing	35.2	15.4	7.7	15.4	9.4	-4.6	-10.6	2010	HighS	Harbin	24.4	15.2	10.0	15.9	11.7	-0.3	-4.5		
1986	HighT	Beijing	32.3	12.5	7.7	13.2	9.3	5.7	1.8	2010	HighT	Harbin	24.6	15.6	10.0	16.1	11.6	10.0	5.5		
1986	LowR	Beijing	32.8	13.1	8.6	15.6	10.4	-29.5	-34.7	2010	LowR	Harbin	23.3	14.2	11.4	15.6	13.2	-20.8	-22.5		
1986	Th	Beijing	55.8	21.4	11.9	20.9	13.1	-69.2	-77.0	2010	Th	Harbin	36.6	18.9	16.1	19.4	17.0	-53.4	-55.8		
1995	HighS	Beijing	22.9	9.5	7.7	10.8	9.3	-9.2	-10.7	2018	HighS	Harbin	18.8	12.7	10.0	13.8	11.8	-2.4	-4.4		
1995	HighT	Beijing	26.8	12.5	7.7	13.2	9.3	5.7	1.8	2018	HighT	Harbin	18.7	12.7	10.0	13.8	11.6	7.8	5.6		
1995	LowR	Beijing	22.5	10.2	8.5	11.8	10.3	-33.3	-34.8	2018	LowR	Harbin	20.1	13.6	11.2	14.9	13.3	-21.5	-23.1		
1995	Th	Beijing	38.0	14.6	11.6	15.2	12.9	-74.9	-77.3	2018	Th	Harbin	26.8	18.3	15.9	18.8	17.3	-54.0	-55.5		
2010	HighS	Beijing	17.8	10.4	7.7	11.7	9.3	-8.4	-10.7	2001	HighS	Shanghai	26.6	20.4	14.1	22.5	16.1	5.9	-0.5		
2010	HighT	Beijing	17.8	10.7	7.7	11.8	9.2	4.3	1.7	2001	HighT	Shanghai	31.1	21.4	14.5	23.5	16.5	17.3	10.3		
2010	LowR	Beijing	17.9	10.5	8.5	12.0	10.3	-33.1	-34.8	2001	LowR	Shanghai	27.2	19.0	14.2	21.1	16.2	16.3	-21.1		
2010	Th	Beijing	25.0	13.7	11.6	14.6	12.8	-75.5	-77.3	2001	Th	Shanghai	40.9	27.5	18.7	29.5	20.7	-45.0	-53.9		
2018	HighS	Beijing	13.2	8.3	7.6	9.8	9.3	-10.2	-10.7	2010	HighS	Shanghai	28.7	20.4	14.1	22.5	16.1	5.9	-0.5		
2018	HighT	Beijing	12.9	8.4	7.7	9.8	9.2	2.3	1.7	2010	HighT	Shanghai	31.1	21.4	14.5	23.5	16.5	17.3	10.3		
2018	LowR	Beijing	14.4	9.2	8.4	10.9	10.2	-34.2	-34.8	2010	LowR	Shanghai	28.6	19.0	14.2	21.1	16.2	16.3	-21.1		
2018	Th	Beijing	20.2	12.9	11.6	13.8	12.8	-76.3	-77.4	2010	Th	Shanghai	36.1	23.3	18.6	25.5	20.6	-49.1	-53.9		
1986	HighS	Harbin	35.6	17.9	9.9	17.8	11.7	1.6	-4.5	2003	HighS	Shenzhen	21.7	15.3	15.0	16.2	15.9	-2.0	-2.3		
1986	HighT	Harbin	36.2	18.6	9.9	18.2	11.6	12.1	5.5	2003	HighT	Shenzhen	23.4	15.4	15.2	16.3	16.1	9.5	9.2		
1986	LowR	Harbin	35.4	17.6	11.4	17.8	13.1	-18.7	-23.3	2003	LowR	Shenzhen	20.6	15.4	15.1	16.2	15.9	-24.7	-24.9		
1986	Th	Harbin	61.0	27.5	15.8	25.9	16.9	-46.9	-55.9	2003	Th	Shenzhen	23.6	17.7	17.3	18.4	18.1	-63.2	-63.6		
1995	HighS	Harbin	24.6	13.4	9.9	14.3	11.7	-1.9	-4.5	2012	HighS	Shenzhen	20.9	15.2	14.9	16.0	15.8	-2.1	-2.4		
1995	HighT	Harbin	26.4	13.1	9.9	15.8	11.6	9.7	5.5	2012	HighT	Shenzhen	22.9	15.3	15.1	16.2	16.0	9.4	9.2		
1995	LowR	Harbin	24.7	13.9	11.4	15.2	13.2	-21.2	-23.2	2012	LowR	Shenzhen	19.8	15.3	15.1	16.1	15.9	-24.8	-25.0		
1995	Th	Harbin	41.8	20.9	15.4	21.1	17.0	-51.7	-55.8	2012	Th	Shenzhen	22.1	17.5	17.2	18.3	18.0	-63.4	-63.7		

Fig. 2 Simulation results of the building level analysis under defined measures, considering HVAC and DHW systems (kg CO₂/eq/m²)

climate. The findings highlight the potential of passive and active measures to significantly reduce carbon emissions, with passive strategies such as improved insulation and window upgrades proving effective in most regions, except for terraced houses in Harbin and Shanghai. In Shenzhen, active measures like photovoltaic (PV) panels and HVAC system upgrades are essential to meet zero-emission thresholds.

The results show that while baseline buildings generally fall short of ZEB standards, retrofitting can significantly enhance energy performance and reduce carbon emissions. With all measures in place and considering only HVAC and DHW emissions, all cases meet the ZEB threshold. In low-rise buildings, rooftop PV can enable net-negative emissions. For high-rise buildings, integrating façade PV and accounting for shading can further reduce emissions. Continued grid decarbonization will also play a key role in meeting ZEB targets.

The study highlights the need for tailored strategies for different building archetypes and climate zones, offering valuable insights for policymakers, urban planners, and designers. The scalable framework developed provides a robust approach for the global implementation of zero-carbon building standards, with China as a proof of concept. Future research should integrate GIS for broader urban-scale assessments and explore the long-term impacts of climate change on building energy performance. This study supports the transition to low-carbon urban development, aligning with global climate goals and promoting sustainable urbanization.

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References

1. Wang J, Huang Y, Teng Y, Yu B, Wang J, Zhang H, Duan H (2021) Can buildings sector achieve the carbon mitigation ambitious goal: case study for a low-carbon demonstration city in China? *Environ Impact Assess Rev* 90:106633. <https://doi.org/10.1016/j.eiar.2021.106633>
2. Ma M, Ma X, Cai W, Cai W (2020) Low carbon roadmap of residential building sector in China: historical mitigation and prospective peak. *Appl Energy* 273:115247. <https://doi.org/10.1016/j.apenergy.2020.115247>
3. Liu Z, Liu Y, He B-J, Xu W, Jin G, Zhang X (2019) Application and suitability analysis of the key technologies in nearly zero energy buildings in China. *Renew Sustain Energy Rev* 101:329–345. <https://doi.org/10.1016/j.rser.2018.11.023>
4. Braun M, Stetz T, Bründlinger R, Mayr C, Ogimoto K, Hatta H, Kobayashi H, Kroposki B, Mather B, Coddington M, Lynn K, Graditi G, Woyte A, MacGill I (2012) Is the distribution grid ready to accept large-scale photovoltaic deployment? State of the art, progress, and future prospects. *Prog Photovoltaics* 20:681–697. <https://doi.org/10.1002/pip.1204>
5. Opel O, Strodel N, Werner K, Geffken J, Tribel A, Ruck W (2017) Climate-neutral and sustainable campus Leuphana University of Lüneburg. *Energy* 141:2628–2639
6. Guo S, Yan D, Hu S, Zhang Y (2021) Modelling building energy consumption in China under different future scenarios. *Energy* 214:119063. <https://doi.org/10.1016/j.energy.2020.119063>

7. An J, Wu Y, Gui C, Yan D (2023) Chinese prototype building models for simulating the energy performance of the nationwide building stock. *Build Simul* 16:1559–1582. <https://doi.org/10.1007/s12273-023-1058-5>
8. MoHURD: Technical standards for zero carbon buildings (202X)
9. China standard press: technical standard for nearly zero energy buildings (2019)
10. Orehounig K, Fierz L, Allan J, Eggimann S, Vulic N, Bojarski A (2022) CESAR-P: A dynamic urban building energy simulation tool. *JOSS* 7:4261. <https://doi.org/10.21105/joss.04261>
11. Johnson J, Brazier C, Lam T (2022) The China lab guide to megablock urbanisms. Actar D, Inc
12. Zhang Q, Qiao K, Hu C, Su P, Cheng O, Yan N, Yan L (2024) Study on life-cycle carbon emission factors of electricity in China. *Int J Low-Carbon Technol* 19:2287–2298. <https://doi.org/10.1093/ijlct/ctae181>
13. Gan Y, El-Houjeiri HM, Badahdah A, Lu Z, Cai H, Przesmitzki S, Wang M (2020) Carbon footprint of global natural gas supplies to China. *Nat Commun* 11:1–9
14. Zhou S, Zhou C (2021) Evaluation of China's low-carbon city pilot policy: evidence from 210 prefecture-level cities. *PLoS ONE* 16:e0258405. <https://doi.org/10.1371/journal.pone.0258405>

Impact of Offshore Wind Energy Penetration on the Resilience of an Import-Dependent Power Grid



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Abstract The expansion of offshore wind power as part of a transition to low-carbon electricity generation presents challenges for the resilience of power grids. One strategy to address this challenge is to rely on imports from neighboring power systems with excess production capacity. However, constraints due to grid topography and internal generation may limit the import capacity. This study uses a quasi-dynamic power flow simulation based on the IEEE 39-bus system to assess the limits of increasing offshore wind power penetration on the grid's ability to meet demand. The model is a synthetic grid based on the topography of the New England power grid, loads are held constant, and between one and five conventional generators are replaced with wind farms while the remaining generators are constrained by ramp rates. To model wind power production, we have constructed a composite wind farm power curve by smoothing the power curve of a single wind turbine generator. Wind speed data are retrieved from single locations in the WIND Toolkit Long-Term Ensemble Dataset with five-minute resolution. We find that high levels of wind power penetration increase the risk of unmet demand due to physical and operational power flow constraints in certain wind conditions. We also identify critical network elements and imported power limits. These findings both expand and challenge the findings of previous work by shedding light on underlying constraints while considering future wind power technology.

Keywords Wind energy · Wind drought · Electric grid · Resilience

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1 Introduction

Continued development of renewable energy has become a cornerstone of geopolitical agendas worldwide. On average more than 10 GW of offshore wind power have been added in recent years, resulting in over 70 GW of installed capacity at the end of 2023 [9]. Despite recent political opposition in the United States, 39 projects maintain active leases [1]. Several of these areas are off the coast of New England and, if successful, would comprise a total generation capacity of nearly 20 GW.

These ambitions present challenges for grid operators to maintain reliable operations during both high and low wind periods. Reference [8] evaluated a large dataset to find that regions with well-dispersed wind power fleets avoid the most extreme fluctuations. The expansion of offshore wind farms, concentrated in areas of similar wind regimes, exacerbate the issue of variability. Periods of low production due to low wind resource or to high wind shut down are thus more likely in grids with higher penetrations of offshore wind power.

1.1 Resilience

Resilience in the context of energy systems typically falls under what [16] called “engineering resilience”. This is the capacity of a system to return to a stable operational state after a disturbance.

Several authors have already analyzed extreme weather impacts on the grid. Reference [15] review various attempts to model the impacts of extreme weather on the grid and summarize various measures to improve grid resilience. Reference [7] review a series of frameworks and assessments of the resilience, vulnerability, and exposure of power grids. Reference [11] review the literature with a focus specifically on wind farms and wind turbine generators (WTGs); they note a lack of resilience studies pertaining specifically to wind energy.

As [6] highlights, the presence of wind power in itself can be a threat to resilience, even when all systems are operating normally. To investigate the effects of storms on offshore wind energy dependent grids, [4] developed a model based on the topography of New England to simulate the grid’s response to extreme wind events with varying penetrations of offshore wind power. Reference [5] further developed the model and compared the results with a new model based on Great Britain’s power grid. The current study develops the New England model further to enforce operational limits and incorporates a wind farm model more representative of current and future offshore wind turbine technology. The current study provides insight into the limiting factors of transmission congestion and voltage constraints for increased wind power penetration, with particular attention paid to a low-wind period when balancing relies on imports.

2 Method

2.1 Power Flow Model

The simulations are conducted using the open source Matlab package MATPOWER version 8.0 [17] and employ a steady-state AC power flow for a network of transmission lines, buses, and generators. The case used here is the IEEE 39-bus synthetic grid model, which geographically represents the New England power grid [10]. In our quasi-dynamic simulation, the results of each time step are used as the input for the following time step. The primary time-varying input is the wind power generation, described in Sect. 2.2. The remaining conventional (synchronous) generators are limited in their ability to follow changes in wind power by ramp rates representative of the generator type. The same ramp rates are used as in [5]. The available generation capacity at each time step depends on the generation at the previous time step as described in Eqs. (1–2). The Newton-Raphson solver is implemented here because of its ability to achieve rapid convergence; no convergence issues were encountered.

Conventional generators are successively replaced by wind farms with an installed capacity of 2.7 times greater than the generator it replaces. This value was chosen to match the annual energy production of the replaced generators based on the finding of [2] that wind farms in British waters had an average capacity factor of 33% and the assumption that the generators the wind farms replace would have had a capacity factor of 90%. The generation of each wind farm is determined by wind speeds as described in Sect. 2.2. The output at time t for generator g ($P_g^{out}(t)$) is determined by setting all conventional generators to the maximum allowed by its ramp rate as indicated in Eq. 2 and then applying the following five strategies, in order, until a solution is reached that satisfies the criteria for relative power flow (S_{rel}) at the “to” bus and bus voltage magnitude (V_m) for all lines and buses, respectively: $S_{rel} < 150\%$ and $0.85 < V_m < 1.10$. Further discussion of the limits follows in Sect. 3.

1. If the total generation is greater than 80% of the total load, reduce the load of the bus with the lowest V_m by 5% of its maximum value.
2. Reduce the output of the largest generator by 5% of its installed capacity.
3. Reduce the largest generator by 1% of installed capacity with the load profile from the last converged solution.
4. Reduce the load at the bus with the lowest V_m by 5% with the generation profile from the last converged solution.
5. Increase the transmission capacity of all lines by 10% and apply strategies 1 and 2 again.

$$P_g^{min}(t) = \max(P_g^{out}(t-1) - P_g^{inst} \cdot RR_g \cdot \Delta t, 0) \quad (1)$$

$$P_g^{max}(t) = \min(P_g^{out}(t-1) + P_g^{inst} \cdot RR_g \cdot \Delta t, P_g^{inst}) \quad (2)$$

Strategies that apply load shedding are attempted 250 times before continuing to the next strategy, and strategies that apply generation curtailment are attempted 1000 times before continuing. A strategy fails to produce valid solution when either 10 iterations of the Newton–Raphson method have failed to converge or if the converged solution does not meet the criteria for S_{rel} and V_m .

2.2 Wind Farm Model

To generate wind farm data representative of real world data without modeling the complex wind flows within and around wind farms, a modification to the multi-turbine power curve approach introduced by [13] is used. This also avoids the advanced behavior of modern WTGs that adapt to wind conditions on the order of 1 Hz, such as that described by [12].

To limit the risk of all WTGs in a large offshore wind farm cutting out at the same time, newer offshore WTGs often employ a tapered cut out strategy with a delay before starting up again. We propose the power curve shown in Fig. 1. The smoothed curves around cut-in wind speed (v_{cutin}) and cut-out wind speed (v_{cutout}) reflect the wind speed variation throughout the wind farm, including wake effects. We also take note of the findings of [14], which highlight how technical availability affects a multi-turbine power curve. We assume, based on industry standards, that the wind farms never generate more than 95 % of installed capacity. The power curve in Fig. 1 was drawn using key points to approximate the shape of the curve applied by [5] based on the WTG power curve presented by [12]. The intervening points are interpolated using cubic spline functions.

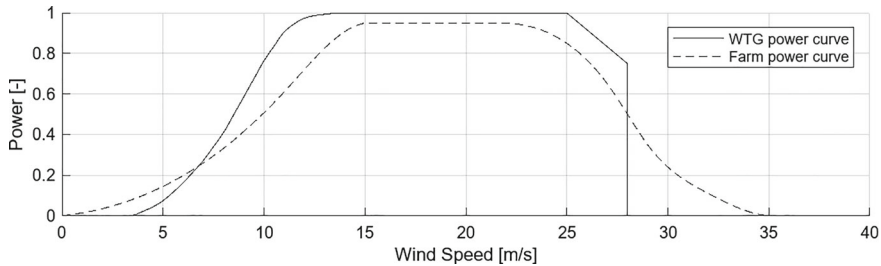


Fig. 1 Normalized power curve of an offshore WTG (solid) with the wind farm power curve applied in this simulation (dashed)

2.3 Wind Data

Up to five wind farms are simulated based on wind data from five locations off the southern coast of New England. Wind data was downloaded from the Wind Resource Database, using the Wind Toolkit Long-Term Ensemble Dataset [3] at five-minute time resolution and a height of 150 m. The locations were chosen as the approximate midpoints of five active wind lease areas listed by [1]. Despite being spread over an area of more than 3000 km², their wind profiles are similar.

2.4 Simulation Setup

The simulation is run for five wind power penetration levels under a 48-hour period in November 2020 when winds initially approached v_{cutout} , fell below v_{cutin} , and then returned to a level of production less than P_{rated} .

Wind penetration indicates the maximum share of wind power that could theoretically be fed onto the grid if export and transmission capacity were sufficient. The key parameters for the study are the disconnected load (P_{discon}), energy not supplied (E_{discon}), power imported (P_{import}), power flow at the to bus (S_{to}), relative power flow (S_{rel}), and bus voltage magnitude (V_m),

$$E_{discon} = \sum_{\forall t \in T} P_{discon}(t) \quad (3)$$

$$P_{import} = P_{bus31} - P_{inst,G2} \quad (4)$$

$$S_{rel} = \frac{S_{to}}{S_{limit}} \quad (5)$$

Imports are not constrained, and thus inability to meet load is a result of transmission constraints. We identify critical network elements (CNEs) as the transmission lines which exceed their rated limits (i.e. $S_{rel} > 100\%$) and buses that suffer voltages below standard limits (i.e. $V_m < 0.9$).

The wind levels 1–5 are defined by wind farms integrated at the 1–5 first buses of {32, 33, 34, 35, 36}, which corresponds to wind power penetrations of 23%, 35%, 47%, 58%, and 67%, respectively.

3 Results and Discussion

We focus on wind levels four and five because load shedding does not occur at lower wind levels. The overall behavior of the system during the simulation period is captured in Fig. 2, which shows the summary of power into and out of the grid. Inputs come from wind power, conventional generators, and imports. Outputs go to

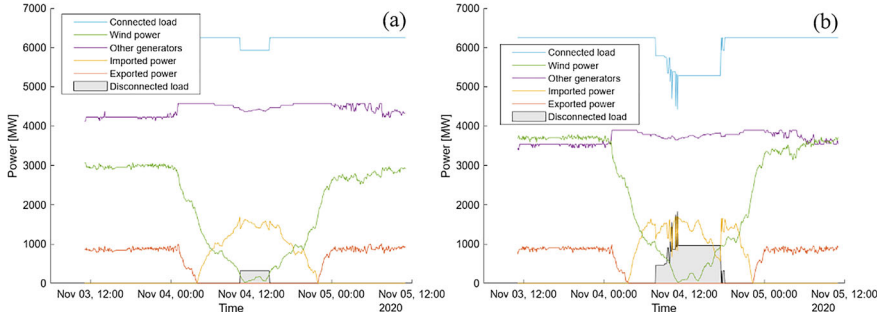


Fig. 2 Summary of power inputs and outputs for wind levels **a** four and **b** five during a period of low wind

connected load and exports. The shaded area represents the disconnected load, i.e. the amount that the load must be reduced in order to find a valid solution given the available production, imports, and transmission capacity.

At wind level four, P_{discon} reaches a maximum of 324 MW when total wind energy production drops below 216 MW. The situation persists for 4.4 h, leading to an E_{discon} of 17 GWh. At wind level five, P_{discon} reaches a maximum of 1830 MW when total wind energy production drops below 960 MW. P_{discon} finds a stable level at 967 MW, and the situation persists for 10 h, leading to a total E_{discon} of 105 GWh. The import capacity appears to reach a limit around 1600 MW because of constraints on lines 6–11 and 2–3.

The lines where transmission is exceeding rated capacity are colored red in Fig. 3. Figure 3a shows that the line connecting buses 6 and 11 is the primary limiting line during the period of low wind power generation. At high wind, Fig. 3b shows a significantly different power flow profile. The line from bus 6 to bus 11 remains a

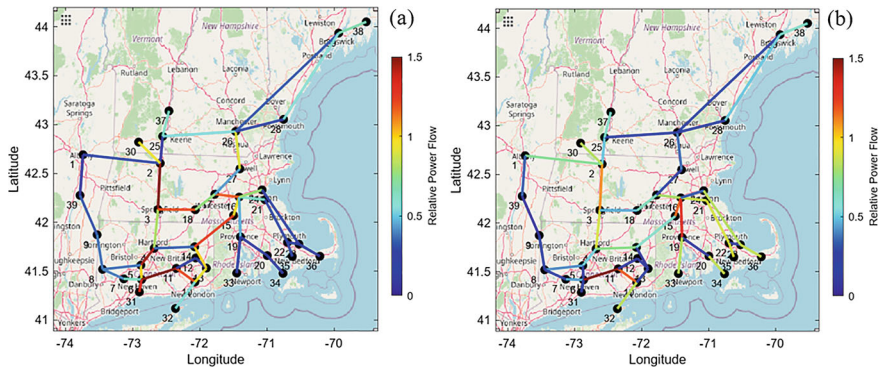


Fig. 3 **a** Low wind; **b** High wind. Relative power flow (S_{rel}) on transmission lines during the time step when **a** P_{import} and **b** P_{wf} are at a maximum

Table 1 Buses and lines identified as CNEs during wind level 5.

Line CNE	Connected buses	Max. S_{rel}	Bus CNE	Min. V_m
13	6–11	1.4941	4	0.894
3	2–3	1.4933	5	0.874
8	4–5	1.4491	6	0.873
14	6–31	1.3356	7	0.868
24	14–15	1.2303	8	0.871
18	10–11	1.1953	12	0.893
7	3–18	1.1941		
26	16–17	1.1712		
23	13–14	1.0048		

limiting element despite being surrounded by lines with moderate or even low relative power flow. Table 1 summarizes the lines with $S_{rel} > 100\%$ and buses with $V_m < 0.9$ for wind level 5. In this case, the most overloaded line is that between buses 6 and 11, closely followed by the line connecting buses 2 and 3. These lines, especially the latter, are regularly experiencing congestion throughout the study period.

We highlight values of S_{rel} because it is the limiting parameter with the chosen operational limits. This may be different with stricter voltage limits; 11 buses reach a V_m outside the range 0.90–1.05 p.u. at wind level 5. Limits on S_{rel} are also generous (up to 150%). Lowering this limit during testing led to complete failure of the system.

The enforcement of S_{rel} reveals a challenge with the model. The wind farms have been sized to be multiples larger than the generators they replace and thus are the largest generators in the system. So the strategy of reducing the largest generator leads to significant wind energy curtailment. Attempts to implement a merit order dispatch strategy or to run optimum power flow simulation on the current system have so far been unsuccessful. The system must be modified to accept the larger generators. At present, the wind farms never produce more than 60% of rated capacity.

Future improvements could incorporate realistic grid modifications such as branch capacity increases, reactive power compensation, and energy storage devices. The introduction of a flexibility market could also be used such that reductions in load are voluntary. All of the above would improve the resilience of the grid and allow for increased wind energy penetration. Periods of wind below 4 m/s on average for all wind farms (approximately that which leads to load shedding in this simulation) occur 11% of the time in 2020. By contrast, high wind speeds that would have led to similar output based on the proposed power curve (> 32 m/s) occur during less than 0.1% of 2020. Even if this lost capacity is predictable for day-ahead allocations, without significant grid upgrades, transmission congestion can prevent other capacity from reaching load centers.

4 Conclusions

The rapid expansion of offshore wind energy presents challenges for grid operators to accommodate new power flow patterns. The current study simulates increasing wind energy penetration on a grid with constrained transmission capacity. These constraints give rise to a limit on import capacity and prevent the system from meeting demand. Using a wind farm power curve that reflects recent advancements in WTG technology, we find that low wind periods can lead to load shedding while being much more common than storm conditions. Ongoing development of the model includes simulation-based investigation of the proposed wind farm power curve, market-based generator dispatch, and grid modifications.

References

1. Bureau of ocean energy management: lease and grant information. <https://www.boem.gov/renewable-energy/lease-and-grant-information>
2. Crabtree CJ, Zappalá D, Hogg SI (2015) Wind energy: UK experiences and offshore operational challenges. *Proc Inst Mech Eng Part A J Power Energy* 229(7):727–746
3. Draxl C, Wang J, Sheridan L, Jung C, Bodini N, Buckhold S, Aghili C, Peco K, Kotamarthi R, Kumler A, Phillips C, Purkayastha A, Young E, Rosenlieb E, Tinnesand H (2024) WTK-LED: the WIND toolkit long-term ensemble dataset. Tech Rep NREL/TP-5000-88457, 2473210, MainId:89236
4. Forsberg S, Thomas K, Bergkvist M, Göteman M (2023) Resilience to storm conditions of power systems with large dependencies on offshore wind. *J Phys Conf Ser* 2626(1):012017
5. Forsberg S, Göteman M, Thomas K, Bergkvist M (2024) Resilience to extreme storm conditions: a comparative study of two power systems with varying dependencies on offshore wind. *Res Eng* 23
6. Göteman M, Panteli M, Rutgersson A, Hayez L, Virtanen MJ, Anvari M, Johansson J (2025) Resilience of offshore renewable energy systems to extreme MetOcean conditions: a review. *Renew Sustain Energy Rev* 216
7. Jufri FH, Widiputra V, Jung J (2019) State-of-the-art review on power grid resilience to extreme weather events: definitions, frameworks, quantitative assessment methodologies, and enhancement strategies. *Appl Energy* 239:1049–1065
8. Kiviluoma J, Holttinen H, Weir D, Scharff R, Söder L, Menemenlis N, Cutululis NA, Danti Lopez I, Lannoye E, Estanqueiro A, Gomez-Lazaro E, Zhang Q, Bai J, Wan YH, Milligan M (2016) Variability in large-scale wind power generation. *Wind Energy* 19(9):1649–1665
9. Lee J, Zhao F (2024) Global wind Report 2024. Tech rep, Global Wind Energy Council, Brussels
10. Li Z (2024) Simulation data of 10-machine 39-bus power system. <https://iee-dataport.org/documents/simulation-data-10-machine-39-bus-power-system>
11. Modaberi SA, Tohidi S, Zadeh SG, Bolandi TG (2023) A review of power system resilience assessment and enhancement approaches by focusing on wind farms and wind turbines. *IET Renew Power Gener* 17(9):2391–2410
12. Murcia Leon JP, Koivisto MJ, Sørensen P, Magnant P (2021) Power fluctuations in high-installation—density offshore wind fleets. *Wind Energy Sci* 6(2):461–476
13. Nørgaard P, Holttinen H (2004) A multi-turbine power curve approach. In: *Proceedings of Nordic wind power conference*, pp 1–5, Gothenburg
14. OFGEM: Electricity capacity assessment Report 2013. Tech rep, OFGEM, London

15. Panteli M, Mancarella P (2015) Influence of extreme weather and climate change on the resilience of power systems: impacts and possible mitigation strategies. *Electr Power Syst Res* 127:259–270
16. Walker B (1996) Engineering resilience versus ecological resilience. In: Schulze P (ed) *Engineering within ecological constraints*. The National Academies Press, Washington, DC
17. Zimmerman R, Murillo-Sánchez CE, Thomas RJ (2011) Matpower: steady-state operations, planning, and analysis tools for power systems research and education. *IEEE Trans Power Syst* 26(1):12–19

Improving Energy and Water Performance of Swimming Pools: Prototype and Validation ECOPOOL+++



Fátima Farinha , Miguel Oliveira , Gina Matias , Francisco do Carmo, João Abrantes , and João Vieira 

Abstract In Algarve region, more than 72% of swimming pools are uncovered, and 65% have no water heating. Covers play a crucial role in safety, reducing water evaporation, and minimizing heat losses. In unheated pools, usage is limited to periods when the water temperature is comfortable. In Southern Europe, where sunlight is abundant, swimming pools are typically used for a maximum of five months per year. Therefore, solar energy for water heating is strongly recommended and should be widely adopted. Maximizing solar gains to ensure a comfortable temperature for the maximum number of daylight hours throughout the year requires integrating various renewable energy systems, depending on the region, along with energy storage solutions. Additional strategies, such as minimising heat losses through the tank and preventing water leaks, are also critical for improving the energy and water performance of swimming pools. These principles guided the ECOPOOL+++ project, which aims to develop innovative heated swimming pools with reduced thermal losses and integration of smart energy and water management systems. A key aspect of this project involved constructing a prototype at the University of Algarve's Penha Campus in Faro, Portugal, and validating the proposed solutions in situ. This paper presents the prototype in detail, along with validation task and their significance in refining the initially conceived solutions.

Keywords Energy and water efficiency · Environmental impact · Sustainability · Swimming Pools · Prototype

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1 Introduction

Most existing swimming pools demonstrate considerable energy inefficiencies, primarily due to heat and water losses that contribute to environmental degradation [1]. In outdoor swimming pools, the dominant modes of energy loss occur through evaporation, followed by radiation and convection. The water surface is the area where the most substantial heat exchanges take place. A standard thermal insulated pool cover can reduce energy losses by 50–70% [2], and specialized covers can achieve reductions of up to 95% [3]. Heat losses via conduction through the tank walls and floor are often neglected but should be considered, particularly in heated pools [4]. Implementing solutions to minimize heat losses from the tank and water surface enhances energy efficiency and contributes to the sustainability of swimming pools, however, these measures do not generate heat. Thus, outside the summer period or in areas with low solar exposure, external heat sources are required to maintain a comfortable water temperature. Several methods [5] including solar energy, geothermal heat, and biomass heating can be employed. The effectiveness of solar energy depends on the availability and intensity of solar radiation, which is particularly favorable in Southern Europe. The incorporation of intelligent and predictive control and monitoring system (SMART), enables real-time optimization of multiple variables.

2 Ecopool+++

The ECOPOOL++ project aimed to design a sustainable and innovative swimming pool solution [6, 7] incorporating:

- a durable and low-maintenance thermal insulation system based on black agglomerate cork applied to the inner walls and bottom of the tank;
- a thermally efficient cover for the water surface;
- solar energy capture systems, including solar panels (17.2 m^2) and heat-reflective flooring;
- heat storage system, containing phase change materials (FlatCE filled with PlusICE S30, 200 units, 1 m^3);
- a photovoltaic electricity generation system (4 m^2);
- optimized hydraulic circuits to enhance filtering and regeneration efficiency (backwashing);
- a SMART control and monitoring system for management energy supply and consumption, monitoring water usage (including filter regeneration), detecting leaks in the tank and pipes, and regulating water temperature.

3 Prototype

To test and validate these developments, a prototype was constructed at the University of the Algarve's Penha Campus in Faro, Portugal. The prototype comprises a 10m × 5m pool with an average depth of 1.5 m. The design was developed by Cristal Construções, in collaboration with architect Mário Martins.

Figures 1 and 2 illustrate the location and 3D rendering of the pool, along with the technical area designated for solar collectors and photovoltaic panels on the roof.

Figures 3 and 4 depict aspects of the construction phase, including the tank structures, machine room, and heat recovery floor, which occupies the lateral space on one side of the pool. This system incorporates approximately 200 m of piping with a 25 mm diameter.

Fig. 1 Location of the prototype

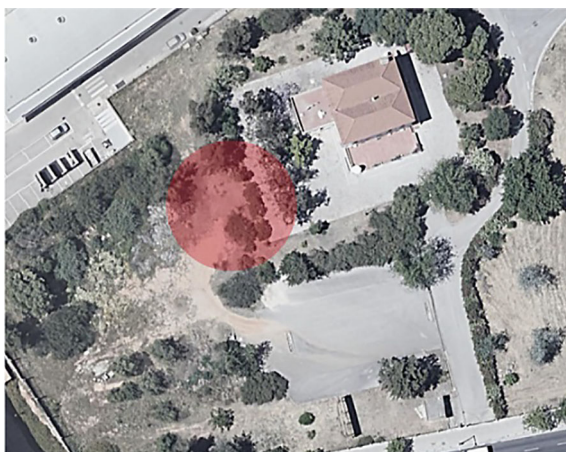


Fig. 2 3D by architect Mário Martins





Fig. 3 Construction phase: main tank, secondary tanks and machine room

Fig. 4 Heat recovery floor piping during construction





Fig. 5 Exterior view of the prototype

Figure 5 and 6 present an exterior view of the pool and technical space, along with the hydraulic circuits within the machine room. At this stage, the pool was being filled.

4 Monitoring and Validation

The primary objective of monitoring the prototype was to validate and improve the automation and control system. The process included:

- stress tests on the routing system to identify and correct data transmission errors;
- testing the functionality of all equipment connected to the automation system;
- verifying manual and automatic control operations via panel switches and automation system software;
- simulating various operating scenarios to assess system performance and interactions between the automation and SMART modules;
- final system parameterization to adjust the automation code and optimize its real-world application.



Fig. 6 Machine room with hydraulic circuits

Figure 7 presents graphs generated by the SMART platform, showcasing monitored parameters recorded over a period of several hours.

Additionally, a series of validation tests were conducted, including:

- mechanical and hygrothermal performance of the walls and tank floor insulation system;
- operability of the water cover system;
- effectiveness of heating and cooling energy systems;
- water management strategies, including leak detection and reuse;
- automation and control system functionality, particularly the SMART system's operation.

Long-term monitoring of the prototype and its energy consumption will determine whether more complex and costly system lead to effective savings compared to traditional approaches, as well as their contribution to extending pool usage time.

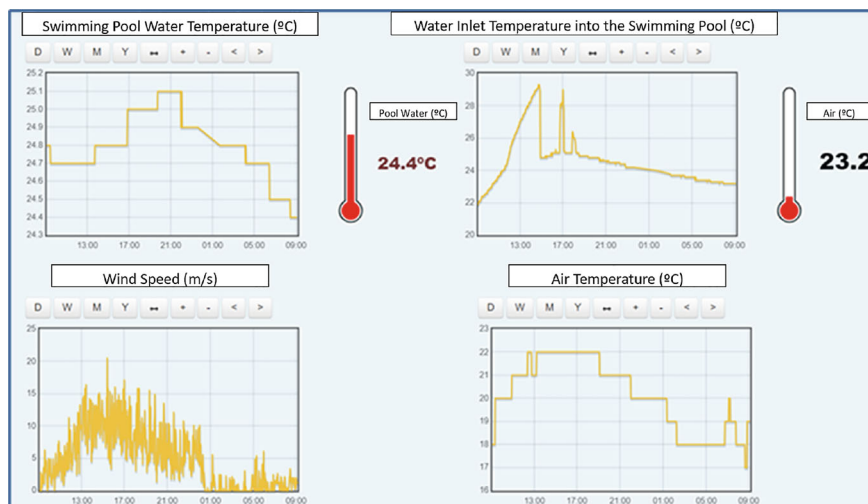


Fig. 7 Graphs generated by the SMART platform

5 Conclusions

The ECOPOOL+++ project investigated and tested an innovative outdoor swimming pool solution aimed at reducing thermal and water losses while maximizing renewable energy gains to extend operational periods. This paper provides a comprehensive analysis of the prototype built at University of Algarve in Faro, Portugal, as well as the monitoring and validation tests conducted. The findings highlight the importance of this research in enhancing the sustainability of outdoor swimming pools. Detailed conclusions about the prototype's performance require a long period of monitoring, corresponding to more than 2 years.

Acknowledgements The ECOPOOL+++ project was funded by FEDER, Projectos de I&DT Empresas em Copromoção, Programa Operacional Regional do Centro, Programa Operacional Regional do Algarve (ALG-01-0247-FEDER-047231). The professional expertise and valuable cooperation of all the partners are gratefully acknowledged. Authors are grateful for the Foundation for Science and Technology's support through funding the researches units CERIS (<https://doi.org/10.54499/UIDB/04625/2020>) and C-Made (<https://doi.org/10.54499/UIDB/04082/2020>).

References

1. Gallion T, Harrison T, Hulverson R, Hristovski K (2014) Estimating water, energy, and carbon footprints of residential swimming pools. In: Water reclamation and sustainability, pp 343–359
2. US Department of Energy: Swimming Pool Covers. <https://energy.gov/energysaver/swimming-pool-covers>. Last accessed 22 Mar 2025

3. Muleta M (2016) Effectiveness of pool covers to reduce evaporation from swimming pools. Final-Report2016. https://cdn.ymaws.com/www.npconline.org/resource/resmgr/Docs/Evaporation_Study_Report.pdf. Last accessed 22 Mar 2025
4. Bernhard M, Marc O, Quilichini E, Castaing-Lasvignottes J (2019) Sensitivity analysis of an outdoor swimming pool under dynamic conditions. In: *Procedia manufacturing* 35:124–129
5. Katsaprakakis DA (2015) Comparison of swimming pools alternative passive and active heating systems based on renewable energy sources in Southern Europe. *Energy* 81:738–753
6. Oliveira MJ, Farinha F, Inverno A, Monteiro J, Cabrita C, Venturinha A (2022) Sustainability challenges in outdoor swimming pools. In: *Bienvenido-Huertas D, Moyano-Campos J (eds) New technologies in building and construction. Lecture notes in civil engineering*, vol 258. Springer, Berlin
7. Oliveira MJ, Inverno A, Farinha F, Monteiro J, Cabrita C et al (2022) ECOPOOL+++: Developing a sustainable outdoor heated swimming pool. In: *Acta polytechnica CTU proceedings*, vol 38, pp 389–395

Dynamic Simulation of Integrated PV-Powered Energy Storage and Electric Vehicle Systems for Sustainable Residential Buildings in Southern Italy



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Abstract The transition to sustainable energy systems is crucial for reducing carbon emissions and improving energy efficiency in buildings, especially with the growing adoption of photovoltaic (PV) systems and battery energy storage systems (BESS). This study presents a dynamic simulation-based assessment of an integrated PV-BESS system combined with electric vehicle (EV) charging in a single-family dwelling in Southern Italy. Using DesignBuilder and EnergyPlus, a dynamic model was developed integrating real-world climatic data, building geometry, and dynamic user behaviors. The analysis evaluates two PV-BESS configurations and four potential EV charging integration patterns. It compares a shortage configuration (Configuration A) with a surplus configuration (Configuration B), assessing their impacts on self-consumption, grid dependency, economic feasibility, and environmental performance. Configuration A achieves a renewable energy share slightly above 60%, meeting 66% of the dwelling's energy demand, relying on the grid for 42%, and exporting 8% of surplus electricity. Configuration B meets 120% of the energy demand, reducing grid dependency to 20% but exporting 43% of the generated electricity. The economic assessment, based on life cycle cost (LCC) and payback period (PBP), shows that Configuration A has a lower LCC but an unfeasible PBP. In contrast, Configuration B, despite achieving a viable PBP, would exceed its system lifespan. The environmental analysis highlights Configuration B's superior sustainability, with an energy return ratio (ERR) 37% higher than that of Configuration A. These findings underscore the trade-offs between energy self-sufficiency, economic viability, and environmental performance, advocating for optimized configurations that support decarbonization and grid resilience in residential contexts.

Keywords Battery energy storage systems · Electric vehicles · Optimization strategies · Renewable energy sources

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1 Introduction

Since the industrial revolution, the power and transport sectors have been major greenhouse gas contributors. To mitigate this, renewable energy sources (RES), such as photovoltaic (PV) systems, and green mobility solutions like electric vehicles (EVs), have grown significantly. However, integrating PV systems and EVs presents technical challenges, including intermittent generation and increased demand, leading to overgeneration and grid overload. Battery Energy Storage Systems (BESS) help manage energy, store surplus power, reduce grid dependency, and lower costs [1].

Despite extensive research on PV-BESS integration, dynamic interactions between building energy systems and EV charging remain underexplored. While studies such [2] emphasize PV-BESS modeling, few incorporate real-world EV charging patterns, which significantly impact system efficiency and costs [3]. Regional climatic variations—critical to energy performance—are often overlooked [4]. Lifecycle cost analyses [5] help assess long-term affordability, but many rely on oversimplified assumptions, leading to inaccurate cost models.

This study aims to fill these gaps by developing a scalable approach for aiding PV-BESS sizing in residential applications to enhance self-consumption and self-sufficiency while evaluating economic and environmental impacts. It integrates PV systems, BESS, and EVs, analyzing energy generation, storage, and consumption interactions. A techno-environ-economic assessment is applied to exploit self-consumption while ensuring economic and environmental sustainability. This approach is designed to address high variability in demand, such as diverse EV charging profiles, ensuring system performance under dynamic load conditions.

2 Methodology

Energy dynamics are modeled using DesignBuilder and EnergyPlus, considering climatic data, building envelope, household loads, and PV generation to provide a dynamic understanding of energy flows. The TABULA web tool [6] defines the envelope and energy system, aiding energy assessments and refurbishments. The selected archetype, a single-family dwelling in Bari (Climatic Zone C [7]) faces rising cooling demand due to the urban heat island effect but benefits from high solar potential. Three occupants with varying schedules influence energy use, with EV charging as a key demand factor (see Figs. 1 and 2). Table 1 lists the climatic data and the archetype geometric and envelope-system specifications.

On a residential scale, EVs are typically parked and charged overnight, but different EV charging profiles have been addressed in this study. The simulation evaluates two PV and storage configurations under four EV usage scenarios. This enables a comprehensive assessment of energy flows and system performance. Table 2 lists the technical specifications of the PV module, inverter, battery, and EV.

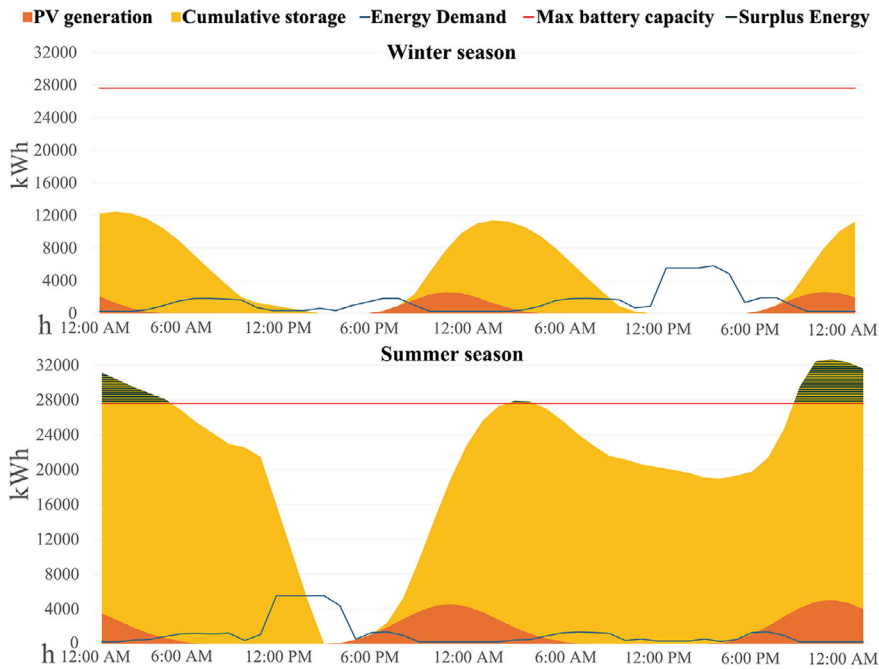


Fig. 1 Profile 1 Configuration A. Representative 48 h winter and summer scenarios

Table 4 presents two PV-BESS configurations: a shortage scenario (A), characterized by a renewable energy share slightly above 60% (RES quota), and a surplus scenario (B), which provides a renewable energy supply exceeding the system’s demand. These configurations are used to evaluate self-consumption, grid interaction, and economic feasibility.

Four EV charging profiles assume a full charge cycle from 10 to 90% battery capacity, as specified in the technical datasheet, but happening at different moments of the day. Table 3 summarizes these profiles. Given the vehicle’s range and typical usage, daily charging to maximum SOC is unnecessary. Instead, charging is expected on alternate days, except on weekends, when a full charge is assumed on both Saturdays and Sundays. The system model and simulation results provide a baseline for optimizing PV-BESS-EV configurations to improve efficiency and reduce grid dependence.

However, assumptions exclude load shifting due to user behavior and omit grid benefits like peak reduction and power quality improvements, while real-time BESS management is not considered despite its potential to reduce degradation. Economic feasibility is evaluated using Life Cycle Cost (LCC) and Payback Period (PBP) [8], incorporating financial parameters from [9], inflation and discount rates from the European Central Bank (ECB) [10]. 2024 electricity prices from the Southern Italian market (GME) [11] were 109.14 €/MWh for purchases, with surplus energy sales on 80 €/MWh, both converted into \$/kWh for financial consistency. Environmental

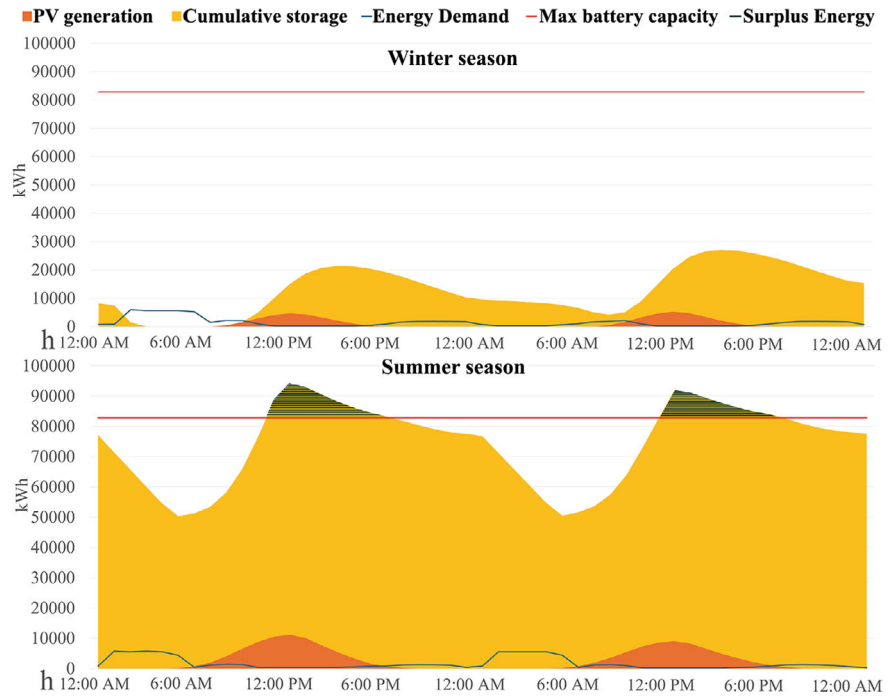


Fig. 2 Profile 1 Configuration B. Representative 48 h winter and summer scenarios

Table 1 Climatic and geometric specifications of the building in Bari, Southern Italy

Climatic data city of Bari			Geometry and technical characteristics [9]		
Heating period [7]	15 November–15 March		Type	Single-family residential	
Climatic zone [7]	C	–	Gross volume (V)	605	m ³
Temperature-days	1185	GG	Gross surface (S)	442	m ²
Min air temperature	8.9	°C	Number of floors	2	–
Wind speed	4.21	m/s	S/V ratio	0.73	–
Design external temperature (summer)	32.3	°C	Design internal temperature winter/summer	20/26	°C
Design internal temperature (winter)	0	°C	U—Windows	2.00 g _{gl} = 0.67	W/m ² K
R.H. (summer)	50	%	U—Roof	0.8	W/m ² K
R.H. (winter)	41.7	%	U—Walls	0.33	W/m ² K
Max air temperature	27.5	°C	U—Ground and intermediate floor	0.3	W/m ² K
			Hydronic heat pump	COP 3.85 EER 5.05	–

Table 2 Technical specifications of the main components

PV module			Inverter		
Power	440	Wp	Capacity	6 or 12	kW
Efficiency	22.53	%	Efficiency	98.4	%
Power temp. coeff.	− 0.30	% °C	Max ch./disch. power	5	kW
Size	1.72 × 1.13	m	Standby load	< 2.5	W
Lifetime	20	years	Lifetime	20	years
Nominal op. temp.	42.5	°C	Range op. temp.	− 25 ~ + 60	°C
BESS			EV and Battery		
Type	LiFePO ₄	–	Instantaneous max power	110(150)	kW(hp)
Capacity single module	6.9	kWh	WLTP cycle range	270–389	km
Max capacity	82.80	kWh	Battery type	Li-ion	–
Efficiency	98	%	Capacity	40	kWh
Depth of Discharge	100	%	Min–max SOC	10–90	%
Max ch./disch. power	7–10.5	kW	AC charging power	6.6	kW
Range op. temp.	− 20 ~ + 55	°C	DC fast charging power	50	kW
Lifetime	10	years			

Table 3 EV charging profiles considered in the simulation

Profile	Pattern	SOC (%)
EV Profile 1	00:00–06:00	10–90
EV Profile 2	06:00–12:00	10–90
EV Profile 3	12:00–18:00	10–90
EV Profile 4	18:00–24:00	10–90

performance is assessed through Renewable Energy Factor (REF), Carbon Intensity (CI), and Emission Reduction Ratio (ERR) [12], with Italy’s 2024 grid Emission Factor (EF) of 270 gCO₂eq/kWh and a 49% renewable electricity mix [13].

3 Results and Discussion

Environmental performance is assessed through Renewable Energy Factor (REF), Carbon Intensity (CI), and Emission Reduction Ratio (ERR) [12], with Italy’s 2024 grid Emission Factor (EF) of 270 gCO₂eq/kWh and a 49% renewable electricity mix [13]. An hourly dynamic simulation for Configurations A and B across all EV charging profiles assessed self-consumption and grid interaction. Figures 1 and 2

Table 4 Data for economic and environmental assessments

Configuration/Economic and environmental parameters				A	B
PV		kWp		7.04	13.64
Inverter		kWA		6.00	12.00
BESS		kWh		27.60	82.80
PV Panels [9]	496	\$/kW	C _{in} [\$]	17,939.84	49,737.44
Inverter [9]	62	\$/kW			
BESS [9]	255	\$/kWh			
Inflation rate [10]	1.1	%	PWF [8]	16.52	16.52
Discount rate [10]	2.9	%			
PV lifespan [9]	20	years			
BESS lifespan [9]	10	years			
C _m [9]	5	% (of C _{in})	C _{op} [\$]	1411.66	2329.80
C _{el,buy} [11]	0.12	\$/kWh			
C _{el,sold} [11]	0.087	\$/kWh			
RI [9]	15	% (of C _{in})	RI [\$]	2690.98	7460.62
EF [13]	0.27	kgCO ₂ eq/kWh			
Emi ₀ [12]		kgCO ₂ eq		65,071.47	65,071.47
Emi [12]		kgCO ₂ eq		27,040.57	13,109.76

compare PV generation, energy demand, and storage over two 48 h periods in winter (high grid reliance) and summer (increased self-consumption). The results highlight seasonal variability in PV-BESS-EV interactions and their impact on energy autonomy and efficiency. The analysis of Configuration A underscores its fluctuating energy independence, where significant grid reliance persists during winter and partial self-sufficiency is achieved in summer. Additionally, frequent cycling of the battery system due to mismatched generation and demand patterns can lead to accelerated degradation, impacting long-term economic feasibility. A key distinction between the two configurations lies in their battery usage patterns. Configuration A exhibits frequent deep charge–discharge cycles, accelerating battery wear and increasing operational costs. Conversely, Configuration B employs an enhanced energy storage strategy that mitigates battery degradation. These comparative findings highlight the advantages of Configuration B in maintaining grid independence and improving system efficiency.

Table 5 reports annual values for key parameters, providing a comprehensive view of the system’s long-term performance and energy dynamics. The simulation results highlight both similarities and stark differences in PV-BESS-EV system performance under the two configurations. Configuration A meets about 67% of annual energy demand, with an average grid reliance of 42%, peaking in winter, and exports only 8% of surplus energy. In contrast, Configuration B exceeds 120% of the annual energy

demand, limiting grid dependence to 20%, while 43% of generated energy remains surplus.

From an economic perspective, Table 6 shows that Configuration A presents a significantly lower LCC across all four profiles, approximately half that of Configuration B. Among the profiles, Profile 3 yields the lowest LCC in both configurations, suggesting a more favorable match between system operation and demand patterns. Despite its lower LCC, Configuration A remains economically unfeasible due to unfavorable PBP, while Configuration B achieves an average PBP of 28 years but still exceeds the 20-year lifetime assumption, thus limiting its financial viability.

From an environmental standpoint, CI in Configuration A averages 1352.03 kgCO₂eq/year, whereas Configuration B remains consistently lower. Profile 3 achieves the lowest CI values in both configurations, indicating optimized use of PV and reduced grid reliance. In Configuration A, Profile 3 reaches the highest ERR (61.40%), while REF remains stable around 67% in A and 100% in B for all profiles.

The study reveals the centrality of EV charging profiles in influencing the overall system efficiency. Profile 3, aligned with midday solar peaks, demonstrates the most balanced performance across both configurations by consistently outperforming other scenarios across all assessment metrics, indicating that demand-side management strategies can play a pivotal role in maximizing the value of renewable generation. These synergies underline the importance of aligning EV charging with PV production patterns and storage availability to optimize system performance. A sizing strategy inspired by Profile 3 could effectively reduce CI, enhance ERR and REF, and shorten PBP, promoting both environmental and economic sustainability.

Table 5 Annual energy balance for Configurations A and B

	PV generation		Energy demand		Grid penetration		Surplus energy	
	kWh		kWh		kWh		kWh	
	A	B	A	B	A	B	A	B
1	7998.52	14,673.91	12,051.90	12,051.90	5348.52	2466.85	1295.14	5088.86
2	8067.65	14,880.34	12,048.94	12,048.94	4695.76	2386.18	714.47	5217.58
3	8071.96	14,878.90	12,052.36	12,052.36	4652.20	2405.59	671.80	5232.13
4	7997.45	14,673.14	12,047.89	12,047.89	5333.57	2452.31	1283.13	5077.56

Table 6 Economic and environmental assessments

	LCC [8]		CI [8]		ERR [12]		REF [12]	
	\$		kgCO ₂ eq		%		%	
	A	B	A	B	A	B	A	B
1	38,810.86	80,939.95	1444.10	666.05	55.62	79.53	66.37	100.00
2	38,351.35	80,594.99	1267.86	644.27	61.03	80.20	66.96	100.00
3	38,326.32	80,612.56	1256.09	649.51	61.40	80.04	66.97	100.00
4	38,798.49	80,927.36	1440.06	662.12	55.73	79.65	66.38	100.00

4 Conclusions

The approach presented assesses PV-BESS integration with EV charging to enhance self-sufficiency and reduce grid reliance. Through dynamic simulations, it evaluates system energy performance, environmental and financial viability to identify the optimal balance between cost-effectiveness, sustainability and self-sufficiency.

Results show that shortage scenarios, despite achieving high self-consumption levels, remain significantly dependent on the grid and are financially unviable. Surplus scenarios attain full self-sufficiency but require substantial upfront investment and exhibit an excessive payback period. These results confirm that smart charging aligned with RES is a key enabler for maximizing the performances of integrated PV-BESS-EV system. The integration of real-world climatic data, building geometry, and dynamic user behaviors into the simulation model enhances the study's relevance and applicability. As a result, it provides actionable guidance for designers, planners, and policymakers aiming to support decarbonization through integrated energy and mobility solutions.

Future work will refine PV-BESS-EV sizing through advanced multi-objective optimization, leveraging Response Surface Methodology (RSM) and stochastic modeling to optimize self-consumption, peak shaving, and grid independence while enhancing both the economic viability and environmental burdens. The role of EV charging schemes will be explored in detail, evaluating their impact on optimizing energy management and further improving system efficiency.

References

1. Shufian A, Fattah SA (2024) Integrated rooftop solar PV-based residential advanced energy management system: an economic involvement of energy systems for prosumers. *Clean Energy Syst* 9:100150. <https://doi.org/10.1016/j.cles.2024.100150>
2. Schilt U (2023) Modelling of multi-energy systems of residential buildings with calliope and validation of results. *J Phys: Conf Ser* 2600:032005. <https://doi.org/10.1088/1742-6596/2600/3/032005>
3. Park M, Wang Z, Li L, Wang X (2023) Multi-objective building energy system optimization considering EV infrastructure. *Appl Energy* 332:120504. <https://doi.org/10.1016/j.apenergy.2022.120504>
4. Alqahtani N, Balta-Ozkan N (2021) Assessment of rooftop solar power generation to meet residential loads in the City of Neom, Saudi Arabia. *Energies* 14:3805. <https://doi.org/10.3390/en14133805>
5. Wang M, Tan S, Lee CK, Hui SYR (2018) A configuration of storage system for DC microgrids. *IEEE Trans Power Electron* 33:3722–3733. <https://doi.org/10.1109/tpel.2017.2723909>
6. TABULA WebTool. <https://webtool.building-typology.eu/#bm>
7. DPR 412/93. Regulation containing rules for the design, installation, operation, and maintenance of heating systems in buildings for the purpose of containing energy consumption. *Gazzetta Ufficiale*
8. Jahanbin A, Abdolmaleki L, Berardi U (2024) Techno-economic feasibility of integrating hybrid battery-hydrogen energy storage system into an academic building. *Energy Convers Manage* 309:118445. <https://doi.org/10.1016/j.enconman.2024.118445>

9. Jahanbin A, Abdolmaleki L, Berardi U (2025) Cross-climate analysis of techno-economic metrics in bi-level electrical and hydrogen storage systems for off-grid electrification of buildings. *J Energy Storage* 107:114938. <https://doi.org/10.1016/j.est.2024.114938>
10. Bank EC (2024) BCE, Banca Centrale Europea, Eurosisistema. <https://www.ecb.europa.eu/stats/html/index.it.html>
11. GME: Gestione Mercato Elettrico. <https://www.mercatoelettrico.org/it-it/>
12. Dai C, Ma T, Zhang Y et al (2025) Improvement of building energy flexibility with PV battery system based on prediction and load management. *Build Simul* 18:65–85. <https://doi.org/10.1007/s12273-024-1216-4>
13. CO₂ emissions per kWh in Italy—Nowtricity. <https://www.nowtricity.com/country/italy/>

A Solar-Biomass Hybrid Energy System Towards Zero-Energy Buildings: A Climate-Based Tailored Optimization for Limited-Space Houses



Alireza Norouzasias , Ehsan Gholamian karkon , Gabriele Lobaccaro , and Mohamed Hamdy 

Abstract This work analyzes the techno-economic and environmental performance of a solar-biomass hybrid energy system optimized for small-size residential buildings in cold and Mediterranean climates. Based on real-time consumption data, dynamic simulation in TRNSYS, and a rule-based strategy, a photovoltaic-thermal panel, biomass heating, thermal storage, and an absorption chiller comprise a hybrid system. Performance assessment in Trondheim, Norway, and Rome, Italy, reveals that in both these regions, higher solar irradiation leads to PVT panels fulfilling up to 88% of DHW demand and 72% of cooling demand, while biomass covers more than 66% of heating demand in winter in Trondheim. An optimization using a TOPSIS approach enhances efficiency by 3.7% in Trondheim and 4.3% in Rome, while lowering CO₂ emissions by 4.2 kg/MWh and 2.8 kg/MWh, respectively. The levelized cost of energy decreases by up to €16.9/MWh in Trondheim and €16.8/MWh in Rome. These results indicate that the system has a high degree of adaptability towards changing climatic phenomena while being effective in limiting emissions as well as costs, thereby favoring near-zero energy housing in various urban settings.

Keywords Residential heating and cooling · Renewable energy optimization · Photovoltaic-thermal panels · Energy needs · CO₂ emissions

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1 Introduction

The international imperative to move towards green energy solutions has never been more pressing, urged by the pressing issues of climate change, energy insecurity, as well as urbanization [1, 2]. Residential buildings, representing a substantial fraction of energy consumption as well as greenhouse emissions globally, present immense opportunities for change towards near- or zero-energy levels [3, 4]. Such achievement, however, is highly challenging in space-restricted houses—such as urban, high-density residential sites—where design freedom is restricted. Furthermore, variability in climate, particularly between cold climates and Mediterranean regions, also calls for energy systems that are capable of meeting contrasting winter and summer heating as well as cooling needs.

Historically, integrating renewable energy into buildings has centred around single-source technology, like solar PV or biomass-boiler installations [5]. Although these are effective in given circumstances, weaknesses such as solar variability or biomass logistics do challenge reliability and affordability. Considering these shortcomings, solar-biomass hybrid energy systems have become an attractive alternative. By leveraging solar-biomass resource complementarities, these systems provide robust, low-carbon alternatives that can meet various energy needs in a range of climates and scales of operation, from residential to commercial, to meet a given energy requirement.

Increasing research has delved into hybrid configurations to obtain energy autonomy in a building. A 4E analysis was used by Gholamian et al. [6] to maximize a solar energy system integrated into a building, achieving dramatic reductions in carbon intensity as well as energy cost. Ma et al. [7] also designed a solar biomass combined cooling, heating, and power (CCHP) system on a micro-scale basis for compact urban homes. The proposed hybrid renewable CCHP system with ICE shaft power distribution reduces annual costs by 40.37% and CO₂ emissions by 88.93% compared to traditional systems. The role of optimized design was also emphasized in a techno-economic analysis by Dahiru et al. [8] for hybrid systems under Mediterranean climatic conditions. Their findings indicated that properly sized solar-thermal collectors with biomass components would meet significant seasonal cooling demands while being economically viable. Krarouch et al. [9] provided a comparative analysis of hybrid systems in Morocco, where biomass emerges as a necessity for space heating whereas solar power-run cooling would be desirable in warm regions.

Optimization methods are key to being able to deliver viable performance on both spatial and climatic constraints. Multi-objective optimization methods such as TOPSIS and NSGA-II have been applied by Mayer et al. [10] to manage energy yield, cost, and footprint in solar-biomass micro-projects. The study shows that smart building energy management using integrated thermal and electrical storage can reduce electricity costs by up to 35% in residential buildings. The design of storage is also an important consideration. Azad et al. [11] suggested micro-hybrid adaptive thermal storage, where optimum tank size based on occupancy of a building

and weather forecasting was found to significantly enhance energy efficiency and self-sufficiency. Considering multi-objective optimization, the framework reduces building energy costs by up to 29.5% and CO₂ emissions by 31.7% through smart scheduling of HVAC, batteries, and appliances. Norouzasas et al. [12] present a case study evaluating the integration of PV/T systems in residential buildings at high latitudes using TRNSYS simulations. Their results show that PV/T systems can significantly reduce energy costs and improve efficiency in cities like Oslo and Trondheim, without relying on battery storage or heat pumps. The study highlights the role of climate-specific design in maximizing PV/T system performance.

Overall, extant literature affirms the technical and environmental feasibility of solar-biomass hybrid installations in residential ZEBs, yet there exists a knowledge gap in formulating space-specific optimization strategies that account simultaneously for space limitation as well as climate variation. Addressing that gap, this research formulates and optimizes a solar-biomass hybrid energy system tailored specifically to houses with space constraints in cold and Mediterranean climates, intending to inject further momentum into the emerging field of scalable, location-specific zero-energy buildings.

This study investigates the following objectives:

- To design a compact hybrid solar-biomass energy system tailored to small residential buildings.
- To assess the system's performance—technically, economically, and environmentally—in both cold and Mediterranean climates.
- To optimize core system features like PVT panel area, biomass capacity, and storage volume for minimal emissions and cost.
- To compare climate-specific performance using simulations paired with intelligent rule-based controls.

2 Methodology

2.1 System Description

Figure 1 presents the schematic layout of the proposed solar-biomass hybrid energy system, specifically developed for compact residential buildings situated in cold and Mediterranean climates. The system is structured around three interconnected operational loops: the solar loop, the heating loop, and the cooling loop.

The solar loop initiates with photovoltaic-thermal (PVT) panels that simultaneously generate electricity and thermal energy. Thermal energy is conveyed via a circulation pump to a centralized heat storage tank (HST), where it is preserved for subsequent use. The operation of this loop is governed by a controller utilizing on/off and proportional-integral-derivative (PID) control logic to maximize the availability of solar energy for domestic needs. From the heat storage tank, thermal energy is supplied to the heating loop, where it may be supplemented by an auxiliary biomass

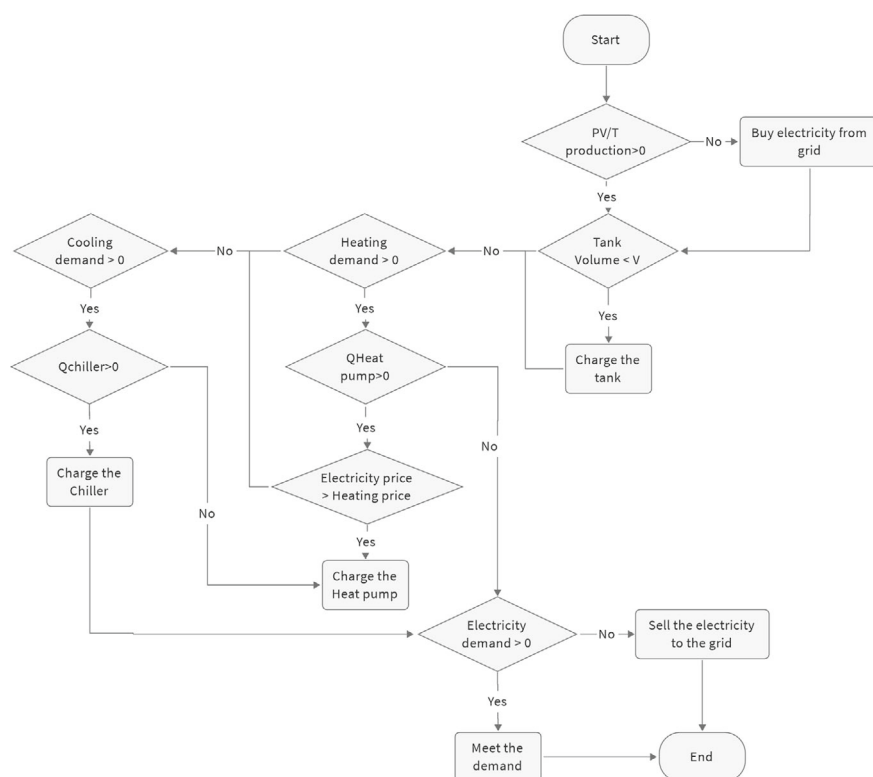


Fig. 2 The operational flowchart of flow proposed system

The first step of the algorithm is to determine the building's immediate energy use. The system gives priority to collecting energy from photovoltaic (PVT) panels to meet heating and domestic hot water (DHW) needs when the amount of solar radiation is enough. When there isn't enough solar input, the controller decides whether to turn on the heat pump or the biomass heater based on the current cost of energy and biomass. The heat exchanger transfers heat from the chosen source to the load. The thermally driven absorption chiller is activated when cooling is necessary, which is usually in the summer in Mediterranean climates. By adapting in real-time to changes in the economy and the environment, this reasoning enables effective distribution of resources.

2.2 Building Model and Climatic Context

A 100–150 m² compact residential building with conventional insulation and occupancy characteristics is the object of the simulation. Using meteorological data from

the Typical Meteorological Year (TMY), the model is tested in two different climates. Whereas Trondheim, Norway, stands for a cold climate, Rome, Italy, for a Mediterranean one. The DHW system is adjusted to meet the demands of the Mediterranean region via seasonal operating methods, with a reference temperature of 45 °C that is in line with Nordic standards requirement.

2.3 Performance Evaluation

Energy, financial, and ecological indicators were used to evaluate the system's performance. To determine the overall system efficiency (η), the total input energy was divided by the thermal and electrical energy that might be used, which includes district heating and cooling (DHW), space heating, and cooling. To calculate the emission factor (ξ), the mass of CO₂ emitted per unit of useable energy output was used. To assess financial performance, Levelized Cost of Energy (LCOE), estimates were used. This measure shows the total cost of the system divided by the amount of energy that may be used. Using these parameters, we tested the system in several different optimization settings and environmental conditions.

The expression of the performance indices is as follows:

$$\eta = \frac{\dot{Q}_{\text{PVT}} + \dot{Q}_{\text{chilled water}} + \dot{Q}_{\text{DHW}} + \dot{Q}_{\text{space heating}} - (\dot{E}_{\text{auxiliary}} + \dot{E}_{\text{heat pump}} + \dot{E}_{\text{chiller}})}{\dot{E}_{\text{heater}} + \dot{E}_{\text{solar}}} \quad (1)$$

$$\xi = \frac{\text{CO}_2}{\dot{Q}_{\text{PVT}} + \dot{Q}_{\text{chilled water}} + \dot{Q}_{\text{DHW}} + \dot{Q}_{\text{space heating}}} \quad (2)$$

$$\text{LCOE} = \frac{C_{\text{total}}}{\dot{Q}_{\text{PVT}} + \dot{Q}_{\text{chilled water}} + \dot{Q}_{\text{DHW}} + \dot{Q}_{\text{space heating}}} \quad (3)$$

3 Results and Discussion

Plotted throughout the whole year (8760 h), Fig. 3 compares the heating demand profiles of a typical residential structure in Rome with those of Trondheim. Typical subarctic temperature conditions, the two coldest months, January and December, produce two notable peaks on the Trondheim curve, which display a clear bimodal pattern. The heating season is rather long, lasting over seven months, and the need for heating stays strong for long periods of time.

Cold snaps or high operating demands cause short-term fluctuations, as seen by the abrupt, uneven spikes. The heating demand pattern is lower and more compressed in the Rome profile, which is in keeping with the features of a Mediterranean climate.

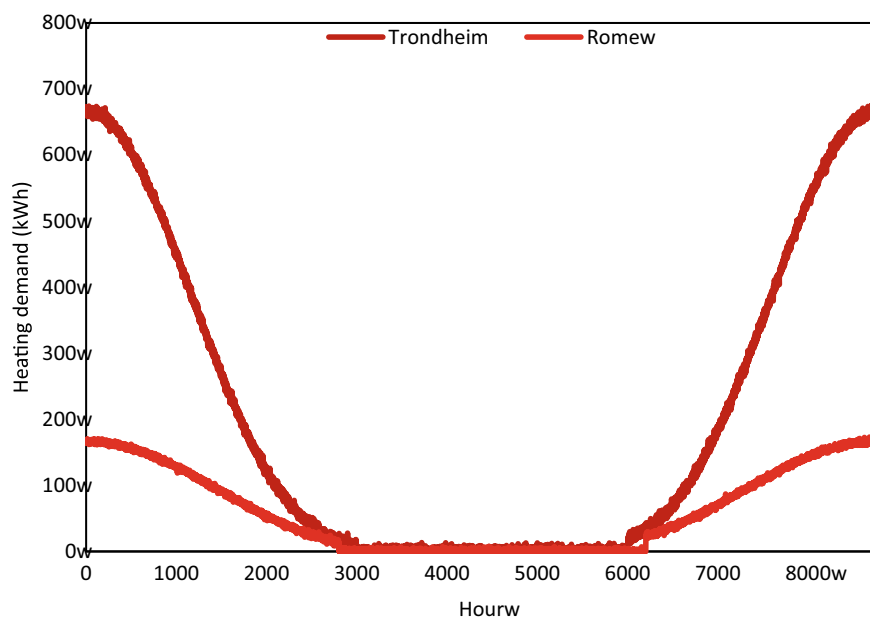


Fig. 3 Annual heating demand profile of a considered residential buildings in Trondheim and Rome

An approximately four-month heating season results from demand that starts later in the year and drops sooner. Because of the milder weather and shorter cold influences, the total burden is much less and less severe than in Trondheim. The climatic dependence of space heating demands is brought to light in this comparison, which further emphasizes the importance of designing and optimizing hybrid energy systems for each location.

Excluding the influence of solar thermal systems, Fig. 4 shows simply the heat pump and biomass heater's hourly heating needs in Rome and Trondheim. The image emphasizes the significant temperature differences affecting heating requirements at both locations. From October to April, Trondheim has notable and sustained heating needs. The profile's two notable winter peaks match the two coldest times of the year: the beginning and the conclusion. Dealing with the ongoing great demand calls for major biomass operations; heat pump support is given irregularly during warmer months. By comparison, Rome uses much less overall and has a significantly shorter heating season. Most of the peak heating needs are during the winter months of December through February. Rome's heating needs are much lower than Trondheim's even at peak demand because the Mediterranean area's milder winter temperatures and shorter heating load duration. The picture clearly shows the requirement of properly distributing resources and expanding systems for climate adaptation. While Rome's system has smaller infrastructure needs and advantages from lower auxiliary energy contributions, Trondheim's system calls for significant biomass heating capacity to preserve winter resilience.

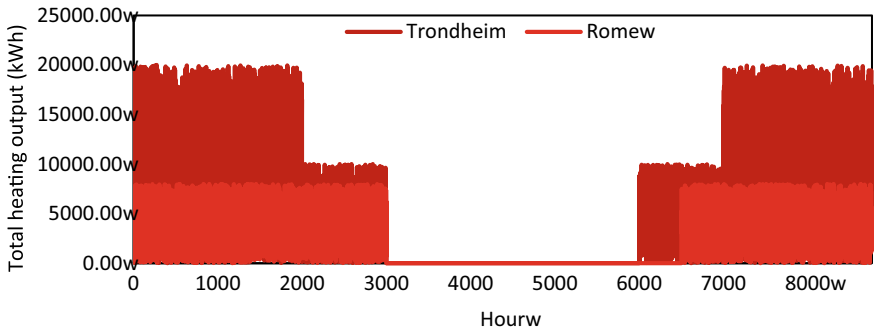


Fig. 4 Comparison of heating output in Trondheim and Rome excluding solar effect

For two climates-Trondheim (cold) and Rome (Mediterranean), Fig. 5 shows a thorough assessment of the influence of PVT panel area on system efficiency, Levelized Cost of Energy (LCOE), and CO₂ emissions. The information shows three main themes stressing how more collector surface area influences system behavior in different climate settings. First, at both sites, system efficiency rises with panel area but at varying rates. Efficiency in Trondheim increases from around 32% at 1000 m² to 37% at 1400 m².

Higher sun radiation helps Rome to regularly outperform from 36% to more than 40% throughout the same spectrum. Longer sun availability in Rome, which improves solar thermal energy collection and lowers auxiliary input dependency, explains this discrepancy. Second, with rising panel size the LCOE shows a nearly linear drop. In both situations, solar input balances the need for more costly fuel-based parts, hence lowering the cost of energy. Longer heating seasons and more dependence on biomass or auxiliary heating cause Trondheim to have a higher baseline cost.

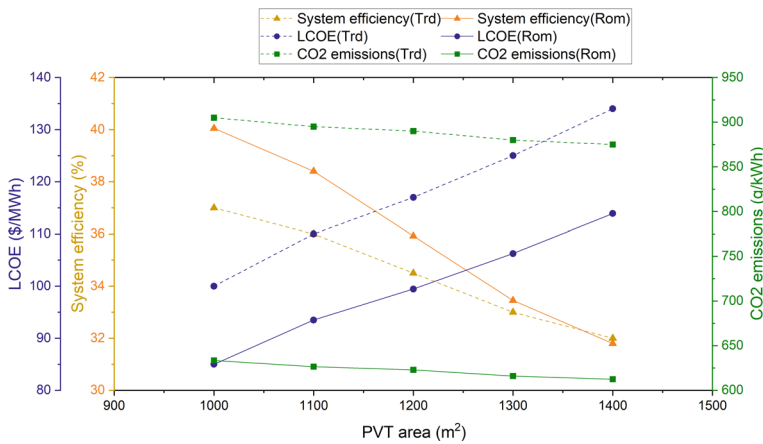


Fig. 5 Comparison the effect of panel area on performance indicators in Trondheim and Rome

With a sharper downward trend, Rome has much lower LCOE values, suggesting improved economic viability in sun-rich areas. For example, at 1400 m², Rome's LCOE falls well below that of Trondheim, therefore making the system more cost-attractive in Mediterranean uses. Panel area drives CO₂ emissions, displayed on the secondary right axis, down consistently. Reflecting less fossil backup, Trondheim's emissions drop slowly from just over 0.905 to around 0.875 kg/kWh. By comparison, Rome starts around 0.63 and drops to about 0.61 kg/kWh, much lower. Higher solar input drives this improvement by displacing biomass and auxiliary energy sources, therefore reinforcing the environmental value of such systems in southern climes. The number generally shows that more PVT panel area improves system performance on all criteria; however, in Rome, the benefits are more pronounced because of better solar potential. When creating hybrid systems for zero-energy buildings, the statistics highlight the need for climate-aware sizing techniques.

Figure 6 shows how system efficiency, LCOE, and CO₂ emissions for Trondheim and Rome are affected by different thermal storage tank capacity. The findings show the trade-offs included in increasing thermal storage capacity within a solar-biomass hybrid system. System efficiency in all regions shows a slow drop as tank capacity rises from 7 to 9 m³. Efficiency in Trondheim falls from around 39–33.5%; Rome begins higher and falls from 41 to 35%. Increased thermal losses and reduced stored heat use as tank capacity rises, especially during warmer times with less demand, account for the drop in efficiency. Rome, enjoying a more steady and solar-rich environment, has a steadily better efficiency profile throughout all volumes.

Larger tanks show an increasing LCOE. While in Rome it climbs more modestly because of larger solar gains and lower auxiliary energy demand, the LCOE in Trondheim climbs from 90 to 121 \$/MWh as storage capacity grows. Oversized designs are less economically attractive, particularly in colder areas, since larger tanks need more investment and have declining marginal returns in energy production. Like LCOE, CO₂ emissions rise with tank size. Emissions in Trondheim increase from

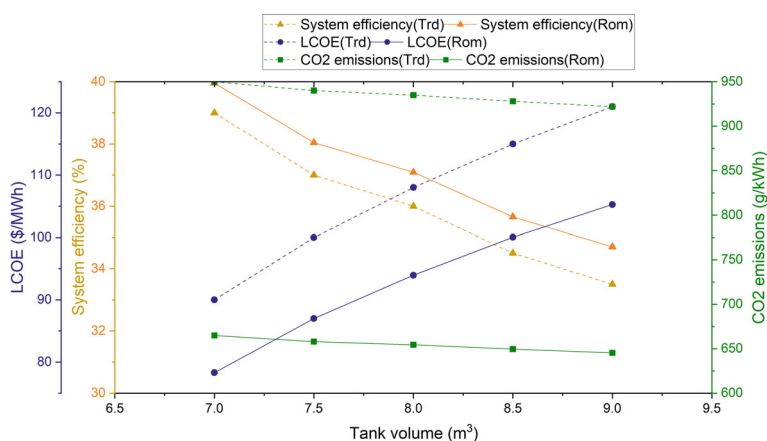


Fig. 6 Comparison the effect of tank volume on performance indicators in Trondheim and Rome

Table 1 Comparison of performance indices before and after optimization

Indicator	Trondheim (Design)	Trondheim (TOPSIS)	Rome (Design)	Rome (TOPSIS)
Efficiency (%)	30.1	33.8	33.2	37.5
Total cost (€/h)	11.7	9.6	9.8	7.4
LCOE (€/MWh)	121.5	104.6	106.0	89.2
Emission index (kg/MWh)	11.9	7.7	8.3	5.5

around 950 to 922 g/kWh; in Rome, owing to more solar thermal energy use, emissions stay much lower (from 665 to 645 g/kWh). These findings support the idea that, if not matched with real demand patterns, oversizing storage tanks might have less desirable energy and environmental effects. To sum up, whereas a reasonable tank capacity (around 7.5–8.0 m³) may maximize system balance, higher volumes lead to less efficiency, more expense, and more pollutants. Because of the harsher environment and longer warmer season, this impact is more noticeable in Trondheim than in Rome.

Table 1 compares the performance indicators between the original design parameters and the improved results using the TOPSIS method for both Trondheim and Rome. Efficiency, total cost, LCOE, and emission index are the four key performance parameters. Optimization in Trondheim increased the system efficiency from 30.1 to 33.8%, hence suggesting a 3.7% point increase in energy conversion performance. The whole operational cost was reduced from €11.7/h to €9.6/h, saving €2.1 per hour. The LCOE was cut from €121.5/MWh to €104.6/MWh, indicating significant cost savings of €16.9/MWh. The emission index dropped from 11.9 to 7.7 kg/MWh, implying an environmental gain of 4.2 kg CO₂ per MWh. Given its improved sunlight conditions, Rome's improvements were even more evident. Efficiency increased from 33.2% in the initial design to 37.5% following optimization.

The total cost fell from €9.8/h to €7.4/h. The LCOE dropped from €106.0/MWh to €89.2/MWh; emissions dropped from 8.3 to 5.5 kg/MWh. These results highlight the higher performance and more sensitivity of the Rome case to collector size and solar input optimization. The TOPSIS method usually enhanced system performance in both climates. Rome was seeing more notable gains due to better solar resource availability. In both cases, the optimal solutions provide improved technical, economic, and environmental outcomes.

4 Conclusion

Across two distinct climates-cold (Trondheim) and Mediterranean (Rome)-this study demonstrated the viability and benefits of employing a solar-biomass hybrid energy system for modest residential buildings. Climate setting has been shown by thorough

modeling and simulation to have a major impact on the energy balance, economic output, and environmental effect of the system. Rome's favorable light conditions let PVT panels provide more energy, hence improving system efficiency and lowering dependence on biomass and extra heating. In contrast, Trondheim relied more on biomass support during long winters, which generated greater emissions and operating expenses but remained below acceptable levels for zero-energy design. Use of TOPSIS optimization enhanced all performance measures. The system efficiency in Trondheim increased from 30.1 to 33.8% while LCOE dropped from €121.5 to €104.6/MWh and emissions were reduced from 11.9 to 7.7 kg/MWh. Post-optimization results in Rome showed an efficiency gain from 33.2% to 37.5%, with LCOE falling from €106.0 to €89.2/MWh and emissions decreasing from 8.3 to 5.5 kg/MWh. These findings validate the need for tailored hybrid system designs and climate-specific optimization in attaining energy efficiency, cost-effectiveness, and emissions reduction. The approach outlined in this article offers a scalable roadmap for transitioning to low-carbon housing in both cold and solar-rich regions.

References

1. Norouzasias A, Attia S, Hamdy M (2024) Impact of space utilization and work time flexibility on energy performance of office buildings. *J. Build. Eng.* 98:111032. <https://doi.org/10.1016/j.jobbe.2024.111032>
2. Piraei F, Matusiak B, Lo Verso VRM (2022) Evaluation and optimization of daylighting in heritage buildings: a case-study at high latitudes. *Buildings* 12:131. <https://doi.org/10.3390/buildings12122045>
3. Yin H, Norouzasias A, Hamdy M (2025) PCM-incorporated building envelope for improving cost savings in residential buildings under cold climates. In: Berardi U (ed) *Lecture notes civil engineering*. Springer, Singapore, pp 384–392. https://doi.org/10.1007/978-981-97-8305-2_53
4. Ghorbani Naeini H, Norouzasias A, Piraei F, Kazemi M, Kazemi M, Hamdy M (2023) Impact of building envelope parameters on occupants' thermal comfort and energy use in courtyard houses. *Archit Eng Des Manag.* <https://doi.org/10.1080/17452007.2023.2254294>
5. Giorio M, Manni M, Köker NI, Bertolin C, Thebault M, Lobaccaro G (2025) Interactive platforms for solar energy planning in smart cities: a state-of-the-art review of solar cadasters. *Sol Energy* 287:113227. <https://doi.org/10.1016/j.solener.2024.113227>
6. Gholamian E, Zare V, Javani N, Ranjbar F (2022) Dynamic 4E (energy, exergy, economic and environmental) analysis and tri-criteria optimization of a building-integrated plant with latent heat thermal energy storage. *Energy Convers Manag.* <https://doi.org/10.1016/j.enconman.2022.115868>
7. Ma Z, Dong F, Wang J, Zhou Y, Feng Y (2023) Optimal design of a novel hybrid renewable energy CCHP system considering long and short-term benefits. *Renew Energy* 206:72–85. <https://doi.org/10.1016/j.renene.2023.02.014>
8. Dahiru AT, Tan CW (2020) Optimal sizing and techno-economic analysis of grid-connected nanogrid for tropical climates of the Savannah. *Sustain Cities Soc.* <https://doi.org/10.1016/j.scs.2019.101824>
9. Krarouch M, Allouhi A, Hamdi H, Outzourhit A (2024) Energy, exergy, environment and techno-economic analysis of hybrid solar-biomass systems for space heating and hot water supply: case study of a Hammam building. *Renew Energy.* <https://doi.org/10.1016/j.renene.2024.119941>

10. Mayer MJ, Szilágyi A, Gróf G (2020) Environmental and economic multi-objective optimization of a household level hybrid renewable energy system by genetic algorithm. *Appl Energy*. <https://doi.org/10.1016/j.apenergy.2020.115058>
11. Azad AH, Shateri H (2023) Design and optimization of an entirely hybrid renewable energy system (WT/PV/BW/HS/TES/EVPL) to supply electrical and thermal loads with considering uncertainties in generation and consumption. *Appl Energy*. <https://doi.org/10.1016/j.apenergy.2023.120782>
12. Norouzasias A, Lobaccaro G, Hamdy M (2025) Integration of PV/T system for achieving energy-efficient buildings: a case study of residential buildings at high latitudes. In: Berardi U (ed) *Lecture notes civil engineering*. Springer, Singapore, pp 553–560. https://doi.org/10.1007/978-981-97-8313-7_75

Exploring the Theory Versus Reality of Passive House Performance: A Comparative Study of Occupied Versus Unoccupied Dwellings in the Republic of Ireland



Bailie Wilson, Aggelos Zacharopoulos, Trevor Hyde, Shane Colclough, Jayanta Mondol, and Chiara Salaris

Abstract In Ireland, the Passive House standard is gaining popularity. As of 2024 report indicates 45 Passive House-certified homes have been completed nationwide, reflecting a significant rise in demand for energy-efficient construction (PHAI Homepage. <https://phai.ie/> [1]). While passive house standards are designed to optimise energy efficiency and indoor comfort, performance can vary depending on occupancy lifestyle, habits, and how the residents live. Factors such as heating preferences, ventilation management, and energy consumption habits can influence the building's energy use and overall performance. This paper explores how the performance of Passive House buildings can differ based on occupant behaviour and habits, highlighting the gap between theoretical design principles and real-world usage. Operational data was collected from two social housing units in County Monaghan, Ireland, built to Passivhaus standards—one occupied home and one unoccupied home acting as a control. Data collection spanned a minimum of one year, gathering environmental performance metrics and energy consumption data. By comparing occupied and unoccupied Passive Homes, this study examines the impact of human behaviour and its effect on these low-energy buildings, offering insights into the importance of

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occupant engagement in achieving the desired sustainability outcomes. This study contributes to the growing body of knowledge on low-energy buildings and emphasises the critical role of energy-efficient standards in achieving carbon neutrality within the domestic sector.

Keywords Passive house · NZEB · Post occupancy evaluation · Thermal comfort · Indoor environmental quality · Energy consumption

1 Introduction

1.1 *Irish Housing Stock Energy Efficiency*

Over the years, Ireland has introduced various policies and grants to enhance the energy performance of residential buildings, reflected in updates to Irish Building Regulations and the promotion of renewable technologies. Despite this progress, widespread adoption of energy-efficient practices remains restricted by perceived barriers such as high upfront costs and limited government financing support. Furthermore, while renewables accounted for 42% of electricity generation in 2023, mainly from wind (35.8%) and a growing solar capacity, fossil fuels still supplied 82.6% of total energy, with the transport and heating sectors heavily dependent [2].

Despite the amendments to Building Regulation Part L initially in 2002, 2012 and 2022, the residential sector still consumes 27.5% of energy (equivalent to 9.8 Mt CO₂) [2], and accounts for 15.5% of energy-related CO₂ emissions. The Sustainable Energy Authority of Ireland's Residential Energy Survey in 2022 [3] highlights that, despite improvements in building regulations, a large proportion of homes remain energy inefficient, driving up energy bills and hindering progress toward a low-carbon housing sector.

Both space heating and water heating in Irish homes continue to rely heavily on oil, posing a challenge to climate goals. In 2022, oil-related CO₂ emissions amounted to 6.71 Mt [4] and space heating accounts for approximately 61% of household energy use, while domestic hot water contributes 20%, making them the most energy-intensive domestic activities [2].

In this context, the Passive House standard creates a path to low-energy housing, offering energy savings of up to 80% compared to non-passive house buildings [5]. Councils across the island are evaluating the potential of using Passive House standards for new social housing projects as a cost-effective solution that can tackle issues such as fuel poverty and improve the quality of homes. There is increasing interest in understanding whether these homes can deliver both long-term performance and cost efficiency for new builds. Additionally, there is a growing need for updated comparative case studies that evaluate the performance of passive homes in the context of the newly adopted nZEB standards across Europe.

1.2 Occupancy and Behaviour

Identifying occupancy behaviour is essential for improving energy demand estimations in dwellings. Occupancy has been analysed in dwellings across Northern Ireland to assess “Real Life Energy Use” [6], with findings that electricity consumption per person decreases as the number of occupants increases. The COVID-19 pandemic has significantly altered energy usage patterns, with increased heating and electricity demand due to remote work and lifestyle changes. A study conducted in England and Wales during the pandemic revealed a 7.8% increase in electricity demand and a 0.1% decrease in gas consumption in the first year, followed by a 2.2% rise in electricity use and a 0.2% increase in gas usage in the second year [7]. Additionally, households with children and those where adults transitioned to work-from-home arrangements exhibited higher electricity consumption, averaging 1400 Wh daily. While global studies have examined how occupant behaviour influences domestic energy consumption, there has been less focus on the UK and Ireland. These studies suggest that energy efficiency is shaped by a combination of building design, technology, user habits, occupancy age, location, and daily routines. As energy efficiency measures aim to reduce carbon emissions and consumption, the rebound effect may counteract these efforts, especially as households adjust their habits and extend utility usage [8]. Therefore, considering occupancy behaviour is key to optimising energy consumption and ultimately mitigating carbon emissions.

1.3 Approach of Research

Studying an occupied passive house reveals real-life insight into energy consumption, indoor air quality, and thermal comfort, through occupant behaviour and appliance use. It demonstrates the impact of user habits on performance and system maintenance. On the other hand, a non-occupied passive house provides a controlled setting to evaluate baseline energy and thermal performance, and system function without human influence, enabling a direct comparison. Integrating both approaches offers a comprehensive assessment of passive house performance, connecting ideal conditions with practical, everyday use.

Specifically, the aims of this study include;

- To compare and analyse environmental conditions in both occupied and unoccupied passive homes built to the passive house standard.
- To explore how occupant behaviour and lifestyle choices affect the performance of passive homes.
- To evaluate the disparity between theoretical expectations and real-world performance in passive homes, focusing on energy efficiency, comfort, and indoor air quality.
- To examine the influence of occupancy on the effectiveness of passive house systems, including heating and energy consumption.

Table 1 Characteristics of the building, heating, ventilation and renewable system

	Unoccupied passive house	Occupied passive house
Building type	House-semi detached	House-semi detached
Orientation	South west	South west
Ventilation	MVHR compact P unit	MVHR compact P unit
Air tightness (n50)	0.6 @ 50 Pa	0.6 @ 50 Pa
Floor area (m ²)	106	106
Renewable Technology	N/A	N/A
Windows	Triple glazed	Triple glazed
Construction Type	Timber Frame	Timber Frame
Completed Year	2022	2022

Table 2 Comparison of passive house building standard and Republic of Ireland nZEB regulations

Building standard	Passive house	Republic of Ireland nZEB
Thermal Bridges	0.01 (Wm/K)	0.08 (Wm/K)
Airtight	0.6 ach ⁻¹	5m ³ m ² hr ⁻¹
Heat recovery ventilation	Yes	No
Orientation	Yes	No
Certification	Possible	No
Overheating	Potential	Under discussion

2 Methodology

2.1 Design and Scope

This study analyses domestic energy performance using quantitative data collected exclusively from monitoring equipment. Measurements of temperature, CO₂ concentrations, energy consumption, and heating system usage were gathered to provide an assessment of household energy use. Comparing an occupied and unoccupied passive house enables a revelation of the impact of occupancy on energy efficiency (Tables 1 and 2).

2.2 Data Collection and Metrics

Monaghan County Council in Ireland issued two passive homes for assessment of compliance with Part L of the Irish building regulations and the feasibility of this approach for low-energy housing in the social housing sector.

Energy consumption in these dwellings was measured using clamp-on meters connected to an energy monitor device, the Emoncms, which monitored ventilation, the Nilan Compact-P unit (a mechanical, ventilation and heat recovery unit), and total household energy consumption. Data was recorded at 5 min intervals for a minimum of one year.

Temperature and CO₂ levels were recorded from 2023 to 2025 using Netatmo Weather Station monitors at 30 min intervals in living rooms, kitchens, and bedrooms. Sensor accuracies: ± 0.3 °C (0 °C –0 °C) for temperature, ± 100 ppm (up to 1000 ppm), $\pm 10\%$ (above 1000 ppm) for CO₂.

Temperature bands have been established, and the percentage of time individual temperatures exceed the thresholds is presented to assist the reader in obtaining insights with respect to the building regulations (as defined by the DEAP software, used to ensure compliance with Irish building regulations). Passive Houses are designed to have a uniform set temperature of 20 °C throughout. A temperature threshold has therefore been set at 20 °C. Thresholds have been defined to reflect the set temperatures in DEAP at 21 °C for the living room and 18 °C for the other parts of the dwelling. A set temperature of 24 °C is required in DEAP in the case of air-conditioned buildings, and the final threshold temperature of 25 °C reflects the temperature that passive houses are allowed to exceed for no more than 10% of the time.

2.3 Analysis Methods

Data from both the unoccupied and occupied passive house underwent structured analysis to assess variations in thermal performance, energy consumption, and indoor environmental quality (IEQ). Graphical methods, such as combination graphs and boxplots, highlighted trends and variability across the two passive homes under investigation.

3 Results-Indoor Temperatures and Energy Consumption

Figure 1 illustrates temperature management in unoccupied and occupied passive homes and how it may differ throughout the year. The 10 p.m.–7 a.m. period was selected to represent typical occupancy hours, to provide a clearer understanding of indoor temperatures during occupied periods. In the occupied living room, temperatures remain consistently higher with limited variability due to heating that may have been driven by human presence and/or maintaining comfort even during colder months of Irish weather (November–February). However, the unoccupied living rooms show wider temperature fluctuations and lower average temperatures, especially during cold months, suggesting a lack of active heating. Despite a lack of data in the unoccupied passive house kitchen, during warmer months (May–September),

temperature differences are less pronounced, which may be due to internal gains, but the unoccupied home still demonstrates broader ranges and occasional spikes, most likely due to occasional occupancy and solar gains particularly in the Summer months.

The occupied passive house can maintain a more stable and higher average temperature (21.2 °C) compared to the unoccupied passive house (19.4 °C), with 55.7% of the time spent in the 21–24.9 °C range, compared to 33.3% in the unoccupied case. (Fig. 2) The unoccupied passive house is significantly more prone to temperatures below 18 °C (29.8%), while the occupied passive house does not reach these lower temperatures, indicating that occupancy stabilises temperatures.

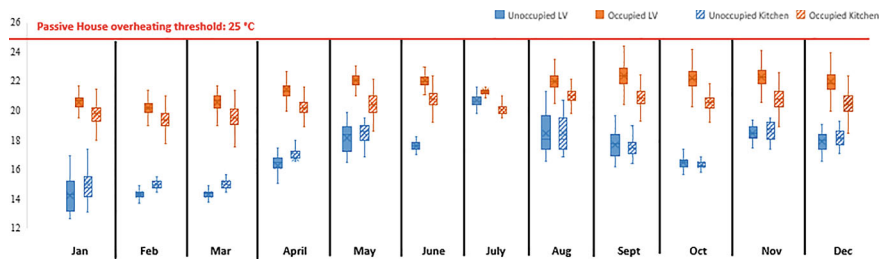


Fig. 1 Livingroom and kitchen temperatures from January 2024–December 2024

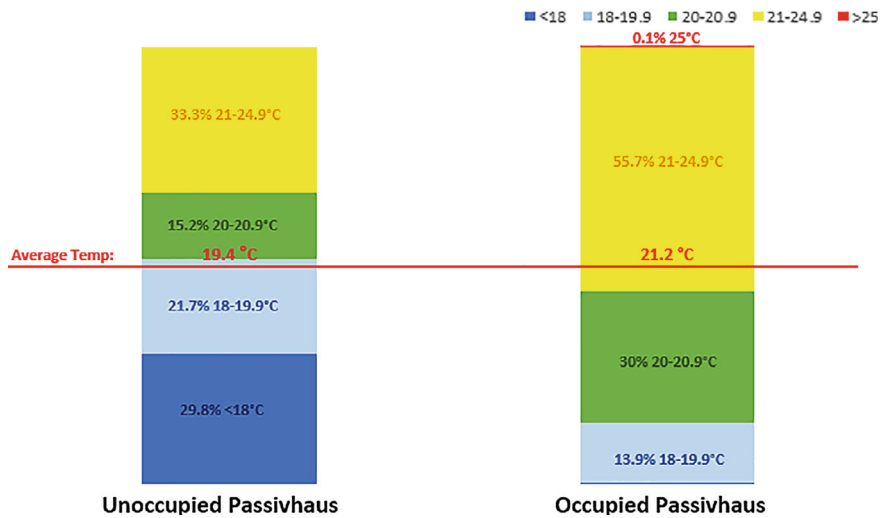


Fig. 2 Temperature range percentage of occupied and unoccupied Passivhaus

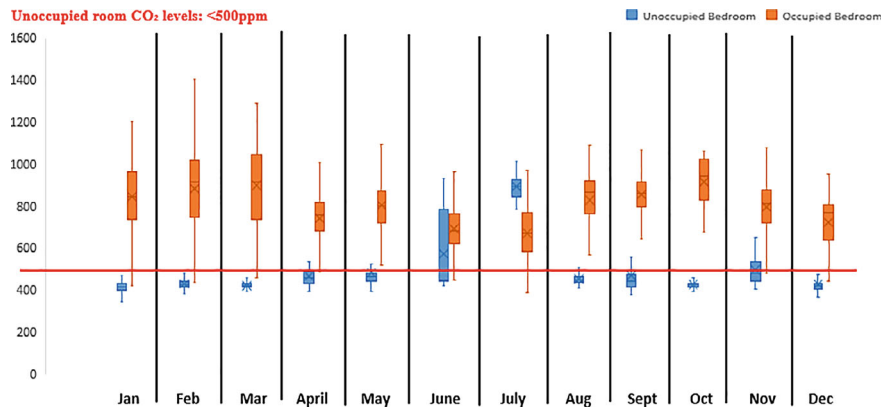


Fig. 3 Bedroom CO₂ concentrations January 2024–December 2024

3.1 CO₂ Concentrations

CO₂ concentrations were measured in bedrooms during typical usage periods. Illustrated in Fig. 3, occupied bedrooms show higher CO₂ levels compared to unoccupied bedrooms, which generally maintain concentrations below the unoccupied room threshold of 500 ppm. Minor fluctuations, especially in summer (June–August), likely reflect brief occupancy and occasional window openings. With this, use of the unoccupied bedroom resulted in peaks reaching 1000 ppm, though monthly averages remained around 600 ppm due to extended unoccupied periods. Despite these fluctuations, the overall pattern remains consistent throughout the year, with occupied bedrooms consistently displaying higher CO₂ concentrations than unoccupied bedrooms.

3.2 Energy Consumption—Nilan Compact P and Total Consumption

Figures 4 and 5 illustrate seasonal variations in system performance and energy demand, driven by occupancy patterns and climate conditions in high-performance buildings.

In the winter profile (Fig. 4), energy consumption in the unoccupied passive home remains low all day, with minimal fluctuation. However, the Nilan Compact P—serving ventilation, heating, and hot water—shows a distinct operational plateau between 07:30 and 14:00, followed by a sharp evening spike at 20:00. This suggests a scheduled heating period and a manually triggered heating booster. In contrast, the occupied passive home shows highly variable energy consumption, particularly in the evening, indicating occupant activity. The associated Nilan Compact P usage

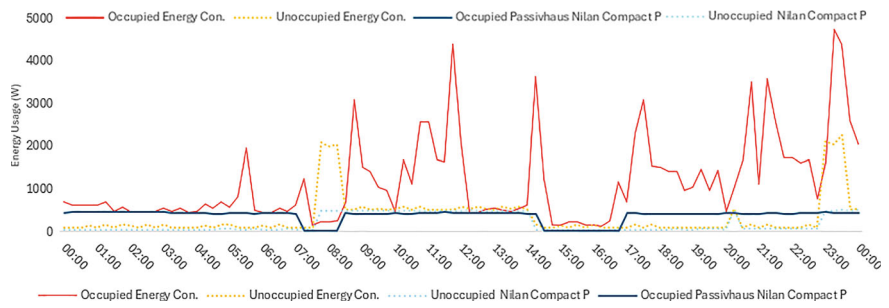


Fig. 4 24 h winter profile—occupied and unoccupied passive homes energy and Nilan compact P use

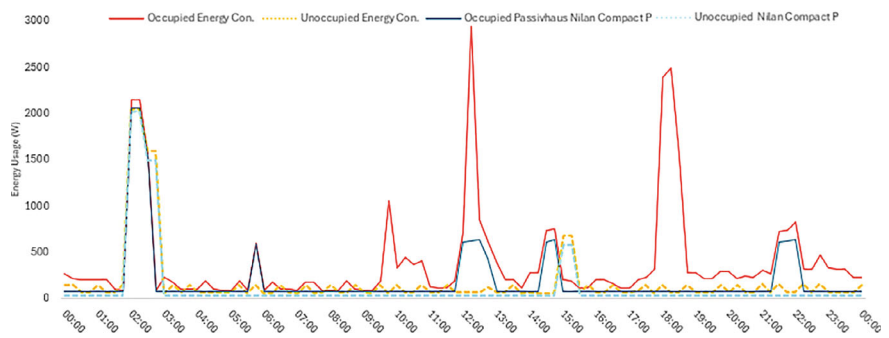


Fig. 5 24 h summer profile—occupied and unoccupied passive homes energy and Nilan compact P use

remains consistently higher, reflecting continuous heating, ventilation needs, and domestic hot water demand.

In the summer profile (Fig. 5), overall energy consumption is lower than in winter, reflecting reduced heating and electrical demand. In the unoccupied passive home, energy use and Nilan Compact P operation are minimal, indicating minimal occupancy, background loads, and system idling. In the occupied passive home, energy consumption shows distinct peaks around 02:00, 11:30, 13:00, 18:00, and 22:00, suggesting occupant-driven activities such as appliance use and water heating. The Nilan Compact P mirrors this pattern with short, sharp bursts of activity, likely due to hot water demand.

4 Discussion

This paper has provided insights based on a comparative analysis of two passive homes, one of which those unoccupied, and the other a family of two adults and two children. The key findings from the analysis include:

1. The occupied passive home maintains a warmer average temperature (21.2 °C versus 19.4 °C) and spends more time within the ideal 20–20.9 °C range (29% versus 15.2%). In contrast, the unoccupied home spends 29.8% of the time below 18 °C, indicating minimal presence and heating.
2. Occupied bedrooms show higher CO₂ levels than unoccupied ones, reflecting the influence of human presence on indoor air quality.
3. CO₂ concentrations were slightly lower in summer months in the occupied home, which can be due to window openings and less occupancy.
4. Seasonal energy use varies by occupancy and climate: winter shows higher, more variable demand, especially in the occupied passive home, driven by heating and occupant activity; summer profiles are lower overall, which can be due to less heating and ventilation demand as windows are more likely to be open, and more natural lighting.

5 Conclusion

Occupancy brings various heat sources such as human presence, use of electrical appliances, and active heating systems, which all contribute to higher internal temperatures. The occupied passive home reached and maintained higher temperatures, with an average of 21.2 °C, over three degrees Celsius higher than the unoccupied passive home, and spent 30% of the time within the ideal temperature range of 20–20.9 °C.

Seasonal variations indicate that energy demand decreases during summer months, likely due to reduced heating requirements, an increase in natural ventilation, and lower occupancy. Additionally, occupied bedrooms exhibit higher CO₂ concentrations throughout the year.

The conclusion of theory vs reality reveals how occupant behaviour and lifestyle choices impact building performance, revealing discrepancies between theoretical expectations and realistic outcomes in energy efficiency, comfort and air quality.

This research underscores the importance of considering real-world occupancy dynamics when evaluating passive house performance, providing valuable insights for improving energy efficiency and comfort in future designs.

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Disclosure of Interests The authors declare that they have no competing interests.

References

1. PHAI Homepage. <https://phai.ie/>. Last accessed 31 Mar 2025
2. SEAI, Energy in Ireland 2023 Report. <https://www.seai.ie/sites/default/files/publications/Energy-in-Ireland-2023.pdf>. Last accessed 02 Mar 2025
3. SEAI, Energy in Ireland 2022 Report. <https://www.seai.ie/sites/default/files/publications/Energy-in-Ireland-2022.pdf>. Last accessed 02 Mar 2025
4. EPA. https://www.epa.ie/publications/monitoring--assessment/climate-change/air-emissions/2023-EPA-Provisional-GHG-Report_Final_v3.pdf. Last accessed 27 Feb 2025
5. Peper S, Feist W (2002) Klimaneutrale Passivhaussiedlung Hannover-Kronsberg—Analyse im dritten Betriebsjahr. Proklima, Hannover
6. Yohanis F et al (2008) Real life energy use in Northern Ireland dwellings. *J Build Perform* 2(5):99–110
7. Zapata-Webborn F et al (2023) The impact of COVID-19 on household energy consumption in England and Wales from April 2020 to March 2022 vol 297, p 113428
8. Energy efficiency of UK homes—House of Commons Library. <https://commonslibrary.parliament.uk/research-briefings/cbp-9889/>. Last accessed 04 Jan 2024
9. Anon. DEAP 4.2.0 Software. Sustainable energy authority of Ireland (n.d.)

Performance Analysis of an Innovative Radiant Floor System Incorporating Two Phase Change Materials: An Experimental Investigation



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Abstract The configuration and composition of Radiant Floor Systems (RFS) are essential for an optimal thermal performance, seeking high indoor thermal comfort in buildings. When phase change materials (PCMs) are incorporated into radiant floors to provide thermal energy storage capacity, the system's configuration becomes increasingly relevant. However, there are still very few large-scale experimental studies dedicated to the thermal performance of RFS incorporating PCMs. In this

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study, a new configuration for a RFS incorporating PCMs is proposed. The innovative RFS incorporates two macroencapsulated PCMs with different operating temperatures, selected to meet both heating and cooling demands. The thermal performance of a large-scale test specimen is experimentally evaluated under controlled conditions using a climatic chamber, subjecting the innovative PCM-RFS to different environment conditions, and comparing the results with a reference RFS. Despite the system's ability to operate in heating and cooling, the herein presented work addresses only a heating scenario. The results confirmed that the PCM-RFS has the ability to slowly release heat over a significant period of time after the system is switched off, capable of maintaining the indoor temperature steady within comfort levels.

Keywords Radiant floor system · Phase change materials (PCMs) · Thermal performance · Heating · Thermal energy storage

1 Introduction

Despite concerted international efforts embodied in climate change mitigation agreements, global greenhouse gas (GHG) emissions continue to gradually increase worldwide, reaching record levels in recent years [1, 2]. The role of buildings in this regard remain a serious concern, as indoor heating and cooling is still the main responsible of energy consumption, contributing significantly to CO₂ emissions in the sector [3, 4].

Of the different indoor heating and cooling systems in buildings, the advantages of radiant floors have led to its widespread use [5]. As recently reviewed, the configuration and composition of RFS are key parameters for enhanced thermal performance and energy efficiency, seeking high indoor thermal comfort [6]. The incorporation of materials with latent heat storage capacity such as PCMs in RFS to act as thermal batteries, increases the thermal inertia of the system, allowing to attenuate temperature fluctuations and, potentially, overcome the mismatch between energy supply and demand, addressing the challenge of renewable energy intermittency [7, 8].

Heng et al. [9] reported indoor thermal comfort benefits of incorporating PCM into RFS by experimentally evaluating the heat storage and release performance of a hydronic RFS incorporating macroencapsulated PCM. Larwa et al. [10] studied the temperature distribution and heat flux of a hydronic RFS incorporating macroencapsulated PCM, noticing the importance of the thermal conductivity of the mortar layer and that positioning the PCM layer below the heating pipes promotes the performance of the PCM-RFS. Chen et al. [11] carried out an experimental study using a small-scale setup followed by numerical simulation using a calibrated model. The authors observed that the test room equipped with PCM-RFS resulted in longer thermal

comfort periods than a reference room, and numerical simulation results revealed the test room with the PCM-RFS having the lower daily electricity cost and higher indoor air comfort time ratio. Wang et al. [12, 13] numerically studied different types of PCM incorporation in the RFS configuration, evaluating the corresponding effect on the thermal performance of the resulting PCM-RFS. Qi et al. [14] studied the use of a microencapsulated PCM slurry as substitute of water for the heat transfer fluid in hydronic RFS. Yuan et al. [15] used numerical simulation to compare the heat storage and release characteristics of a sand-based RFS, a conventional RFS and a PCM-RFS.

From the literature, the majority of the studies are of numerical nature. When experimental, the studied PCM-RFS apparatuses are typically of reduced-scale dimensions, potentially compromising representativeness. Large-scale experimental studies dedicated to the thermal performance of RFS incorporating PCM are still scarce. Notably, Cesari et al. [16] assembled and studied a full-scale RFS incorporating two types of macroencapsulated PCM, subjected to a real-scenario environment. Nevertheless, and despite the promising obtained results, some envelope-related challenges and experimental constraints were reported. This study puts forward a novel configuration for a RFS incorporating two PCMs. The innovative RFS setup incorporates two macroencapsulated PCMs having different operating temperatures, selected to meet heating and cooling demands. The objective of this study is to evaluate the thermal performance of the novel large-scale PCM-RFS configuration under controlled heating conditions using a climatic chamber, comparing the thermal results with a reference RFS setup.

2 Materials and Methods

2.1 Experimental Setup and Materials

The experimental setup apparatus is composed of two hydronic RFS test specimens: a reference RFS (RFS_{Ref}); and the innovative RFS incorporating two macroencapsulated PCMs (PCM-RFS). The RFS_{Ref} is representative of conventional hydronic heavyweight RFS, with mortar as the load bearing thermal diffusion medium embedding the water pipes. The RFS_{Ref} configuration is composed of the following layers: (i) thermal insulation (EPS); (ii) mortar medium; (iii) water pipes arranged in spiral configuration, completely embedded in the mortar.

The configuration of the innovative PCM-RFS test specimen consist in the following layers, from the base to the finishing material on the floor surface: (i) thermal insulation (EPS); (ii) macrocapsules containing two different PCMs, alternatively positioned in a checkerboard pattern. Sand was used to fill the gaps between the macrocapsules; (iii) water pipes arranged in spiral configuration; (iv) mortar medium, embedding the water pipes; and (v) finishing layer of vinyl flooring.

The two test specimens have equal horizontal dimensions of $1.50 \text{ m} \times 1.50 \text{ m}$ for scale representation. Each of which is equipped with an enclosure structure consisting of EPS, with the dimensions of 1.50 m (width) $\times$ 1.50 m (length) $\times$ 3.0 m (height) and 150 mm of thickness (walls and roof). To monitor indoor and floor surface temperatures, K-type thermocouples are installed at different locations and heights (6 levels with 9 sensors *per* level), fixed in their defined position by a support structure. The operating range of these sensors is between -100 and $450 \text{ }^{\circ}\text{C}$, with an accuracy of $\pm 0.5 \text{ }^{\circ}\text{C}$. The technological characteristics of the calibrated climatic chamber are: dimensions of 3.6 m (length) $\times$ 5.6 m (width) $\times$ 4.0 m (height); operating temperature range from -30 to $80 \text{ }^{\circ}\text{C}$, and of humidity from 20 to 90% , with humidity control between 2 and $60 \text{ }^{\circ}\text{C}$.

The load bearing heat transfer medium embedding the water pipes in RFS_{Ref} is a high conductive cementitious mortar composition for RFS applications. The thermophysical properties of this mortar are: hardened bulk density of $2050 \text{ kg} \cdot \text{m}^{-3}$; thermal conductivity of $2.5 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$; and specific heat capacity of $1000 \text{ J} \cdot \text{kg}^{-1} \cdot ^{\circ}\text{C}^{-1}$. Regarding the innovative PCM-RFS specimen, sand was used to eliminate any voids between the PCM macrocapsules, ensuring a continuous medium within the PCM-RFS configuration. A calibrated fine particle sand was used (particle dimension $< 0.5 \text{ mm}$) with a density of $2660 \text{ kg} \cdot \text{m}^{-3}$. The heat transfer medium embedding the water pipes in the novel PCM-RFS specimen is a solution from Saint-Gobain Portugal with the commercial designation of *weberfloor radiant*. This is a self-levelling cementitious mortar with the following thermophysical properties: hardened bulk density of $2100 \text{ kg} \cdot \text{m}^{-3}$; thermal conductivity of $1.7 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$; and specific heat capacity of $1000 \text{ J} \cdot \text{kg}^{-1} \cdot ^{\circ}\text{C}^{-1}$. The water pipes are made of peroxide crosslinked polyethylene (PE-Xa) with $\text{Ø}16 \times 1.5 \text{ mm}$ and thermal conductivity of $0.35 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$. The same pipe solution and configuration was applied in both test specimens. The finishing material used in the PCM-RFS specimen is a conventional vinyl flooring with 3.2 mm of thickness, composed of heterogeneous polyvinyl chloride. The two PCMs incorporated in the PCM-RFS configuration are organic solutions from Rubitherm® with the commercial references of *RT18HC* and *RT28HC*. These have peak melting temperatures of 18 and $28 \text{ }^{\circ}\text{C}$, and respective latent heat of $260 \text{ kJ} \cdot \text{kg}^{-1}$ and $250 \text{ kJ} \cdot \text{kg}^{-1}$, selected to address cooling and heating RFS operation. The pure PCMs were poured into plastic containers of parallelepiped shape with dimensions of $165 \text{ mm} \times 75 \text{ mm} \times 20 \text{ mm}$, in a total of 180 ml of PCM *per* macrocapsule.

2.2 Heating Strategy

The experimental procedure consisted of subjecting the innovative PCM-RFS and the RFS_{Ref} to the same heating scenario. Both specimens were subjected to equally controlled conditions: the environment temperature imposed was controlled by the climatic chamber, and the temperature of the inlet supply water by a thermostatisation unit. The test procedure begins by installing each RFS specimen inside the climatic

chamber, with the sensors applied to the support structure. The climatic chamber is activated at that point, bringing environment temperature to the defined constant value of 7 °C. Once the temperature inside the climatic chamber stabilizes, the enclosure structure is assembled on the RFS test specimen and sealed, creating an indoor environment whose initial temperature (indoor and on the floor surface) is equal to the temperature of the chamber (ambient). The RFS specimen is then switched on and inlet water circulation begins, performing continuous heating until the temperature inside the enclosure reaches its maximum value. The system is then switched off, until indoor temperature equals ambient temperature once again, completely discharging the RFS. The inlet supply water temperature was fixed at 45 °C, and the water flow rate at 2 l min⁻¹.

3 Results and Discussion

The results of the RFS test specimens are presented and discussed in this section. The temperature profiles refer to the thermocouples positioned at the centre of each RFS setup, at the floor surface and at a height of 1.2 m. For a clear reading, the plotted results are: black series—RFS_{Ref}; and red dashed series—PCM-RFS. The results of the temperature profiles from the floor surfaces are presented in Fig. 1, and those corresponding to the indoor air temperature are revealed in Fig. 2.

The temperature profiles from Figs. 1 and 2, highlight the different performances of the two RFS specimens. As observed in Fig. 1, given the same test conditions, the RFS_{Ref} experienced a higher heating rate until reaching steady-state conditions presenting higher surface floor temperatures, reaching a maximum value of 30.40 °C. On the other hand, due to its characteristics the PCM-RFS have revealed lower heating rate until steady-state conditions, reaching a maximum surface floor temperature

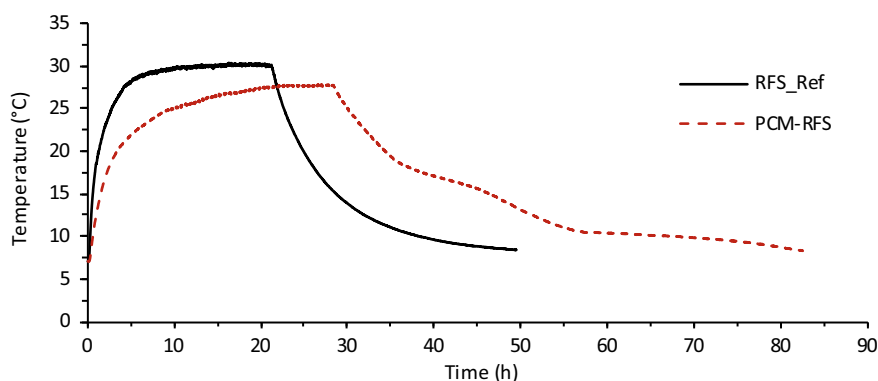


Fig. 1 Temperature profiles of the RFS specimens: thermocouple on the floor surface (central position)

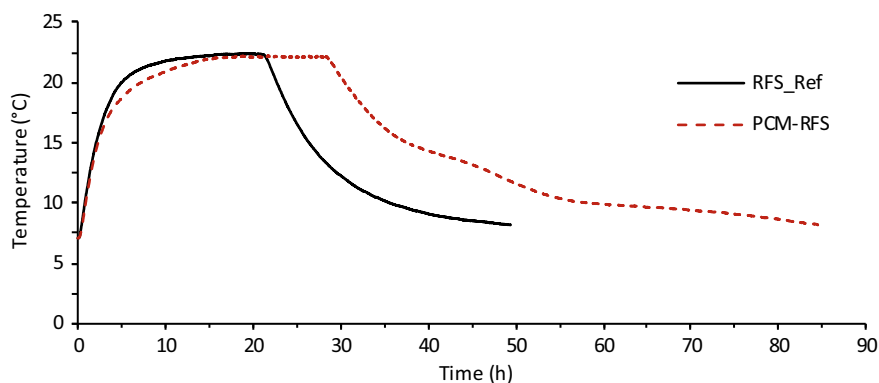


Fig. 2 Temperature profiles of the RFS specimens: indoor air temperature from thermocouple located at a height of 1.2 m (central position)

of 27.78 °C, highlighting the energy retention capacity of this RFS configuration. Furthermore, the discharge of thermal energy from the heat absorbed by the incorporated PCM at the temperature of 18 °C is clearly observed for approximately 9 h (from the 36th to the 45th hour of the test). Thus, the behaviour of PCM-RFS during cooling revealed a much smoother decrease in surface temperature than RFS_{Ref} , promoting thermal comfort.

In terms of the indoor air temperature performance exhibited in Fig. 2, the two specimens were able to achieve similar maximum values of 22.26 and 22.40 °C for the PCM-RFS and PCM_{Ref} , respectively. These results are evidence that, despite the lower heating rate and surface floor temperature, the PCM-RFS specimen is capable of reaching a maximum indoor air temperature similar to that of RFS_{Ref} , well within the thermal comfort range. It is noteworthy that the RFS_{Ref} takes 28.5 h after switched off to reach the set minimum temperature of approximately 7 °C, equalling the external ambient temperature. On the other hand, the PCM-RFS takes about 54 h (surface)-56 h (indoor air) to cool down from the steady-state equilibrium temperature to the defined minimum temperature of nearly 7 °C. This behaviour translates into a difference in thermal discharge time between the two RFS specimens ranging about 25.5 h–27.5 h, from the moment they are switched off until they reach equilibrium with the external environment conditions, highlighting the properties of the PCM-RFS as it is the one that took the longest to discharge.

As mentioned, the peak melting temperatures of the incorporated PCMs were selected to address different RFS operating conditions: 18 °C for cooling operation, and 28 °C for heating operation. However, it is clear from the results that both PCMs actively contributed for the improved thermal performance of the PCM-RFS in the studied heating scenario. Since the inlet supply water temperature was maintained at 45 °C and the maximum temperature of the surface floor was of 27.78 °C, the PCM with peak melting temperature of 28 °C was always being mobilized throughout the entire operating time of the PCM-RFS. This would have largely contributed to the

lower heating and cooling rate of this RFS configuration. However, the influence of the PCM with peak melting temperature of 18 °C is particularly evident after the PCM-RFS had been switched off, during the cooling phase of the experiment, resulting in c. 9 h of thermal energy discharge. This behaviour highlights the potential advantages of incorporating more than one PCM with different operating temperatures in the same RFS configuration, for operation in a cascade concept [17, 18]. The obtained results are in line with the literature. Cesari et al. [16] report the thermal storage capacity of the PCM incorporated in a comparable RFS configuration, as well as the ability to maintain a steady temperature for a period of time of about 9 h after the switching off of the system, due to the thermal discharge of the incorporated PCM.

4 Conclusions

This study puts forward a novel configuration for a RFS incorporating two macroencapsulated PCMs with different operating temperatures (peak melting temperatures of 18 and 28 °C). The objective was to evaluate the thermal performance of the proposed PCM-RFS large-scale configuration under controlled heating conditions using a climatic chamber, comparing the thermal results with a reference RFS. One of the main limitations of this research is the difficulties of testing additional operating strategies, such as alternative intermittent heating and cooling schedules, due to time constraints and restricted access to equipment, given the time-intensive nature of these experiments.

The test results showed that there is a clear difference in thermal behaviour between the two RFS specimens. Although the RFS_{Ref} specimen was able to reach a steady-state temperature at a higher rate, the PCM-RFS specimen showed far greater performance with a lower rate of temperature decrease, allowing for an extension of thermal comfort. Indoor air temperature profiles were similar between the two RFS specimens under heating operation, reaching a very close maximum temperature when in steady-state. A major difference is observed in the time required for temperature decrease between the two RFS specimens of 25.5 h–27.5 h, from the moment the RFS specimens are switched off until they reach equilibrium with the external environment conditions, a behaviour that highlight the advantages of the PCM-RFS as it was the specimen that took the longest.

Overall, the results obtained in this research indicate that the long-term benefits of incorporating different PCMs in the same RFS configuration are actually positive, in terms of thermal performance of the studied PCM-RFS. However, additional factors should be considered in future studies, such as the energy consumption of the RFS specimens. Future developments should include analysing the thermal performance of the novel PCM-RFS under different intermittent heating and cooling operation schedules. A numerical simulation model will also be developed to evaluate the impact of key parameters, such as the quantity of the incorporated PCMs

and different melting temperatures, on the thermal performance of the proposed PCM-RFS configuration.

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References

1. Lin T-Y, Chiu Y, Chen C-H, Ji L (2015) Renewable energy consumption efficiency, greenhouse gas emission efficiency, and climate change in Europe. *Geoenergy Sci Eng* 247:213665
2. Copernicus climate change service (C3S), European commission: global climate highlights (2024), <https://climate.copernicus.eu/copernicus-2024-first-year-exceed-15degc-above-pre-industrial-level>. Last accessed 20 Jan 2025
3. González-Torres M, Pérez-Lombard L, Coronel JF, Maestre IR, Yan D (2022) A review on buildings energy information: trends, end-uses, fuels and drivers. *Energy Rep* 8:626–637
4. Cornette JFP, Blondeau J (2024) Operational greenhouse gas emissions of various energy carriers for building heating. *Clean Energy Syst* 9:100148
5. Rhee KN, Olesen BW, Kim KW (2017) Ten questions about radiant heating and cooling systems. *Build Environ* 112:367–381
6. Rebelo F, Figueiredo A, Vicente R, Almeida RMSF, Ferreira VM (2023) Innovation and progress in the incorporation of phase change materials into radiant floor systems. *J Energy Storage* 74:109495
7. Rebelo F, Figueiredo A, Vicente R, Almeida RMSF, Ferreira VM (2024) Experimental analysis of a radiant floor system incorporating phase change materials: thermal performance and energy efficiency. *J Energy Storage* 102:114084
8. Babaharra O, Choukairy K, Hamdaoui S, Khallaki K, Hayani Mounir S (2022) Thermal behavior evaluation of a radiant floor heating system incorporates a microencapsulated phase change material. *Constr Build Mater* 330:127293
9. Heng W, Wang Z, Wu Y (2021) Experimental study on phase change heat storage floor coupled with air source heat pump heating system in a classroom. *Energy Build* 251:111352
10. Larwa B, Cesari S, Bottarelli M (2021) Study on thermal performance of a PCM enhanced hydronic radiant floor heating system. *Energy* 225:120245
11. Chen W, Liu Y, Liang X, Luo F, Liao T, Wang S, Gao X, Zhang Z, Fang Y (2023) Experimental and numerical investigations on radiant floor heating system integrated with macro-encapsulated phase change material. *Energy* 128375
12. Wang Z, Gao W, Gao Y (2025) Effect of the integration mode of phase change materials on thermal performance of radiant floor heating systems. *J Energy Storage* 110:115275
13. Wang Z, Gao W, Gao Y (2024) Influence of hot water pipe position on the performance of radiant floor heating systems integrated with PCM. *Case Stud Therm Eng* 61:105030
14. Qi D, Xie W, Zhao C, Song B, Li A (2023) Evaluation of the integrated performance for floor heating using micro-encapsulated phase change material slurry. *Renew Energy* 217:119169

15. Yuan P, Huang F, Duanmu L, Wang Z, Zheng H, Gao S, Zhu C, Dong G (2025) Experimental and theoretical study on thermal storage performance of sand-based thermal storage floor in rural areas, Inner Mongolia, China. *J Energy Storage* 106:114906
16. Cesari S, Bacciga E, Emmi G, Bottarelli M (2024) Enhancement of a radiant floor with a checkerboard pattern of two PCMs for heating and cooling: results of a real-scale monitoring campaign. *Appl Therm Eng* 246:122887
17. Gao T, Han X, Shi L, Geng Y, Zhang H, Song T (2024) Performance investigation of a solar-driven cascaded phase change heat storage cross-seasonal heating system for plateau applications. *Sci Rep* 14:20957
18. Yu Q, Sun B, Li C, Yan F, Li Y (2024) Analysis of heat charging and release processes in cascade phase change materials energy storage floor heating systems: Performance evaluation. *J Energy Storage* 78:110020

Portugal's New Building Renovation Plan: Advancing ELPRE for Sufficient Building Rehabilitation



Gabriela Barbosa and Joana Mourão

Abstract Portugal has aligned itself with the European Union's Renovation Wave, a key initiative under the European Green Deal, recognising the urgent need to decarbonise its building stock. With 75% of EU buildings classified as energy-inefficient, Portugal recognises the necessity to accelerate renovation rates to enhance energy performance and sustainability. In 2021, the country introduced the Long-Term Strategy for Building Renovation (ELPRE), a framework designed to rehabilitate residential buildings while addressing technical, financial, and regulatory barriers. Through targeted policies and incentives, ELPRE promotes energy efficiency, climate resilience, and affordability. It monitors key indicators, including primary energy consumption, renewable energy use, CO₂ emissions, and the area of renovated buildings. However, true sustainability extends beyond these factors. The European Green Deal advocates for climate-neutral buildings, considering operational energy, embodied energy (from materials and construction processes), and water efficiency. Therefore, additional indicators, such as embodied energy and water reuse, are essential for tracking progress and aligning with the revised Energy Performance of Buildings Directive (EPBD). The recast of the EPBD in 2024 requires EU member states to replace their existing long-term renovation strategies with National Building Renovation Plans (NBRPs), creating a more structured and ambitious approach to energy efficiency. This study critically assesses ELPRE and proposes key recommendations to strengthen building renovation and conversion efforts. It defines strategic goals for thermal comfort, operational and embodied energy efficiency, and water conservation, ensuring Portugal's alignment with evolving EU sustainability objectives while enhancing the resilience of its building sector.

Keywords Energy sufficiency · Building renovation · Public policies · ELPRE

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1 Introduction

The European Union (EU) has made building renovation a central focus of its European Green Deal, acknowledging that the built environment plays a crucial role in achieving climate neutrality by 2050. It is estimated that 85–95% of the buildings today will still be in use by that time [1]. Approximately 75% of the building stock in the EU is characterised by energy inefficiency [2], making the built environment a significant contributor to greenhouse gas emissions and increased energy consumption. Recognising this challenge, the European Union launched the Renovation Wave [1], a key initiative within the European Green Deal [3], to significantly increase renovation rates to improve energy efficiency and sustainability.

Portugal committed to this movement, understanding the need to decarbonise the building stock to meet climate goals and social needs. In 2021, the government introduced the Long-Term Strategy for Building Renovation (ELPRE), a framework designed to support the rehabilitation of residential buildings in an integrated and efficient way. This strategy aligns with EU directives and aims to overcome persistent barriers, including technical feasibility, financial constraints, and regulatory hurdles.

ELPRE has been instrumental in establishing key energy performance indicators and tracking metrics, including primary energy consumption, CO₂ emissions, and the proportion of renewable energy usage. However, an exclusive focus on operational energy efficiency is no longer sufficient. The broader challenge of sustainable renovation involves more than merely reducing energy consumption. It requires attention to critical aspects, such as embodied energy, which refers to the energy consumed in the production and transportation of building materials, considering a life-cycle approach. Additionally, water efficiency is a crucial factor for resource conservation, climate adaptation, and building adaptability, ensuring that buildings can be repurposed or upgraded efficiently over time.

The 2024 recast [4] of the Energy Performance of Buildings Directive (EPBD) introduced more ambitious strategies to enhance building energy efficiency. EU member states must now implement National Building Renovation Plans (NBRP), replacing the previous long-term strategy with a more structured and ambitious framework. This change necessitates a reassessment of ELPRE to ensure it aligns with the new European standards and embraces a broader, more forward-looking approach to sustainability, regeneration and resilience.

This study critically analyses ELPRE, systematically evaluating its strengths and limitations while proposing a more comprehensive framework for future building renovations in Portugal. The primary objectives are to assess the impact of ELPRE and identify areas where it may be deficient. The research advocates for introducing additional sustainability indicators that provide a deeper understanding of rehabilitation efforts and trends. Furthermore, it underscores the significance of incorporating embodied energy and water efficiency into sufficient building renovation strategies, ensuring that buildings are designed to minimise unnecessary energy consumption

before implementing efficiency measures. Lastly, it provides policy recommendations to guide Portugal towards a more effective NBRP, aligning with the new EPBD.

2 The Policy Framework for Building Renovation

In response to the urgent challenges posed by climate change, the European Green Deal seeks to achieve climate neutrality for the EU by 2050. It emphasises the importance of placing people at the heart of this transition, ensuring that the shift toward a sustainable economy is just and fair, leaving no one behind. One of the interim goals is to reduce net greenhouse gas emissions by at least 55% by 2030 compared to 1990 levels. Given that buildings account for 40% of the EU's energy consumption, the sector must aim for a 60% reduction in emissions and a 14% decrease in energy use compared to 2015. The Renovation Wave, a key initiative under the Green Deal, is crucial in making buildings more energy-efficient, less carbon-intensive throughout their life cycle, and more sustainable. Additionally, applying circular economy principles to renovation will help minimise materials-related greenhouse gas emissions and promote resource efficiency in the building sector. This strategy also aims to double the renovation rate while creating green jobs and ensuring improved living standards for all citizens.

To meet its decarbonisation objectives and facilitate the energy and economic transition, Portugal has approved the National Energy and Climate Plan 2030 (PNEC 2030). This plan outlines the goals and strategies for 2030, specifically aiming to reduce gas emissions and enhance energy efficiency by lowering primary energy consumption by 32.5%. Additionally, it seeks to increase the use of renewable energy sources, targeting a 47% share in gross final energy consumption. Regarding buildings, the PNEC 2030 outlines specific actions to reduce carbon intensity and promote the energy renovation of the building stock, with a primary focus on implementing the Nearly Zero Energy Buildings (NZEB) concept in constructing new buildings and retrofitting existing ones.

Portugal established a long-term strategy in 2021 to support the renovation (ELPRE) of the national stock of residential and non-residential public and private buildings by 2050. This strategy aims to convert the building stock into a decarbonised and highly energy-efficient one, facilitating the transformation of existing buildings into Nearly Zero Energy Buildings (NZEB) properties. It includes a roadmap with indicative measures and objectives for 2030, 2040, and 2050 and the respective goals to fulfil European energy efficiency and GHG emission reduction targets.

As outlined in the 2024 EPBD proposal, the current ELPRE will be replaced by a new NBRP introduced by May 2026.

3 Critical Review of ELPRE

The ELPRE initiative aimed to develop a long-term strategy for decarbonising and improving the energy efficiency of residential, public, and private buildings by 2050. Aligned with the European Green Deal and European Recovery Plan, it supports the Renovation Wave initiative, which seeks to increase the rate and quality of building renovations through targeted funding.

The strategy outlines specific measures and objectives for 2030, 2040, and 2050, in line with European targets for energy efficiency and greenhouse gas (GHG) reduction. Key interventions include enhancing building envelopes, upgrading energy systems, integrating renewable energy sources, and adopting advanced renovation technologies. ELPRE proposes financing programs, investment mobilisation, policy incentives, and effective market monitoring mechanisms to address market barriers.

By promoting circularity and resource efficiency, ELPRE intends to build renovations that contribute to environmental sustainability and long-term resilience.

The policies and initiatives outlined in ELPRE are structured around seven strategic lines of action, designed to effectively meet the established objectives.

1. **Building Renovation**—Establishing financial incentives to promote the energy renovation of buildings, with a strong emphasis on enhancing energy efficiency and sustainability, particularly in public structures.
2. **Smart Buildings**—Fostering research and technological innovation to enhance the intelligence and efficiency of buildings.
3. **Energy Regulation and Certification**—Strengthening standards and regulations, including product labelling and utilising energy certificates as financing tools and incentives within the rental market.
4. **Training and Professional Qualification**—Developing educational content to improve energy efficiency and sustainability professional training.
5. **Combating Energy Poverty**—To reduce energy costs for vulnerable households through financial incentives and tax benefits for housing renovations.
6. **Awareness and Information**—Implement educational campaigns and use information technologies to increase citizens' and businesses' awareness of the benefits of energy renovations.
7. **Monitoring and Evaluation**—Establish indicators and systems to monitor the strategy's progress and assess its impact on building energy efficiency.

The lines of action outline a comprehensive set of integrated policies to modernise the built environment. This initiative is guided by a national roadmap that sets clear objectives and progress indicators. Key monitoring metrics include primary energy consumption, renewable energy usage, CO₂ emissions, the extent of building renovations, and the number of hours of discomfort experienced.

Furthermore, there is a strong focus on enhancing comfort and well-being, ensuring access to healthy housing, and combating energy poverty [5]. Revitalising the construction sector is recognised as a strategic economic driver, promoting employment and raising awareness of sustainable building rehabilitation.

Transitioning to a circular economy is another key objective, including promoting sustainable construction through secondary raw materials and biological waste. This approach values environmental services to minimise reliance on non-renewable materials and encourages using alternative water sources, such as greywater and reused water. However, the indicators selected by ELPRE to measure energy renovation progress do not focus on these intentions (Table 1).

Additionally, prioritising the reduction of water consumption in buildings supports water conservation and lowers the energy demands associated with the urban water cycle. Unfortunately, this purpose is not reflected in the progress indicators due to a lack of data.

ELPRE encounters various limitations and challenges that span multiple dimensions, including technical feasibility, financial constraints, and regulatory barriers. Many property owners remain unaware of the benefits of energy efficiency, and access to reliable data regarding the current building stock is limited, complicating the planning of effective renovations. Financial barriers, including the high upfront costs associated with energy-efficient upgrades and the limited availability of accessible financing options, deter investment. Additionally, the scarcity of skilled professionals and the slow adoption of smart energy technologies further obstruct progress, particularly in older buildings. This issue is exacerbated by two-thirds of Portugal's building stock being constructed before any thermal regulations were established in 1990. According to the National Long-Term Strategy to Combat Energy Poverty for 2023–2050 [5] it is estimated that between 1.8 million and 3 million people are experiencing energy poverty. ELPRE aims to achieve primary energy savings and reduce the number of hours of discomfort in the home. Its coordination group produces progress reports and provides timely indicators; however, these do not fully reflect all the challenges and opportunities associated with building renovation and conversion. These related indicators and objectives can and should be complemented by others.

The ECO_HELPRE project, “Long-Term Strategy for the Rehabilitation, Renovation, and Reconversion of Buildings: Habitability, Energy, Materials, and Water,”

Table 1 ELPRE Objectives and Indicators

Objectives	Indicators
Objective 1: Primary energy savings	Percentage of primary energy consumption (%)
Objective 2: Local Renewable Energy	Percentage of local renewable energy (%)
Objective 3: Total Renewable Energy	Percentage of total renewable energy (%)
Objective 4: Reducing CO ₂ eq emissions	Percentage of reduction of CO ₂ emissions (%)
Objective 5: Area of renovated buildings	Area of renovated buildings (m ²)
Objective 6: Renovated buildings	Percentage of renovated buildings (%)
Objective 7: Hours of discomfort	Percentage of hours of thermal discomfort (%)
Objective 8: Investment	Investment in improvement measures (€/m ²)
Objective 9: Savings	Final energy savings (€/m ²)

in the context of science for policy call, aims to address some of these gaps by expanding the assessment framework to incorporate spatial-functional habitability, embodied energy, and material and water efficiency. By considering factors beyond operational energy use, it aims to promote a more sustainable approach to renovation. ECO_HELPRE is a project within the PlanApp portfolio that supports evidence-based policymaking. PlanApp, the Centre for Planning and Evaluation of Public Policies, fosters collaboration between researchers and policymakers. Its initiatives aim to institutionalise these relationships, enhancing engagement between the scientific community, government officials, and public administration professionals.

4 Expanding the Sustainability Scope: Key Additional Indicators

The increased recognition of responsible construction and renovation practices is transforming how we approach the entire life cycle of buildings—from raw material extraction to deconstruction or adaptive reuse. Sustainable construction methodologies must prioritise waste reduction, carbon emission minimisation, and ecosystem preservation for future generations [6]. This entails the integration of innovative materials, efficient resource management, and a thorough assessment of the environmental impacts throughout all phases, from construction to demolition.

The operational carbon refers to the emissions produced during use, including those from heating, cooling, and lighting. These emissions are expected to decline from 75 to 50% of the sector's total emissions over the next few decades. However, efforts to minimise “embodied” carbon emissions, those associated with the design and use of high-energy and carbon building materials like cement, steel, and aluminium, have not kept pace [7]. A holistic approach is needed to address the energy impacts of materials and construction processes, including the often-overlooked role of water-related building installations. Efficient water management, through improved supply, drainage, and wastewater systems, not only enhances climate resilience but also reduces energy consumption due to the water-energy nexus, making it a key component of sustainable building practices [8].

To effectively track the sustainability performance of building renovations, it is crucial to expand the current ELPRE indicators beyond just operational energy. Including indicators such as embodied energy, material circularity, and water efficiency provides a more comprehensive view of environmental impact. This broader perspective aligns with the European Commission's Level(s) framework, a voluntary reporting system that integrates life-cycle indicators into building performance assessment [9].

Several EU countries are already leading in this area. For instance, France's RE2020 regulation requires the inclusion of whole-life carbon indicators in new constructions. The Netherlands employs the TOTEM tool [10] to evaluate the

environmental impact of materials, while Finland incorporates life-cycle carbon assessments in public building renovations.

Regarding water efficiency, [8] highlight the significance of water-related building systems in enhancing climate resilience and supporting urban sustainability strategies. These examples underscore the need for NBRP to adopt similarly comprehensive assessment frameworks that capture building interventions' full environmental life-cycle impact.

Given these challenges, ELPRE, which is set to be replaced by NBRP, must incorporate measurable indicators that comprehensively address these sustainability concerns. Expanding the assessment framework to include embodied energy, material efficiency, water conservation, and circular economy principles is essential for fostering a sustainable construction and renovation approach.

5 Strategic Goals for Future Renovation Plans

The construction sector must adopt a forward-thinking strategy that reduces operational carbon emissions while prioritising life-cycle sustainability, resource efficiency, and climate resilience. By integrating these elements, NBRP can guide policymakers, researchers, and industry professionals in developing responsible and adaptable construction practices for a sustainable future. The NBRP requires each Member State to develop a strategy for transforming residential and non-residential public and private buildings into highly energy-efficient, decarbonised, and ultimately zero-emission structures by 2050.

The plan should include policies, an investment strategy, and emission thresholds for zero-emission buildings. It must establish energy performance standards for non-residential buildings, outline a renovation trajectory for residential buildings with 2030 and 2035 milestones, and provide evidence-based estimates of energy savings and benefits, such as improved indoor environmental quality. The mandatory indicators include the decarbonisation of heating and cooling, construction and demolition waste management, renewable energy in buildings, solar energy deployment, reduction of whole-life-cycle greenhouse gas emissions, integrated district-level renovation, public building improvements, smart technologies and sustainable mobility, addressing market barriers and failures, skills development and workforce training, awareness and advisory tools and promotion of modular and industrialised solutions for construction and building renovation.

However, to enhance the effectiveness of future renovation plans, the NBRP should enhance its indicator framework by incorporating metrics for embodied energy and water efficiency, thereby enabling a more thorough evaluation of sustainability impacts. By prioritising innovative approaches to energy rehabilitation, such as advanced insulation materials, high-performance building envelopes, and passive design strategies, the NBRP can significantly heighten energy efficiency while minimising operational carbon emissions. Furthermore, considerations for spatial and functional transformation should be emphasised, promoting adaptive reuse and

flexible building designs that extend the lifespan of structures and accommodate evolving needs. By integrating these strategies, while considering the specific conditions of the current national building stock, the NBRP can support more sustainable, resilient, and future-ready building renovation initiatives.

6 Conclusion and Future Directions

Portugal's new NBRP, extending the ELPRE initiative, marks a significant policy shift aligned with the European Green Deal's Renovation Wave. With 75% of the EU's building stock deemed energy inefficient, this plan is crucial for achieving climate neutrality and improving the energy performance of buildings, while extending their lifespan. Portugal's strategy within the European regulatory framework reflects its commitment to sustainable urban and building transformation.

Upon examining Portugal's residential building stock in need of rehabilitation, it becomes clear that energy renovations, such as improving the building envelope and installing heating and cooling equipment or renewable energy sources, may not be sufficient for reducing the overall impact on carbon emissions and housing sustainability goals. Given the country's low heating consumption and rising construction costs, operational energy savings alone may not be enough to incentivise building upgrades. On the contrary, if incentivised by public policy, embodied energy savings can become more relevant, motivating upgrades based on minimal intervention for maximal comfort and functionality.

Integrating spatial and functional improvements into energy renovations can create a more inclusive housing supply, addressing energy poverty and housing shortages. However, the current mandatory ELPRE indicators do not fully capture the complexity of rehabilitation needs. The effectiveness of this policy relies on introducing additional sustainability indicators that emphasise energy sufficiency while also considering resource demands and promoting overall human well-being within environmental limits.

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References

1. Renovation wave. https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficient-buildings/renovation-wave_en. Last accessed 14 Apr 2024
2. Estratégia de Longo Prazo para a Renovação dos Edifícios de Portugal (ELPRE PT). <https://www.dgeg.gov.pt/pt/areas-transversais/relacoes-internacionais/politica-energetica/estrategia-de-longo-prazo-para-a-renovacao-dos-edificios-de-portugal-elpre-pt/>. Last accessed 27 Nov 2023
3. European Green Deal. <https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52019DC0640>. Last accessed 18 Nov 2024
4. EPBD 2024/1275. <https://eur-lex.europa.eu/eli/dir/2024/1275/oj>. Last accessed 09 Dec 2024
5. ELPPE (2024)
6. Dipasquale L, Giuffrida G, Jorquera Silva N, Pulselli RM, Caponetto R (2025) Sustainable design of a tiny house: using a life cycle assessment approach to compare the environmental performance of industrial and earth-based building systems. *Buildings* 15:491. <https://doi.org/10.3390/buildings15030491>
7. UNEP, Architecture YC for E.+; Building materials and the climate: constructing a new future. United Nations Environment Programme (2023)
8. Pimentel-Rodrigues C, Silva-Afonso A (2019) Contributions of water-related building installations to urban strategies for mitigation and adaptation to face climate change. *Appl Sci* 9:3575. <https://doi.org/10.3390/app9173575>
9. Level(s)—European Commission. https://green-forum.ec.europa.eu/levels_en. Last accessed 25 Apr 2025
10. TOTEM: an online tool for architects that calculates the environmental footprint of buildings. <https://circulareconomy.europa.eu/platform/en/toolkits-guidelines/totem-online-tool-architects-calculates-environmental-footprint-buildings>. Last accessed 25 Apr 2025

Unlocking the Potential of Solar Renewable Energy Communities in an Urban District in Bari, Italy



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Abstract Supportive policies for energy sharing promote collective mechanisms within renewable energy communities (REC). Recent updates to the European renewable energy framework require Member States to revise incentive mechanisms, shaping new opportunities for collective self-consumption. In urban contexts, while residential functions dominate, mixed-use neighborhoods offer opportunities to integrate load patterns that can enhance the local use of renewable generation. The refinement of occupancy behaviour impact on simulations of energy demand and energy-sharing benefits. This study investigates the energy and financial viability of establishing a solar REC in an urban mixed-use district in Bari, Italy. The analysis considers archetypal residential, commercial, and service-sector buildings. Residential occupancy patterns by household types are defined from census data and time-use survey. Rooftop photovoltaic systems are simulated to meet part of the electricity demand, using self-consumption and self-sufficiency indicators. The energy-related and financial impacts of two collective self-consumption schemes—a multi-family housing models and a virtual energy-sharing model for the community—are compared. The results demonstrate that a solar REC enhances local self-consumption by 10% and self-sufficiency by 4% compared to the single-building scenario, matching different demand profiles. However, annual revenues from energy-sharing incentives remain limited for each member. The evaluation highlights the benefits of RECs supporting urban energy transitions and inform policy design for more effective energy-sharing frameworks.

Keywords Renewable energy communities · Occupants · Energy sharing · Self-consumption · Urban energy transition

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1 Introduction

The transition towards renewable generation has characterized energy policies in recent years, introducing new local forms of aggregations. The Directive n.2018/2001 (so-called RED II) [1] defined Renewable Energy Communities (RECs) as local configurations which foster renewable generation and self-consumption, reducing dependency on fossil fuels and generating social, economic and environmental benefits. European policies provide a framework for the integration of RECs, in which Member States need to identify financial incentives and supportive governance structures. From 2019, Italy has introduced legislative frameworks, economic incentives and potential business models for self-consumption both by multi-family buildings and RECs [2].

Effective REC planning requires representative Urban Building Energy Modelling (UBEM), which accounts for different energy patterns, particularly in urban areas where energy demand varies significantly [3]. Energy demand is influenced by building usages and, in residential case, by types of households and activity routines. One challenge at the urban scale is integrating the diversity of buildings with the same occupancy type and assessing its impact on realistic energy demand. In UBEM, databases of building archetypes are usually classified based on occupancy type, usages and construction properties. The common approach to model mixed-use districts is to couple building construction archetypes with deterministic space-based occupant behavior models, according to the building occupancy type [4]. However, variability in occupancy can be better represented through stochastic models, which estimate the likelihood of specific situations occurring [5]. Previous studies on urban-scale occupant behavior modeling have shown that stochastic approaches are preferable to deterministic ones when high-resolution temporal behavior and peak loads must be captured [6]. In applications focused on monthly or yearly energy consumption, the impact of human behavior may be negligible due to averaging effects at aggregated level [7].

A key challenge for implementing RECs within UBEM remains balancing the variability of energy demand—driven by building usage—with medium and large-scale feasibility studies [8]. Aggregated models and representative occupancy profiles can support district-level analyses while maintaining computational efficiency, helping policymakers and urban planners. The definition of energy flows directly affects the assessment of energy-related indicators, as self-consumption and self-sufficiency rates which need to be maximized in REC, and related benefits from energy sharing [9].

The aim of this paper is to assess the energy and financial-related benefits of a solar REC, integrating different household occupancy profiles into energy simulations. The evaluation redefines household schedules by integrating demographic data at census level and geometric building information. Based on the electricity demand and solar evaluations, the paper calculates the potential for a solar REC in an urban district in Bari, Italy, providing insights into maximizing self-consumption, reducing costs, and fostering community-driven energy transitions. Section 2 will explain

the methodology to define building types and occupancy schedules, from which electricity demand is calculated and related to solar potential. Section 3 will show the main results, then discussed in Sect. 4.

2 Methodology

The methodology consists of a workflow to assess the potential of an urban solar REC. The model includes the integration of household schedule profiles to refine the building energy demand. Rooftop photovoltaics (PV) is then assumed for each building. Simulations run on City Energy Analyst (CEA), which is open-source software classified as a bottom-up, physics-based UBE_M. CEA calculates energy balances of incoming radiation, external environment interaction, occupancy effects, supply, and HVAC systems by building. CEA offers a standard occupant presence and behavior schedules which are customizable, together with both deterministic and stochastic simulations. The building geometries are defined in a shapefile (.shp), containing the footprints and main geometry data, including heights, footprint area, number of floors. Data are collected and then geometries are enriched with information, based on the creation of construction archetypes by function. The construction details for apartment buildings and towers are derived from Tabula [10], while other functions assumed by on-site visits. The main construction parameters for each archetype are summarized in Table 1.

Schedule types are assigned to buildings based on their usage: residential, school, or tertiary. For household schedules, Fig. 1 summarizes the main steps for the elaboration of Time-Use Survey (TUS) [11] and ISTAT census data [12], defining household types, and randomly assigning them to residential buildings within each census section. The residential schedules are customized, based on the hourly probability of an activity. The TUS from ISTAT [11] is the primary dataset, consisting of 24 h time diaries recorded by approximately 20,000 families, totaling around 50,000 individuals. The diaries document the sequence of their activities (multiple aspects of

Table 1 Construction properties of each considered archetype, based on Tabula dataset on-site collection

Archetype	U-value (W/m ² K)				Heating system	WWR
	Wall	Roof	Floor	Window		
Apartment building	0.8; 0.65	0.75	0.98	3.7	NG heating system, with non-condensing boiler (centralized; $\eta = 85\%$)	0.15*
Tower	0.82; 0.76	0.76	0.97	3.7		0.17
School	0.75; 3.2	0.3	2.9	4.8	Radiators with medium-to-high T (70 °C supply, 55 °C return)	0.25
Tertiary	0.75; 3.2	0.3	2.9	4.8		0.25

WWR window to wall ratio
*except for blind perimetral walls

social and domestic life), giving the type, starting and ending time of each occurrence. Attributes distinguish day types (weekdays, Saturday and Sundays), size of household, type of income. Income can be salary from paid work or pensions/other allowances/benefits, from which working or retired households are assumed respectively. In order to calculate the probability (P) of occurrence of each activity from TUS of an average day, a binary matrix (0–1) is built for each hourly timestep. TUS activities are grouped based on whether they occur at home (occupancy) and their associated energy module, such as lighting, appliance usage, or domestic hot water (DHW). The hourly probability of an activity is then determined by summing all occurrences of that activity and dividing by the total number of occurrences in the given time step. The probability of each activity is obtained by each energy module. Then, the hourly P of an activity is calculated as the sum of occurrences of a specific activity out of the total occurrences in that time step. The new schedules are then assigned randomly to each residential building, based on geometric and demographic data. The assignment criteria are the number of employed/retired residents, the estimated number and type of households—disaggregated from ISTAT census [12]—matched with the average area per inhabitant ($\text{m}^2/\text{inh.}$).

Residential schedules substitute the default CEA schedules for each residential building, providing average weighted hourly probability (AWHP) for a representative weekday, Saturday, Sunday/holiday. The construction archetypes and the updated schedules allow to run the “Building energy demand” module, with hourly resolution.

The solar radiation is then assessed from DAYSIM, assuming a 0.25 albedo, and then the potential production from PV panels, assuming an optimized panel title angle

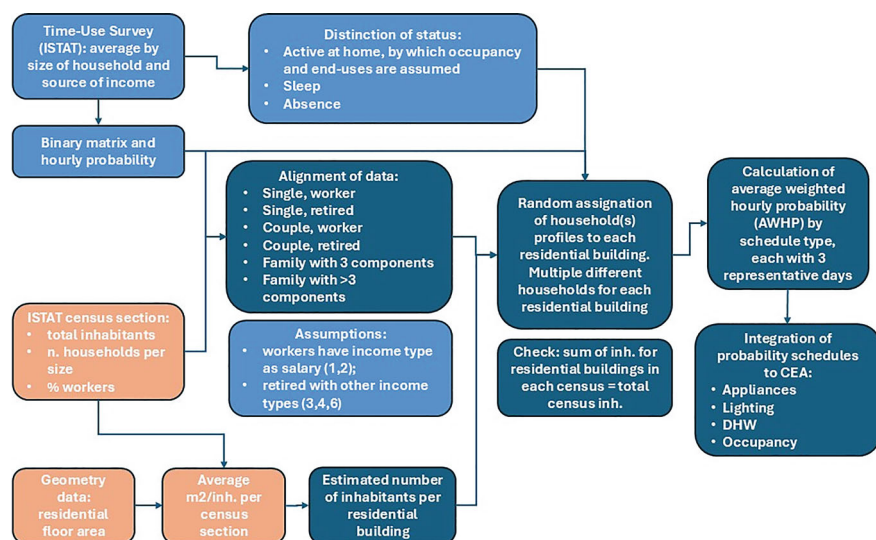


Fig. 1 Methodology to calculate the probability of occupancy by household types and assignment of household types from census to residential buildings. Steps focused on TUS are in light blue, on ISTAT building and census datasets in orange, in dark blue multiple elaboration

of 35° [13], 18% nominal efficiency and 45.1 °C nominal operating cell temperature and an annual radiation threshold of 1000 kWh/m²/y. CEA considers installing PV panels on roof surfaces that receive radiation above the defined threshold. The energy and financial analysis uses the hourly electricity demand and the PV generation. The indexes considered are self-consumption ratio (SCR, self-consumed PV production out of the total), self-sufficiency ratio (SSR, self-consumed PV production related to total energy demand) and collective self-consumption (CSC). CSC is the hourly minimum between total PV production and electricity consumption at the REC level. The first two can be calculated by single buildings and as a REC, while the second is the amount of shared generation among REC members. As a last step, the financial impact of the two scenarios is calculated, considering the price of the purchased electricity from the grid and of selling solar surplus to the grid with average zonal prices (*Ritiro Dedicato*, RiD). In both cases, tariff variations by month and by time band (on-peak, medium and off-peak) are included. For the REC scenario, a further incentive is applied to the hourly CSC. The incentive (*Tariffa Incentivante Premio*, TIP) is equal to 100 €/MWh, plus a tariff for transmission and distribution—similar to a reimbursement for avoided grid losses—set at 10.57 €/MWh and 0.65 €/MWh. The comparison does not include investment costs of solar panels, but only the energy and economic assessment of energy flows.

3 Results

The considered area is a mixed-use neighborhood in Bari, Italy. Bari is located in the temperate dried climate based on Köppen classification and in the Italian climate zone C, with a standard 1034 HDDs and heating season from November 15 to March 31. The average annual solar radiation is about 1634 kWh/m². The area (Fig. 2) includes 117 buildings, distributed among eight census sections. Based on 2021 ISTAT data [12], the total population is 3943 inhabitants and 1487 households. Tower residential buildings have on average 11 floors and 402 m² footprint, while apartment buildings 9 floors and 266 m² footprint area. The schools and other tertiary buildings occupy respectively 5.4% and 0.6% of the total floor area.

The construction properties and energy system are then assigned, based on the archetypes previously defined. Schedules are adapted to the Italian holiday calendar for non-residential, considering week closures during January, July, August and December for schools and January, August and December for other tertiary functions. Regarding residential, different household schedules have been randomly assigned to tower and multi-apartment buildings, based on their floor area and census features. Figure 3 shows the hourly probability of occupant presence in residential buildings for the six representative households and without distinguishing household types, based on the TUS analysis for one weekday, Saturday and Sunday. The hourly values show that the variability of occupancy probabilities is not represented by only one comprehensive profile (dark red dotted line). Trends show higher probability on Sundays compared to weekdays, having higher values for retired households and



Fig. 2 Buildings by usages for the considered mixed-use district in Bari, Italy

lower for workers. Working couples and families with more than three members have similar profiles, as well as retired singles and couples. Occupancy schedules then impact on the lighting, appliances, heating–cooling and DHW schedules. The assigned schedules to each residential building are then averaged and used to calculate the electricity demand. The assessed electricity demand is 6.2 GWh and the PV production is 2.8 GWh for the whole district, having a total installed PV is 19,899 m² and about 3316 kWp.

The first scenario assumes solar use by single buildings, or rather PV generation needs to be consumed in the same hourly step and cannot be shared with other buildings. In this scenario, the total PV self-consumption by single buildings is equal to 2.1 GWh, which leads to 0.84 SCR and 0.24 SSR when calculated the average hourly value for the whole year. The SSR ratio goes from 0.10 to 0.42 for two

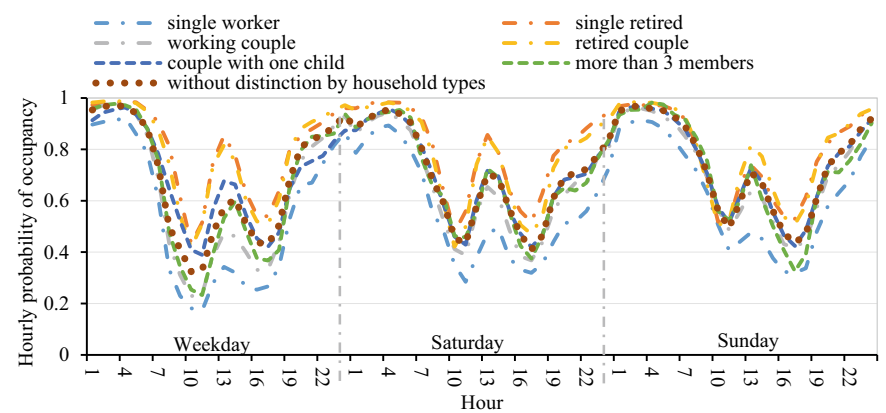


Fig. 3 Hourly probability of occupant presence for each household type for weekday, Saturday and Sunday/holidays, based on the elaboration from TUS

Table 2 Comparison of scenarios for electricity costs (€), generated revenues (€), self-consumed solar generation (MWh) and solar surplus sent to the grid (MWh)

	BAU scenario	Scenario by single building	Scenario with REC
Electricity costs	703,119	471,177	434,777
Revenues	–	58,743	95,389
Self-consumed solar production (MWh)	–	2133	2466
Solar surplus to the grid (MWh)	–	644	311

residential towers, while SCR ranges from 0.29 for one school to 1 for five residential buildings. Despite consistent self-consumption, a solar surplus is available which can be exploited at the community level. Shifting to a REC scenario allows to have energy sharing among users. Therefore, the simulation moves to self-consumption at the single building level to CSC at the community level. The annual CSC is equal to 333,141 kWh, which allows the REC to reach 0.28 SSR and 0.94 SCR. However, an annual surplus equal to 311,146 kWh is still unused, with a peak in May. Therefore, a mechanism should be applied to redistribute the revenues generated from CSC, which are equal to 36,645 €, and from surplus revenues. A financial comparison is provided in Table 2, which shows the main energy-related results, self-consumed production and surplus, with the related financial results, namely electricity costs and generated revenues, for the three scenarios. The business-as-usual (BAU) scenario without PV installation implies energy costs equal to 703 k € for the whole district, which can be reduced by 33% with self-consumption by single buildings and by 38% assuming a solar REC. Apart from savings, the two scenarios can generate revenues: the former creates 59 k€ from hourly surplus generated by single buildings and sold to the grid with RiD, while the latter 69 k€ from CSC (RiD + TIP) and 26 k€ from still available surplus. Therefore, the REC scenario generates 38% higher revenues than the single-building one, which can then be shared among community members. However, equal redistribution will generate limited revenues for each member, generally lower than 15 €/y.

4 Discussion

The aim of the paper is to assess a solar-based renewable energy community for an urban district, redefining the variability of household profiles in the assessment. The case study was a mixed-use district in Bari, Italy. The elaboration of schedule profiles for different household types highlighted variability in occupancy and related end-uses, which then impacted the energy demand for each residential building. For instance, single workers are more likely to be absent from home during weekdays compared to retired households, leading to lower occupancy probabilities and

reduced lighting consumption under the given assumptions. This appears in line with trends of other occupancy profiles, as the ones developed by Bottaccioli et al. [14] for Turin by family size and Osman et al. [5] for Canada by family size and occupation.

Using the redefined occupancy schedules assigned to each residential building, energy demand simulations were performed, followed by a PV performance assessment. Results highlighted significant advantages of transitioning from a business-as-usual scenario to a REC configuration in terms of both self-consumption and financial benefits. Shifting from single-building to a community-based approach allowed for shared solar energy, derived from the hourly surplus of single buildings, and higher solar self-consumption ratio, reaching 0.94 at the district level. The high SCR can be related to the prevalence of mid- and high-rise residential buildings, which have high demand and a limited installable PV surface on their rooftops. The results are consistent with previous studies on solar-based energy communities in terms of SCR and SSR. Schiera et al. [9] found that energy sharing within condominiums results in SCR above 0.5 and SSR above 0.2 for most of buildings. Mehta and Tiefenbeck [15] demonstrated that energy performance is influenced by the prosumer ratio and PV system size; however, being a residential-only communities, the SSR rarely exceeds 37.8% and the SCR 56%. For mixed-use cases, Viti et al. [16] assessed that SSR increased from 36 to 45.3% and SCR from 69.6 to 87.5% shifting from single self-consumers buildings to a REC. Results show a discrepancy of approximately 5% compared to our findings, primarily due to the composition of the community, which is characterized by high-rise buildings.

Energy-related improvement translates into greater financial savings, reducing electricity costs by 38% compared to BAU scenario and increasing revenue by 38% more than the single-building scenario. Savings are in line with values between decentralized and centralized configurations presented by [17]. However, an annual solar surplus equal to 11% of the total PV production remains unused, suggesting the need for further optimization strategies, such as storage solutions or demand-side management. The application of energy remuneration schemes which can reflect the variability of solar production and energy prices would also test the financial viability of urban solar RECs.

5 Conclusions

The decentralization of energy production is calling for new configurations to produce and share renewable generation locally. This study assessed solar-based integration for a mixed-use district, considering the shift of energy management from single-building to community scenarios. The redefinition of residential schedules was integrated into modelling to involve demand variability. REC implies an increase in local use of energy generation due to hourly collective self-consumption, rising SSR from 0.24 to 0.28 and especially SCR from 0.84 to 0.94. The REC scenario provides 38% savings in annual energy costs compared to the single-building one. Results are in

line with outcomes from other studies, even if community composition plays a key role.

Limitations can be identified in the assumed approach. The definition of schedules by representative days relied on deterministic models based on household routines, retrieved from a national time-use survey. Future work should move from annual to seasonal schedules, to enhance occupancy variability and hourly variation of energy demand by keeping reasonable computational efforts. The refinement of hourly energy demand would also impact on the assessment of self-sufficiency and self-consumption at single-building and community levels. The evaluation of PV assumed areas receiving at least 1000 kWh/m² annual solar radiation, while a further step can be the optimization of roof coverage. While the REC model enhances financial returns, the equal redistribution of revenues results in relatively low individual economic benefits, which should favor the aggregated use of these financial returns for the community itself. Overall, findings showed the potential of RECs to maximize local renewable energy use but also highlighted the need for more detailed user-centered assessments and complementary measures to improve energy matching and economic attractiveness of projects. Future research should delve into the link between occupant behaviors of REC members with related energy and economic performance. Assessments can support energy schemes in future REC policies. Beyond the energy systems themselves, the implementation of RECs involves other important challenges, such as the need for dedicated energy managers, coordination efforts, as well as handling administrative procedures and setup costs not considered in this study. Organizational and governance aspects are closely tied to the type of legal entity the community chooses to form—be it a cooperative, association, or non-profit organization—which, in turn, influences the management of energy and financial flows within the community.

References

1. European Commission, Proposal for a Directive of the European Parliament and of the Council amending Directive (EU) 2018/2001
2. Cielo A, Margiaria P, Lazzaroni P, Mariuzzo I, Repetto M (2021) Renewable energy communities business models under the 2020 Italian regulation. *J Clean Prod* 316:128217
3. Hachem-Vermette C, Singh K (2019) Optimization of the mixture of building types in a neighborhood and their energy and environmental performance. *Energy Build* 204:109499
4. Happle G, Fonseca JA, Schlueter A (2018) A review on occupant behavior in urban building energy models. *Energy Build* 174:276–292
5. Osman M, Ouf M, Azar E, Dong B (2023) Stochastic bottom-up load profile generator for Canadian households' electricity demand. *Build Environ* 241(8):110490
6. Evins R, Orehounig K, Dorer V (2016) Variability between domestic buildings: the impact on energy use. *J Build Perform Simul* 9(2):162–175
7. He M, Lee T, Taylor S, Firth SK, Lomas K (2015) Coupling a stochastic occupancy model to Energy Plus to predict hourly thermal demand of a neighbourhood. In: 14th International conference of IBPSA—building simulation 2015, Hyderabad, India, pp 2101–2108
8. Vecchi F, Stasi R, Berardi U (2024) Modelling tools for the assessment of renewable energy communities. *Energy Rep* 11:3941–3962

9. Schiera DS, Minuto FD, Bottaccioli L, Borchellini R, Lanzini A (2019) Analysis of rooftop photovoltaics diffusion in energy community buildings by a novel GIS- and agent-based modeling co-simulation platform. *IEEE Access* 7:93404–93432
10. Episcopo. Tabula web tool. <https://episcopo.eu/building-typology/tabula-webtool/>. Last accessed 11 Mar 2025
11. ISTAT Multipurpose survey on households: aspects of daily life—microdata for research purposes. <https://www.istat.it/en/microdata/multipurpose-survey-on-households-aspects-of-daily-life/>. Last accessed 26 Jan 2025
12. ISTAT Data by census. <https://www.istat.it/en/data/databases/>. Last accessed 05 Mar 2025
13. EU PVGIS. https://re.jrc.ec.europa.eu/pvg_tools/en/. Last accessed 10 Mar 2025
14. Bottaccioli L, Di Cataldo S, Acquaviva A, Patti E (2019) Realistic multi-scale modeling of household electricity behaviors. *IEEE Access* 7:2467–2489
15. Mehta P, Tiefenbeck V (2022) Solar PV sharing in urban energy communities: Impact of community configurations on profitability, autonomy and the electric grid. *Sustain Cities Soc* 87:104178
16. Viti S, Lanzini A, Minuto FD, Caldera M, Borchellini R (2020) Techno-economic comparison of buildings acting as Single-Self Consumers or as energy community through multiple economic scenarios. *Sustain Cities Soc* 61:102342
17. Aghamolaei R, Shamsi MH, O'Donnell J (2020) Feasibility analysis of community-based PV systems for residential districts: a comparison of on-site centralized and distributed PV installations. *Renew Energy* 157:793–808

Balancing Energy Efficiency and Aesthetics: Generative Design for Sustainable Architecture



Susanne Wiese, Andrei Lobov, and Ciara Bertolin

Abstract The building and construction sector is a major contributor to global energy demand and carbon emissions, highlighting the growing need for energy-efficient buildings. Simultaneously, the industry is undergoing a significant transformation, driven by increasing demands for digitalization and standardized practices. As AI and digital tools are advancing at an unprecedented pace, there is a risk of losing the vital connection between buildings and human well-being. This paper explores how generative algorithms can address these challenges by balancing technical optimization, such as energy efficiency, with aesthetic principles. The generative design tool developed, called *Daedalus*, seamlessly integrates with industry workflows, producing Industry Foundation Classes (IFC)—compliant buildings for Building Information Modeling (BIM) standards. The methodology combines site-specific constraints, multi-objective fitness functions and aesthetic parameters while focusing on computational extensibility. This allows for flexible exploration of diverse building configurations, optimizing multiple objectives to detect energy efficient building shapes in terms of orientation, compactness, natural light, and passive climatization. By incorporating the golden ratio and symmetry, the paper investigates a novel approach for generating aesthetic designs. The results demonstrate the tool's ability to produce varied, site-responsive designs that align with both environmental and design goals. The algorithm is extendable and flexible for further development. *Daedalus* is designed for both single buildings and ensembles; however, it can be extended for larger urban developments. This work demonstrates how generative design can be utilized to explore energy efficient building shapes. The results contribute to the development of sustainable buildings from the early design stage, providing a robust framework for future research and practical applications in the workflows of tomorrow's building projects.

Keywords Generative design · Genetic algorithm · BIM · IFC · AEC-industry · Energy-efficient buildings · Golden ratio

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1 Introduction

The demand for indoor comfort significantly contributes to the building sector's energy consumption, with heating, cooling, and lighting systems accounting for a substantial portion of this demand. In response, researchers have explored numerous strategies to optimize building designs for energy efficiency while maintaining comfort and functionality. Optimizing building shape enhances energy performance by affecting compactness, natural lighting, and solar gain. Catalina, Virgone, and Irodache demonstrated how the building's relative compactness (R_c) affects the total energy consumption [1]. The R_c metric compares a building's volume-to-surface area ratio to that of the most compact shape with the same volume, typically a cube. Although a cubic form is energy-efficient due to minimal heat loss, it can compromise daylight access and increase reliance on artificial lighting, especially in offices. Nguyen emphasized in [2] the role of strategic window placement in improving energy efficiency and indoor temperature regulation. In colder climates, such as Finland, aligning a building's longitudinal axis east–west with primary living spaces facing south maximizes solar gains during winter months. Living spaces can act as passive solar collectors, with thermal mass in floors and walls absorbing 60–75% of solar energy entering through windows [2]. Beyond energy efficiency, adequate natural light positively impacts occupants' psychological well-being, enhancing productivity and reducing the risk of depression [3, 4].

Balancing technical optimization with human-centered design is crucial in creating spaces that are not only functional, but also inspiring and harmonious. Yan et al. highlighted this challenge in [5], noting that advanced design tools such as Multi-Objective Optimization (MOO) and building modeling technologies are often underutilized in architectural practice due to their limited integration of qualitative factors like aesthetics. The aesthetic perception of building shapes has been a long-standing concern in architecture, dating back to Vitruvius' *De Architectura* (*Ten Books on Architecture*) [6]. Vitruvius advocated for harmony and proportion, principles echoed by Leonardo da Vinci's Vitruvian Man [7] and further developed by Le Corbusier in his Modulor system [8]. The Modulor applies human proportions and the golden ratio ($GR \approx 1.618$), to architecture, as seen in *Unité d'Habitation* in Marseille where its standardization and efficiency remain relevant today.

In modern architectural practice, these classical principles must be integrated within advanced digital processes. Building Information Modeling (BIM) has become a pivotal tool in this context, enabling architects and engineers to visualize, analyze, and coordinate building designs throughout the entire project lifecycle. BIM creates and manages multi-dimensional, data-rich representations of buildings, incorporating geometric, spatial, and semantic information. It is governed by international standards such as ISO 19650 [9], which ensure best practices for information management and support the architecture, engineering, and construction (AEC) sector's digital transformation. In parallel, optimization techniques such as Genetic Algorithms (GAs) have been increasingly applied to enhance building energy efficiency [10]. The construction sector accounts for 34% of global energy demand, mainly from

heating and cooling [11], highlighting the urgent need for sustainable design strategies. Decisions made in the early design phases are critical for maximizing sustainability outcomes, yet achieving this optimization involves balancing numerous design variables and performance objectives [12]. GA offer a powerful solution to this challenge by optimizing designs, mimicking natural selection, and efficiently exploring large design spaces to balance functionality and constraints. While Single-Objective Genetic Algorithms (SOGAs) focus on optimizing a single criterion, Multi-Objective Genetic Algorithms (MOGAs) can handle multiple conflicting objectives simultaneously. Yan et al. proposed a MOO approach in [5], using a weighted sum function to balance multiple design objectives.

This study aims to integrate BIM with a GA to develop a holistic approach to building design that enhances energy efficiency, occupant comfort, and architectural aesthetics, particularly for buildings in northern climates. This research develops the *Daedalus* algorithm, a computational tool for generating building shapes in early design phase. Unlike previous studies focusing on abstract forms, this study integrates generative design into architectural workflows by producing BIM models via IFC files.

2 Methodology

In the *Daedalus* Algorithm, a GA uses seven weighted fitness functions as reported in Table 1. The GA process involves initializing a population of potential solutions, evaluating them using a fitness function, and refining them through selection, crossover, and mutation as shown in Fig. 1. The algorithm initializes a population based on input parameters such as the target gross floor area (GFA), site dimensions, and building height limit, along with genetic parameters including population size, number of generations, and mutation rate.

In the initialization process the algorithm uses the input parameters as constraints as well as aesthetic constraints which is defined by using the GR inspired by the Modulor system. As shown in Fig. 2, the width and length are generated using the GR, with randomness in the choice of the number of n . This ensures that dimensions are not predefined by the programmer, however constrained within site limits and aligned with the aesthetic proportions and harmony. Similarly, the roof dimensions are constrained, with a maximum height of GR3 and an overhang extending up to GR⁶. In this case, the exponents are predefined; however, they can be easily adjusted to accommodate legislation or climate requirements. As shown in Fig. 1, once a building design is initialized, it is evaluated based on the weighted sum of the fitness functions shown in Table 1. If there are several buildings, the fitness contributions are divided by the number of buildings.

Table 1 Overview and description of all the fitness functions used in the GA

Fitness	Symbol	Formula	Explanation
Compactness	f_c	$\frac{A_{Surface\ Cube}}{A_{Surface\ Building}}$	Building shape compactness
Window to wall ratio	f_{ww}	$\frac{A_{Window}}{A_{Wall}}$	Ratio of window to wall area
Green space	f_{gs}	$min < ifgreenspace < max$	Evaluates compliance with green space target
Number of buildings	f_{nb}	$if\ number\ of\ buildings = target\ number\ of\ buildings$	Conformity checks to target number of buildings
Photovoltaic panels	f_{pv}	$\frac{A_{PV}}{A_{Roof}}$	Ratio of PV panels to roof area
Gross floor area	f_{GFA}	$\frac{A_{GFA}}{A_{Target\ GFA}}$	Target GFA alignment measure
Similarity	f_s	$\frac{Similarity_{Area} + Similarity_{Height}}{2}$	Multiple buildings similarity measure
Total fitness	f	$\sum f_i * w_i$	The total weighted sum

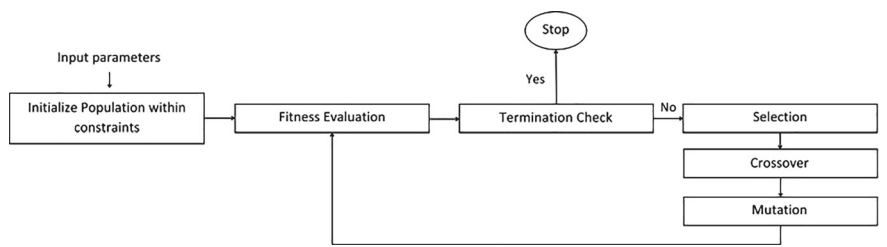
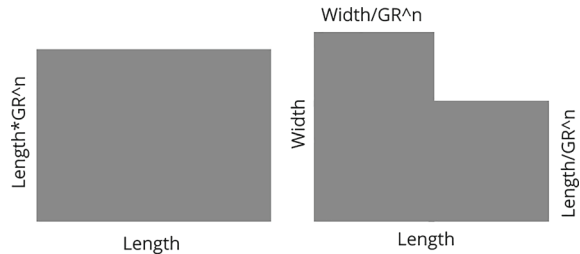


Fig. 1 Flowchart of the iterative process of the algorithm

Fig. 2 Illustration of how the dimensions of a rectangular and L-shaped building are determined by the GA during initialization



3 Results and Discussion

The Daedalus algorithm is designed to generate IFC-compliant building models while optimizing energy efficiency and key architectural parameters using a GA. The UML class diagram reported in Fig. 3 illustrates the program structure, showcasing its core components and their interactions. Daedalus integrates a GA to iteratively refine design solutions based on the constraints described and optimization objectives shown in Table 1. The Building Composer then uses the optimized parameters from the GA to generate IFC files for visualization and compatibility with BIM. The IFC files are generated with python using the *IFCOpenShell* library [13]. The open-source library creates IFC files by initializing a project hierarchy, including project, body, context and site. Each element (e.g., wall, floor, window) is assigned a name and class. As shown, the BuildingComposer can construct three types of roofs and is currently limited to a rectangular site and windows. Nevertheless, Daedalus is designed to be extendable for new classes such as shapes, windows and roofs.

Tests were conducted using both equal and varied weight distributions of the fitness functions. When testing the algorithm with equal weighting ($w_i = 1/7$), results show that after many generations, the output converges to a building number equal to one. This indicates that the fitness for green space (f_{gs}) tends to dominate over the fitness for the ideal number of buildings (f_{nb}). Limited research exists on generating

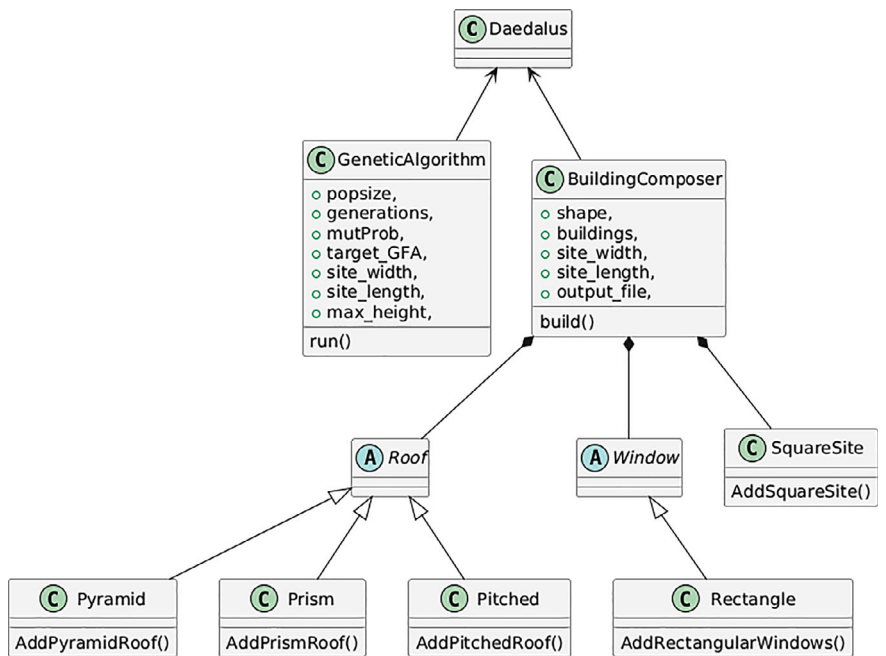


Fig. 3 UML class diagram describing the Daedalus Algorithm

Table 2 The revised weighting for the fitness functions used in the test results

Fitness functions (f_i)	Assigned weighting (w_i)
Compactness (f_c)	0.05
Window to wall ratio (f_{ww})	0.2
Green Space (f_{gs})	0.05
Number of buildings (f_{nb})	0.2
Photovoltaic panels (f_{pv})	0.1
Gross floor area (f_{GFA})	0.3
Similarity (f_s)	0.1

multiple interconnected buildings that harmoniously align in design, functionality, and integration with the urban context. Especially when both considering the optimization of the single buildings and the connection between them. However, for *Daedalus*, optimization is applied not only to individual buildings but to the interplay between buildings. This requirement introduces a significant layer of complexity to the algorithm. When testing the algorithm with a low weight assigned to fitness for similarity (f_s), the output resulted in one very large building and one very small building to maximize the fitness score for number of buildings (f_{nb}). Therefore, it is crucial to assign a sufficiently high weight to fitness for similarity if the goal is to achieve relatively similar volumes for all buildings. The fitness for compactness (f_c) consistently performs better, showing high values even after few iterations. The fitness for green space (f_{gs}), however, can conflict with the fitness for target GFA (f_{GFA}). To address these challenges, variations in the weighting of the fitness functions have been explored. Through multiple adjustments and subsequent observations, an example of a weight distribution that yields high fitness scores and good results has been identified and is shown in Table 2. Figure 4 presents selected test results using the fitness function weighting from Table 2.

The results demonstrate that *Daedalus* generates diverse building designs, influenced by the weighting of the fitness functions and GA parameters as well as by the site constraints, target GFA and maximum height. An analysis of the total fitness scores suggests that a population size of 400 with 4000 generations may be sufficient, as these parameters yield the highest observed fitness values. In general, the total fitness scores indicates that *Daedalus* achieves rapid convergence with a low number of iterations and minimal computational power. A larger number of iterations may therefore not be needed. At the actual stage of *Daedalus* development, the green space fitness function may be too strict or may not significantly contribute to the algorithm efficiency, even with different weightings. In fact, with a high f_{gs} weighting, the algorithm consistently generates a single building to optimize exclusively the green space while neglecting a rational number of buildings. With the weighting reported in Table 2, it can be observed in Fig. 4 that f_{gs} consistently equals zero. Therefore, further research and development of *Daedalus* could either disregard this fitness contribution or refine its calculation to better account for the distribution of outdoor spaces. Last, an observation of the fourth row from the top, in Fig. 4, shows

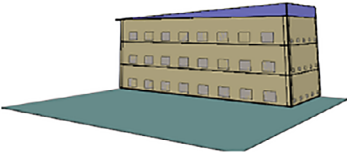
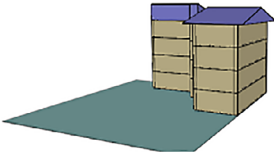
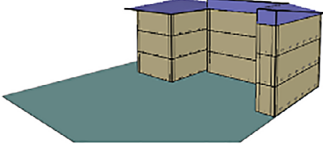
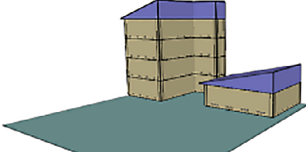
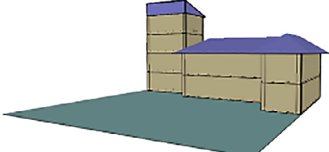
Population Size = 20 Generations = 200 Mutation Rate = 0.1		$f_c = 0.046$ $f_{WW} = 0.086$ $f_{gs} = 0.000$ $f_{nb} = 0.075$ $f_{PV} = 0.074$ $f_{GFA} = 0.162$ $f_s = 0.100$ $f = 0.543$
Population Size = 20 Generations = 2000 Mutation Rate = 0.1		$f_c = 0.047$ $f_{WW} = 0.018$ $f_{gs} = 0.000$ $f_{nb} = 0.150$ $f_{PV} = 0.078$ $f_{GFA} = 0.189$ $f_s = 0.108$ $f = 0.590$
Population Size = 200 Generations = 2000 Mutation Rate = 0.1		$f_c = 0.045$ $f_{WW} = 0.022$ $f_{gs} = 0.000$ $f_{nb} = 0.150$ $f_{PV} = 0.000$ $f_{GFA} = 0.200$ $f_s = 0.200$ $f = 0.617$
Population Size = 400 Generations = 4000 Mutation Rate = 0.1		$f_c = 0.050$ $f_{WW} = 0.019$ $f_{gs} = 0.000$ $f_{nb} = 0.150$ $f_{PV} = 0.079$ $f_{GFA} = 0.197$ $f_s = 0.171$ $f = 0.666$
Population Size = 500 Generations = 5000 Mutation Rate = 0.1		$f_c = 0.050$ $f_{WW} = 0.019$ $f_{gs} = 0.000$ $f_{nb} = 0.150$ $f_{PV} = 0.076$ $f_{GFA} = 0.194$ $f_s = 0.103$ $f = 0.592$

Fig. 4 Results from the Daedalus algorithm using the revised weighting as reported in Table 2

that placing solar PV panels on the roof of the low-rise structure, within the shadow of the tallest building, affects the energy production potential. Therefore, integrating input from a shadow analysis could further optimize the constraints for PV panel placement.

4 Conclusion

The demand for energy-efficient buildings is increasing as the building sector is responsible for a significant share of global CO₂ emissions. To address this issue, previous research has explored the use of Genetic Algorithms to optimize building designs for energy efficiency. However, the application of generative design in this

context often lacks aesthetic integration and seamless integration with BIM workflows, making the procedure less suitable for real-world scenarios. This study developed Daedalus; a Genetic Algorithm for exploring energy-efficient buildings design considering aesthetic proportions. This approach aligns innovative design methods with real world implementation requirements. The Daedalus ability of generating IFC files ensures compatibility with current BIM standards, facilitating practical implementation and collaboration. The approach prioritizes exploration over rigid constraints, allowing for a diverse range of potential solutions. The results show that the tool provides a flexible framework for creating diverse building shapes tailored to specific site conditions. Daedalus is designed to be expandable and adaptable for future advancements by allowing fitness functions to be added or removed, adjusting weightings based on case studies or simulations, and conducting validation tests. This flexibility fosters further development of its potential, enabling it to generate even more diverse outputs, such as various roof types and shapes. Another way to increase the program's design variability is by introducing a hierarchical structure with multiple floor levels per building. Each floor level could have distinct attributes such as height, width, length, and floor plan layout or mixed-use in the building, allowing for more complex architectural designs. In addition, the alignment of the floor plan with the window placement is crucial as well since the program prioritizes larger glazing on the south, east, and west facades, the layout can be adjusted accordingly.

Future development could address the limitation of using a single type of window across the entire facade by enabling the incorporation of multiple window types and sizes. Such enhancements would result in facades that are more dynamic, visually engaging, and aesthetically pleasing. Further, the optimization process for installation location of PV panels can be further refined by avoiding their placement in the shadow of buildings assets generation.

References

1. Catalina T, Virgone J, Iordache V (2011) Impact of building form on energy consumption. In: Building simulation 2011: 12th conference of IBPSA, Sydney, pp 1726–1729
2. Nguyen H (2019) Passive houses in cold climates: overview for homeowners and architects. Metropolia University of Applied Sciences
3. Harb F, Martau B, Hidalgo MP (2015) Lack of natural light at work linked to sleep and depressive symptoms. *Chronobiol Int* 32(3):368–375
4. Bertani DE et al (2021) Shedding light on light: a review on the effects on mental health of exposure to optical radiation. *Int J Environ Res Public Health* 18(4):1670
5. Yan W et al (2015) Multi-objective optimization for sustainable buildings. In: Sustainable human-building ecosystems. ASCE, pp 223–230
6. Pollio V (1999) The ten books on architecture, Howe TN, Rowland ID (eds). Cambridge University Press, New York
7. Da Vinci L (2025) Vitruvian Man. Photograph by Luc Viatour, Meisterdrucke. Available at: <https://www.meisterdrucke.uk/fine-art-prints/Leonardo-da-Vinci/16747/Vitruvian-Man.html>. Last accessed 11 Mar 2025
8. Ostwald MJ (2001) Le Corbusier, The modulator and modulator 2. *Nexus Netw J* 3(1):145–148

9. ISO: ISO 19650-1:2018—Information management using BIM. <https://www.iso.org/standard/68078.html>. Last accessed 11 Mar 2025
10. Fesanghary M, Asadi S, Geem ZW (2012) Low-emission residential design via multi-objective optimization. *Build Environ* 49(1):245–250
11. UN Environment Programme (2024) Global status report for buildings and construction. UN Environment Programme, Nairobi
12. Lim Y-W et al (2018) BIM and genetic algorithm optimization for sustainable building envelope design. *Int J Sustain Dev Plann* 13(1):151–159
13. IfcOpenShell: IfcOpenShell—An open-source library for IFC. Available at: <https://ifcopenshell.org/>. Last accessed 11 Mar 2025

Implementation of a Machine Learning–Based Precooling-Assisted HVAC Load Shifting Procedure to Balance Electric Vehicle Charging Load in a Warehouse



Farzad Dadras Javan, Arya Assadian, Fabio Rinaldi, Sara Perotti, and Behzad Najafi

Abstract HVAC-driven load shifting is a demand-side management strategy that can help prevent grid congestion and the economic penalization of the user, caused by the peak demand surges due to the charging load of electric vehicles. In this context, the present work investigates the impact of a set of HVAC-driven interventions on the load profile of a warehouse (including both storage and office zones) case study, aimed at balancing the charging load of electric trucks upon their arrival. Therefore, a set of interventions is simulated using EnergyPlus and its Python API, which include overcooling of the indoor spaces, maintaining a reduced setpoint for a certain period, followed by a subsequent setpoint relaxation interval. Simulations are conducted for the entire cooling season, and the resulting data is used to train machine learning(ML) pipelines designed to predict the duration of overcooling and setpoint relaxation phases. The performance of various ML algorithms is assessed and compared while employing the sliding training window scheme. Lastly, the selected pipeline is employed to determine the suitable schedule for the aforementioned interventions, and the corresponding impact (through performing re-simulations) on balancing the charging load of electric trucks is assessed.

Keywords Physics-based data-driven modelling · Building energy management · EVs charging load · Energyplus simulation

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1 Introduction

The building sector is responsible for 30% of global final energy consumption, and its energy use grew by about 1% in 2022 [1]. The substantial energy consumption of HVAC systems in buildings presents both challenges and opportunities for improving energy efficiency. HVAC systems are categorized as thermostatically controlled loads (TCLs), allowing their operation to be shed, shifted, or modulated for enhanced demand-side management [2]. Among the various building types, warehouses are of extreme importance. Due to their high thermal inertia and large indoor air volume, conditioned warehouses have substantial HVAC energy demands but also offer considerable flexibility for load management and energy optimization [3]. Additionally, to reduce fossil fuel consumption in the transportation sector, which accounts for nearly 24% of global emissions [4], electrified transportation has been increasingly adopted. However, the large-scale integration of electric trucks and lift trucks in logistics hubs could pose significant challenges to the electrical grid, including thermal overloads and voltage stability issues [5]. The power demand of heavy-duty electric vehicle charging stations can escalate to several megawatts, potentially straining the distribution grid and causing operational issues if not properly managed [6].

The considerable energy demand of buildings, particularly warehouses, offers an opportunity to enhance grid flexibility, mitigate the impact of electric vehicle charging, and reduce the risk of load surges [7]. The HVAC load of buildings can be adjusted and shifted by modifying temperature setpoints during specific periods to reduce energy demand during peak hours. Turner et al. [8] demonstrated that strategic changes to thermostat settings can effectively shift the cooling load of residential buildings, mitigating peak demand on the grid while maintaining acceptable indoor conditions. Dadras Javan et al. [5] proposed a methodology to shift the load of HVAC during the cooling season in order to charge electric trucks without exceeding the building baseline consumption. However, their study did not incorporate any precooling strategies to evaluate the potential for load shifting.

Machine-learning (ML) models can be employed to effectively predict how long HVAC-driven flexibility events can last. Dadras Javan et al. [3] proposed an ML-based approach to predict the duration that load reduction after relaxing the setpoint in a warehouse building would last. Nevertheless, the impact of precooling indoor spaces to shift HVAC loads and integrate the charging demands of electric trucks requires further investigation. Also, estimating the time required for indoor spaces to reach over-cooled setpoints and the duration that the setpoints can be relaxed (the duration that the HVAC-driven flexibility lasts) is essential for the effective planning of vehicle charging schedules. Finally, the models should be deployed in buildings to examine how errors in estimating these durations propagate through the charging schedule.

EnergyPlus is a physics-based simulation platform capable of modelling building energy performance across diverse climatic conditions and operational settings. Its Python API integration enables seamless interaction with real-time data sources and machine learning frameworks, facilitating the development, optimization, testing,

and deployment of different models and control strategies [9]. Therefore, the current work proposes a load-shifting methodology for balancing the energy demand in warehouse buildings equipped with electric vehicle charging facilities during the cooling season. The proposed HVAC load-shifting strategy involves temporarily relaxing the cooling setpoint of a conditioned warehouse (allowing for a maximum of 1.5 °C increase in indoor temperature) upon the arrival of electric trucks to facilitate load balancing. The study initially evaluates the impact of a precooling phase, achieved by lowering the cooling setpoints for 1.5 °C, followed by a preservation phase, on extending the duration of available flexibility. The thermal and energy responses of a warehouse building subjected to the proposed load-shifting strategies are investigated under various climatic conditions and precooling scenarios. The simulation data is then used to train machine learning models that predict the durations of the overcooling and setpoint relaxation phases, enabling the scheduling of electric truck charging ahead of time. Finally, a safety margin is proposed to account for model errors that would allow deployment of the approach in real-case scenarios. The impact of the model error (and the proposed threshold) on reducing the effective charging window (i.e., charging opportunity loss) is then investigated.

2 Methodology

The current work adopts a simulation methodology using EnergyPlus software [10] and its Python API [11] to investigate the thermal and energy performance of a warehouse building located in Bologna, Italy. The simulation accounts for HVAC system specifications, dynamic occupancy schedules, and internal heat gains to capture the building's operational characteristics. In the considered case study, electric trucks can only be charged after the building's operational hours, when the building load decreases significantly, thereby avoiding any substantial surge in the overall energy demand. This study aims to develop and implement machine learning-based HVAC interventions to provide energy flexibility, enabling the charging of electric trucks prior to the end of the building's operational schedule without causing surges in the building's typical daily energy consumption. To achieve this, various HVAC intervention scenarios are proposed, involving the relaxation of cooling setpoints to reduce the cooling load until a predefined temperature threshold is reached. The primary objective is to determine the optimal start time for these interventions based on their expected duration under varying climatic conditions, ensuring that they extend precisely until the closing time of the building. This approach eliminates the need for HVAC reactivation and allows uninterrupted truck charging. To this end, energy simulations are first conducted to model the building's thermal response under these scenarios and generate data on interventions' durations. This data is then used to train ML models capable of forecasting the duration of interventions. Lastly, the safety margin and the resulting loss of charging opportunities due to model errors are quantified.

The simulated case study presented in this work considers a reference warehouse building model that was developed under ANSI/ASHRAE/IES Standard 90.1 [12], located in Bologna, Italy. The thermal properties of the building envelope, including walls and exterior components, were adjusted based on real case studies and Italian construction standards, ensuring consistency with previous warehouse studies in similar climatic zones [13, 14]. In this simulation, the water-to-air heat pump system is modeled using discrete components rather than a packaged unit. On the load side (air), the system includes a fan, a water-to-air cooling coil, a water-to-air heating coil, and a gas-fired auxiliary heating coil (not used in the simulations). These components work together to deliver conditioned air to the thermal zones in response to heating and cooling demands. On the source side, the heat pump is connected to a closed condenser water loop, which is supported by both a boiler and a chiller to provide the necessary thermal exchange for heating and cooling operations [15]. The exterior walls are constructed with layers of extruded polystyrene (XPS) insulation on both sides of a concrete core, followed by a wood stud layer and finished with gypsum board. Additionally, windows are modeled with a simple glazing system having a U-value of approximately $2.7 \text{ W/m}^2 \text{ K}$, a solar heat gain coefficient (SHGC) of 0.6. The building is divided into two thermal zones: 238 m^2 of office space and 4598 m^2 of storage space. Simulations are performed for the whole cooling season, with setpoints of 25°C for the office and 26°C for the storage area. The building's normal working hours for both storage and office areas conclude at 18:00.

In the current work, the baseline scenario would consider the normal operation of the building without interventions in the HVAC system. This scenario would establish the normal energy and thermal behavior of the building under various climatic conditions. Different scenarios are proposed for HVAC interventions. In the first scenario, the cooling setpoint in the storage zones is relaxed at 16:00, allowing the temperature in these areas to increase by 1.5°C . This adjustment significantly reduces the building's overall cooling load during the intervention period, which is concluded once the indoor temperature reaches the predefined threshold. The second proposed scenario involves precooling the storage areas to 24.5°C , followed by an immediate setpoint relaxation that allows the temperature to rise to the same threshold above the building's normal setpoint as in the previous scenario. Similarly, three additional scenarios are proposed, each incorporating a preservation period after overcooling, during which the indoor space is maintained at the lowered temperature for 90, 180, or 300 min, respectively. Subsequently, a comparison is performed to evaluate the effectiveness of the precooling strategy in load shifting by analyzing the increase in the duration of HVAC-driven flexibility. Moreover, the impact of each scenario on the building's energy consumption is assessed and compared with the baseline case, with the aim of identifying the scenario with best trade-off between load shifting performance and energy use. It should be mentioned that in this study, the temperature drifts and ramps are maintained within the limits suggested by ASHRAE Standard 55-2017 [16] and validated by previous experimental studies [17, 18] to ensure thermal comfort of the occupant.

To optimally schedule the start times of HVAC interventions (precooling) and truck charging (setpoint relaxation) without disruptions from HVAC reactivation,

ML models are required. With these predicted durations, the logistics node can coordinate truck arrivals at the hub in advance, ensuring sufficient time for arrival before the charging window begins. For this purpose, the performance of five different regression machine learning algorithms is evaluated in predicting the duration of overcooling and setpoint relaxation. These include Random Forest Regressor, Extra Trees Regressor, Support Vector Regressor (SVR), K-Nearest Neighbors (KNN) Regressor, and Linear Regression, as presented in kaboli et al. [19]. The models are trained using simulation data from the training and validation period, which extends from early June to July 15th. A sliding window training scheme is applied to account for variations in climatic conditions by retraining the model with the most recent data. Accordingly, the period from July 16th to September 15th was designated as the testing and implementation phase.

A safety margin is introduced to prevent overestimation of the flexibility period, which causes the intervention to start too early and end prematurely before 18:00. As a result, the cooling system could be activated while the truck is still charging, leading to a surge in overall load. Hence, all relative overestimation errors observed during the training and validation period are collected. After excluding values above the 90th percentile, a safety margin is defined based on the remaining data. This margin should be subtracted from any prediction made while deploying these models in the implementation period. The reduction in the charging window due to ML model errors, along with the applied safety margin, defines the resulting loss in charging opportunity.

3 Results and Discussions

Table 1 provides the average and maximum durations that setpoint relaxations would last (maximum achievable charging window) during the training and validation period. It is evident that the duration of the charging window is substantially longer during the mid-season period (June) and decreases under more extreme weather conditions. Additionally, it can be observed that both overcooling and extending the maintenance period help expand the charging window, due to the activation of the building's thermal mass. However, an assessment of the energy performance across these scenarios reveals that implementing a 90-minute preservation interval increases baseline energy consumption by nearly 2%, while extending the mid-season charging window by approximately 20% compared to the scenario without maintenance at the overcooling temperature, and by nearly 90% compared to the case with no overcooling. Further improvements can be achieved by maintaining indoor spaces for longer periods; however, this would lead to a more significant increase in energy consumption, potentially justifiable in buildings equipped with photovoltaic (PV) panels. Within the scope of this study, the scenario with a 90-minute maintenance period is selected, as it offers the best trade-off between energy consumption and charging window potential.

Table 1 Max achievable charging window and the total energy consumption in training and validation period

Scenario	June		1–15th July		Energy consumption (kWh) training and validation period
	Mean	Max	Mean	Max	
Without overcooling	29	52	20	25	12,995
Overcooling without preservation	46	101	32	39	13,324
Overcooling with 90-min preservation	55	120	37	45	14,098
Overcooling with 180-min preservation	64	120	41	50	14,745
Overcooling with 300-min preservation	73	120	45	55	15,400

3.1 Machine Learning Modelling and the Obtained Safety Margin

Table 2 presents the results achieved by the ML models in predicting both the duration of overcooling and the length of the setpoint relaxation period across the training and validation phase. The results show that the ExtraTrees algorithm delivers the best overall performance, thanks to its ability to capture nonlinear patterns in the data and its low tendency to overfit, especially on smaller datasets. However, the model struggles to accurately predict overcooling durations, as the HVAC system occasionally struggles to reach the overcooling setpoint on certain days, introducing errors into the predictions.

Next, the maximum relative overestimation errors of the ExtraTrees model during the training and validation periods are collected, and the 90th percentile value (19.83% for this model) is selected as the safety margin threshold. The model is applied during the testing and implementation period. To prevent overestimating the charging window, each prediction is adjusted by subtracting a safety margin, calculated as the prediction multiplied by the derived threshold.

Finally, the reduction in charging opportunity, caused by both the ML model’s prediction error and the applied safety margin, is quantified and summarized in Table 3. The results show that the total opportunity loss across different periods

Table 2 Obtained accuracies for various ML models

ML model	Overcooling		Set point relaxation	
	MAE (Minutes)	MAPE (%)	MAE (Minutes)	MAPE (%)
Random forest	5.74	25	5.16	12
ExtraTrees	5.07	22	4.54	10
SVR	5.21	20	6.79	15
KNN	5.94	28	5.73	13
Linear regression	18.87	132	12.4	29

Table 3 The comparison of obtained and deployable charging windows

	16th–31st of July	August 1st–September 15th
Max. achievable charging window	34	40
Max. deployable charging window	27	32
Lost charging opportunity	7	8

ranges between 7 and 8 min. This would confirm the substantial impact of the ML models' accuracy on the deployable charging window.

4 Conclusions

The current study investigated the potential of various HVAC-driven intervention scenarios to shift the load in a warehouse building, with the aim of enabling electric truck charging during working hours without causing a surge in demand. Accordingly, a simulation-based approach was adopted to model the thermal and energetic behavior of a case study building in Bologna. The study examined scenarios in which the cooling setpoint in storage zones was relaxed under three conditions: without precooling, with precooling but no preservation period, and with both precooling and preservation at the overcooled temperature for varying durations. It was observed that including a 90-minute preservation period at the overcooled temperature offered the best trade-off between energy consumption (nearly 2% increase) and extending the duration of charging window. Subsequently, a predictive approach was employed to estimate the durations of the overcooling and setpoint relaxation periods. These predictions were made two hours in advance, allowing sufficient time for truck notification and arrival. The developed models were capable of predicting the setpoint relaxation duration with an average mean absolute error of around 5 min. However, to mitigate the risk of overestimating the charging window during deployment, which could result in the reactivation of the HVAC system while vehicles are still charg-

ing, a safety margin was introduced. It was demonstrated that applying the obtained threshold during the implementation and testing phase of the models resulted in an average loss of 7–8 minutes in the charging window, highlighting the critical impact of machine learning model accuracy. The observed loss values in this study are primarily attributed to prediction errors resulting from performing the forecasts two hours prior to the actual setpoint relaxation.

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References

1. International Energy Agency (2023) Buildings—energy system. Accessed 14 Mar 2024
2. Luo Z, Peng J, Cao J, Yin R, Zou B, Tan Y, Yan J (2022) Demand flexibility of residential buildings: definitions, flexible loads, and quantification methods. *Engineering* 16:123–140
3. Dadras Javan F, Campodonico Avendano IA, Najafi B, Moazami A, Rinaldi F (2023) Machine-learning-based prediction of HCAC-driven load flexibility in warehouses. *Energies* 16(14):5407
4. Mpoi G, Milioti C, Mitropoulos L (2023) Factors and incentives that affect electric vehicle adoption in Greece. *Int J Transp Sci Technol* 12(4):1064–1079
5. Dadras Javan F, Najafi B, Rinaldi F, Campodonico Avendano IA, Moazami A (2023) Modulating the HVAC demand of a warehouse to provide load flexibility for charging electric trucks. In: *ECMS*, pp 255–261
6. Zhu X, Mishra P, Mather B, Zhang M, Meintz A (2023) Grid impact analysis and mitigation of enroute charging stations for heavy-duty electric vehicles. *IEEE Open Access J Power Energy* 10:141–150
7. Aduda KO, Labeodan T, Zeiler W, Boxem G, Zhao Y (2016) Demand side flexibility: potentials and building performance implications. *Sustain Cities Soc* 22:146–163
8. Turner WJN, Walker IS, Roux J (2015) Peak load reductions: electric load shifting with mechanical pre-cooling of residential buildings with low thermal mass. *Energy* 82:1057–1067
9. National Renewable Energy Laboratory (NREL) (2022) Python opens up new applications for energyplus building energy simulation. Accessed 19 Mar 2025
10. Crawley DB, Lawrie LK, Winkelmann FC, Buhl WF, Joe Huang Y, Pedersen CO, Strand RK, Liesen RJ, Fisher DE, Witte MJ, Glazer J (2001) Energyplus: creating a new-generation building energy simulation program. *Energy Build* 33(4):319–331. Special Issue: BUILDING SIMULATION’99
11. Energyplus python api documentation. <https://nrel.github.io/EnergyPlus/api/python/>, n.d. Accessed 21 Feb 2025
12. Anse/ashrae/ies standard 90.1-2010. energy standard for buildings except low rise residential buildings (2010)
13. Ministero delle Imprese e del Made in Italy. Decreto interministeriale 26 giugno 2015-applicazione delle metodologie di calcolo delle prestazioni energetiche e definizione delle prescrizioni e dei requisiti minimi degli edifici, 2015. Decreto del Ministro dello sviluppo economico di concerto con i Ministri dell’ambiente e della tutela del territorio e del mare, delle infrastrutture e dei trasporti, della salute e della difesa

14. Dall'O' G, Belli V, Brolis M, Mozzi I, Fasano M (2013) Nearly zero-energy buildings of the Lombardy region (Italy), a case study of high-energy performance buildings. *Energies* 6(7):3506–3527
15. EnergyPlus Team (2021) Energyplus input output reference. Accessed 01 July 2024
16. ASHRAE Handbook et al (2005) American society of heating, Refrigerating and Air Conditioning Engineers, Atlanta
17. Favero M, Sartori I, Carlucci S (2021) Human thermal comfort under dynamic conditions: an experimental study. *Build Environ* 204:108144
18. Hensen JLM (1990) Literature review on thermal comfort in transient conditions. *Build Environ* 25(4):309–316
19. Kaboli A, Dadras Javan F, Campodonico Avendano IA, Najafi B, Maria Colombo LP, Perotti S, Rinaldi F (2024) Just-in-time morning ramp-up implementation in warehouses enabled by machine learning-based predictive modelling: estimation of achievable energy saving through simulation. *Energies* 17(17):4401

Optimizing Energy Efficiency in Historical Buildings Using Model Predictive Control for Building Automation and Control Systems



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Abstract The ambitious European targets for decarbonizing the building sector by 2050 present significant challenges, particularly in the energy retrofitting of historical buildings. While conservative restoration approaches emphasize low-impact interventions on both the building envelope and mechanical systems, adapting historical buildings to contemporary functional requirements necessitates modernized system integration. This includes ensuring operational safety, precise indoor environmental control, and increased flexibility to meet updated thermal and energy performance standards by regulatory frameworks. The implementation of Building Automation and Control Systems (BACS) in historical buildings is becoming increasingly prevalent as a strategy to reduce energy consumption while simultaneously enhancing occupant comfort. To support effective design and planning, it is crucial to optimise BACS operational control, particularly in minimising a building's operational energy demand. In this context, Model Predictive Control (MPC) has emerged as an advanced optimisation technique for enhancing energy efficiency in BACS. Unlike conventional rule-based or reactive control methods, MPC employs a predictive optimisation framework that anticipates future building conditions and dynamically adjusts control actions to minimise energy consumption while maintaining thermal comfort. This study evaluates the energy-saving potential of optimising BACS in a historical building located in southern Italy through various MPC strategies. Three control approaches were investigated: the integration of mechanical actuators on windows to enable automated natural ventilation, the dynamic reduction of the heating system's supply temperature, and the optimisation of automatic shading management. The results demonstrate that implementing MPC-based BACS strategies can lead to energy consumption reductions of up to 20%, highlighting the potential of advanced control systems in enhancing the energy efficiency of historical buildings while preserving their architectural integrity.

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Keywords BACS · Historical heritage · MPC · Energy saving

1 Introduction

With the European Green Deal, the European Union has embarked on a comprehensive and far-reaching initiative to move from a fossil fuel-based energy system to a sustainable, low-carbon economy, aiming for climate neutrality by 2050 [1].

A decisive step towards this long-term goal is the ‘Fit for 55’ package, which envisages a 55% reduction in net greenhouse gas emissions by 2030, compared to 1990 levels. Among the various sectors contributing to emissions reduction across the EU, buildings emerge as a major energy consumer and a prime candidate for cost-effective energy savings [2, 3]. As is known, buildings account for about 40% of the EU’s final energy consumption and 36% of its CO₂ emissions. Recognising the importance of this sector [3], numerous policies and initiatives have been introduced to increase the rate of building renovation. Although these efforts are a solid starting point, there remains a significant gap in research specifically for heritage buildings, as the application of appropriate energy retrofits to historic and monumental buildings emerges, where strict regulations on heritage status make it difficult to implement most efficiency measures for these types of buildings [4].

As a matter of fact, a substantial part of the building heritage in Europe is more than 50 years old, and among these, a significant share is more than 100 years old. Recent statistics reveal that 14% of the building stock in the EU-27 dates back before 1919, and about 12% between 1919 and 1945 [5]. According to the UNESCO World Heritage List, Italy possesses 4.7% of the world’s architectural heritage, covering 14% of the country’s territory [6]. Notably, over 4 million of Europe’s 5.37 million historic buildings are located in Italy. Of these, around 49% were constructed before 1919, and 11–12% between 1919 and 1945, many of which are used for residential or public purposes. This substantial and heterogeneous historical building stock is characterised by generally poor energy performance, highlighting the urgent need for large-scale energy upgrades. Consequently, the academic and professional debate around best practices for conservation, restoration, integrated renovation, and energy retrofitting remains active and unresolved. The core challenge lies in striking a careful balance between enhancing energy efficiency and preserving the cultural value of these buildings. Energy retrofit strategies must therefore respect and safeguard architectural integrity, original materials, historical authenticity, and the cultural and social significance embedded in heritage buildings [7].

Along this line, the implementation of building automation and control systems (BACS) in the energy retrofitting of the building heritage is increasingly seen as a promising strategy for enhancing energy efficiency while preserving the architectural and historical integrity of these structures [8, 9]. To support effective design and planning, it is crucial to optimize BACS operational control, particularly in minimizing a building’s operational energy demand [10]. In this context, Model Predictive Control

(MPC) has emerged as an advanced optimization technique for enhancing energy efficiency in BACS [11]. Unlike conventional rule-based or reactive control methods, MPC employs a predictive optimization framework that anticipates future building conditions and dynamically adjusts control actions to minimize energy consumption while maintaining thermal comfort.

This study evaluates the energy-saving potential of optimizing BACS in a historical building located in southern Italy through various MPC strategies. Three control approaches were investigated: the integration of mechanical actuators on windows to enable automated natural ventilation, the dynamic reduction of the heating system's supply temperature, and the optimization of automatic shading management.

2 Methodology

2.1 Case Study Selection

The Administrative Services Pavilion (PSA) of the Bari Policlinico, built in 1936, which houses the offices of the General Management, Administrative Management, Health Management, and the Personnel Office of the Policlinico di Bari, is used as a case study in this research [12].

Due to its architectural and historical significance, the PSA building is subject to conservation constraints imposed by the Superintendency of Archaeology, Fine Arts, and Landscape of the Province of Bari. An initial phase of energy refurbishment was undertaken in 2013, focusing primarily on the modernization of the thermal substation.

The upgraded system is centrally managed by an integrated control unit, facilitating scheduling operations and fault diagnostics across system components. As part of the refurbishment, the previous radiator-based heating and split-unit cooling systems were replaced with a centralized two-pipe fan coil system. This solution employs cassette fan coils with zoning capability, allowing for seasonal and transitional operational flexibility while optimizing energy use. Interventions on the building envelope were executed in strict compliance with preservation guidelines. Modifications permitted by the Superintendency included the replacement of original single-glazed windows and doors with low-emissivity, double-glazed units featuring 5.76 mm glass panes and a 10 mm air gap, achieving a thermal transmittance (U_w) of $2.9 \text{ W/m}^2 \cdot \text{K}$. Additionally, plasterboard ceilings were installed to accommodate the new air distribution infrastructure without altering the building's formal characteristics (Fig. 1).

The lighting system has also been upgraded. The original fluorescent lamps were replaced with 25 W LED downlights. The lighting infrastructure is controlled via a DALI (Digital Addressable Lighting Interface) gateway, enabling individualized management of Distributed Digital Control (DDC) units.

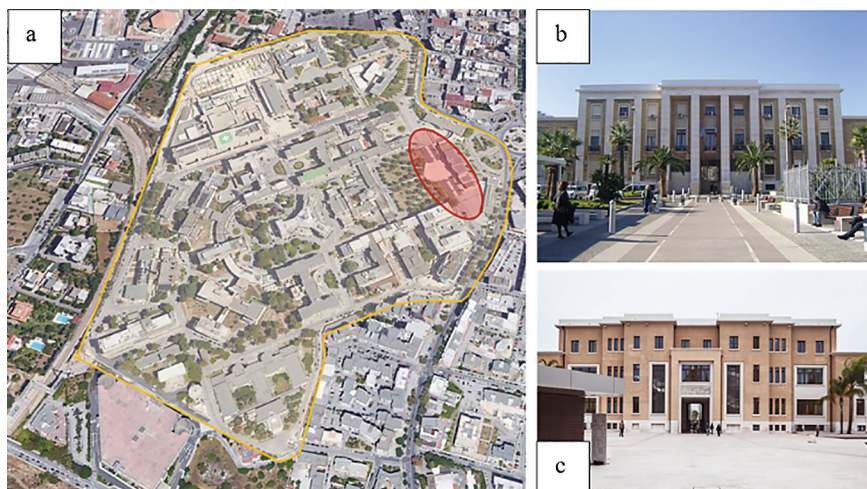


Fig. 1 Location of the administrative services pavilion of the Bari general hospital (a), front view of the PSA (b) and back view of the PSA (c)

To further enhance energy efficiency and operational control, a SCADA (Supervisory Control and Data Acquisition) system—Siemens Desigo—was implemented as part of the energy retrofitting project. This platform provides centralized monitoring, control, and analysis of various building systems, including HVAC, lighting, and power distribution. Within the PSA, the Desigo system manages room thermostats, air handling unit (AHU) flows, fan speeds, and fan coils supply temperatures through the use of multiple damper actuators and control valves.

Environmental parameters such as lighting, thermal comfort, and window shading are dynamically regulated based on building occupancy and room-specific requirements. This is achieved by locally adjusting temperature and illuminance setpoints, ensuring both energy efficiency and occupant comfort according to external conditions with a conventional rule-based logic.

2.2 *Creation and Validation of a Building Simulation Model*

The initial phase of the study involved the development of a dynamic energy model of the case study building. This model was constructed using DesignBuilder software, incorporating detailed geometric, thermo-physical, HVAC system, usage, and occupancy characteristics.

The primary objective of developing the dynamic model was to create a digital twin of the building, which could serve as a testbed for applying Building Automation and Control Systems (BACS) optimization strategies through predictive control models.

This approach aimed to evaluate potential energy savings derived from the integration of artificial intelligence into the energy management of historic buildings.

The model was validated following Methodology D of the ASHRAE Guideline 14-2023. Validation was achieved by comparing the simulated and measured monthly energy consumption for the year 2023, considered as the base scenario, based on the conventional rule-based or reactive control methods of the actual BACS operational mode in the case study building, ensuring that the Mean Bias Error (MBE) and the Coefficient of Variation of the Root Mean Square Error (CV(RMSE)) remained within the acceptable thresholds of $\pm 5\%$ and 10% respectively.

2.3 Weather Forecast and MPC Scenarios Simulation

Following model validation, a software application was developed to embed predictive control algorithms into the energy management system of the case study. The implemented Model Predictive Control (MPC) framework employs mathematical models to forecast the building's thermal behavior based on historical performance data, weather forecasts, occupancy schedules, and other influencing factors. This predictive capability allows for the anticipation of thermal loads and the optimization of system operations.

Predictive control strategies enable the dynamic adjustment of key control variables, such as shading device position, system supply temperatures, on an hourly basis, depending on forecasted internal and external conditions. The optimisation objectives and constraints within this framework include:

- Minimization of costs related to energy consumption,
- Compliance with physical and operational constraints, such as indoor temperature limits, occupant comfort or shading device restrictions.

Hourly measurements of outdoor air temperature, relative humidity, and global horizontal solar irradiance were obtained from the ARPA Puglia database via the weather station in Bari for the period 2020–2023. These data were used to train and validate three predictive models based on Bagged Trees algorithms. Model validation yielded root mean square deviation (RMSD) values of $1.7\text{ }^{\circ}\text{C}$ for air temperature, 12% for relative humidity, and 65 Wm^{-2} for global horizontal irradiance. The validated models were subsequently employed to generate forecast weather data for use in Model Predictive Control (MPC) simulations.

Subsequently, the control algorithms were developed in Python, leveraging several open-source libraries. Notably, the pyEnergyPlus API was used to interface directly with the EnergyPlus simulation engine via input (.idf) and forecasted weather (.epw) files. For the optimization process, the SciPy library's implementation of the Sequential Least Squares Programming (SLSQP) method was employed to solve constrained multivariable optimization problems.

Three predictive control strategies were implemented, each corresponding to a specific BACS optimization logic:

- Strategy 1 (S1): Focuses on controlling window actuators to enable automated natural ventilation. By modulating the window opening angle (up to 30%) based on outdoor temperature forecasts, this strategy aims to reduce cooling loads and enhance indoor air quality through passive means.
- Strategy 2 (S2): Involves dynamic adjustment of the fan coil supply temperature. Using forecasted weather and occupancy data for the subsequent timestep, this logic explores reducing the heating water supply temperature while maintaining thermal comfort according to the building's heating schedule.
- Strategy 3 (S3): Optimizes the control of motorized shading devices based on forecasted solar radiation and average indoor illuminance. This approach aims to minimize energy consumption related to lighting and cooling while ensuring compliance with comfort standards.

In all three strategies, the objective function was defined as the minimization of energy consumption. Constraints included maintaining indoor thermal comfort within the parameters defined by Category II of UNI EN 16798-1 and ensuring sufficient illuminance levels, depending on the specific control logic applied. Forecast variables included outdoor temperature, solar radiation, and wind speed, while system variables comprised heating system flow temperature, the percentage of operable window area, and the activation level of movable shading systems integrated into the building's façade.

Finally, to assess the potential energy savings from the application of advanced control logics based on MPC, results were compared with a baseline simulation, run utilizing the actual weather file and conventional rule-based controls of the BACS.

3 Results

Figures 2, 3, and 4 illustrate the monthly energy savings that can be achieved through the optimized management of Building Automation and Control Systems (BACS) using predictive control strategies. The results demonstrate the significant impact of smart control on reducing both heating and cooling energy demands throughout the year.

Once the implemented strategy involving the optimization of the operation of building openings to promote passive cooling through natural ventilation, it resulted in an annual cooling energy reduction of 14%, equivalent to 15,923.7 kWh compared to the base case scenario. The energy reduction varies from 5.2% in the hottest period, where the cooling potential of natural ventilation in relation to climatic conditions is reduced, to more significant values in the intermediate seasons up to a maximum of 100% in April and October and 61% in May and 32.6% in September (Fig. 2).

Additionally, by dynamically adjusting the supply temperature of the heating system in response to predicted environmental and building conditions (Scenario S2), heating energy consumption was reduced by 19.8%, corresponding to 46,137.4 kWh annually.

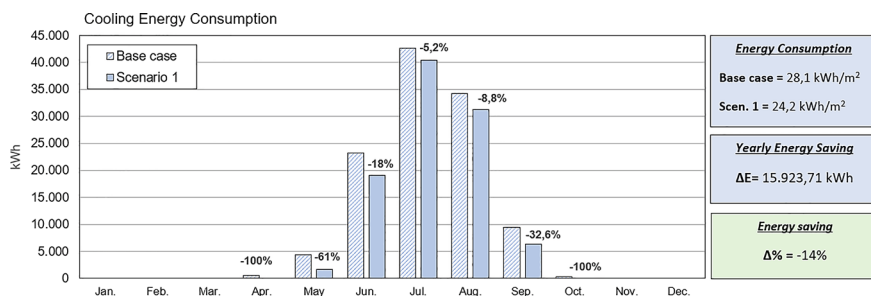


Fig. 2 Monthly cooling energy demand on an hourly basis with scenario S1 compared to the baseline scenario

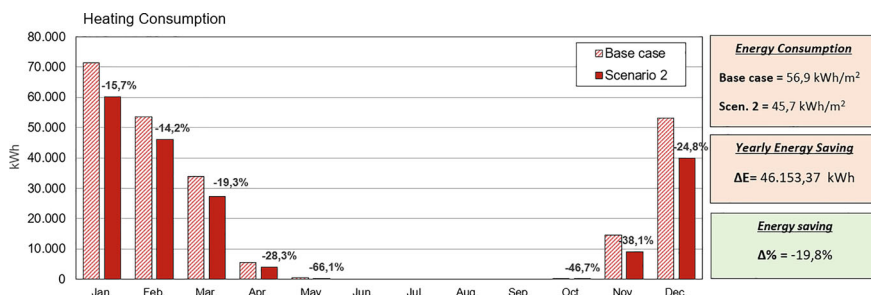


Fig. 3 Monthly heating energy demand on an hourly basis with scenario S2 compared to baseline scenario

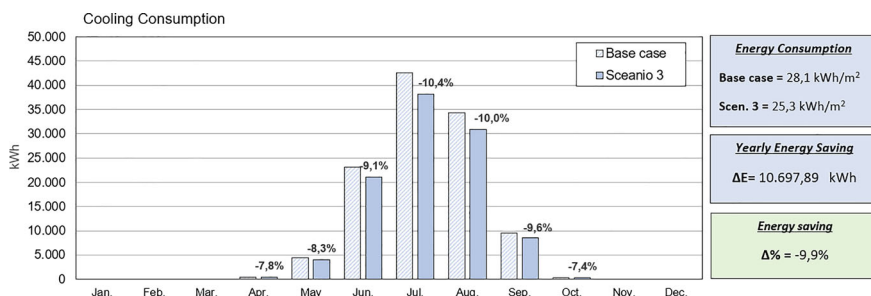


Fig. 4 Monthly cooling energy demand on an hourly basis with scenario S3 compared to baseline scenario

The greatest reduction values are again obtained in the marginal months of the heating season when the heating load is lower. Specifically, a maximum reduction of 38.1% is achieved in November (Fig. 3).

Another important contribution came from the smart management of mobile shading devices applied to transparent building elements (Scenario S3), which helped reduce solar heat gains and consequently decreased cooling energy demand by 9.9%,

saving 10,697.9 kWh per year compared to baseline scenario (Fig. 4). The cooling energy saving peak value is found in the month in which solar radiation is greatest, i.e. July with a reduction of 10.4%.

4 Conclusions

This study, through a validated building energy model by real consumption data from a heritage building, demonstrates the significant potential of the historic building stock to enhance its energy performance in alignment with the European Union's climate neutrality goals. The integration of MPC strategies to optimize BACS operation mode can contribute to reducing the energy use of historic buildings, even considering preservation constraints. Optimization strategies for BACS through artificial intelligence and predictive control models allow their operation to be optimized, increasing the energy savings achievable by the heritage building by up to 20%.

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References

1. European Commission (2019) The European green deal, Brussels, Belgium
2. Ibrahim M, Harkouss F, Biwole P et al (2024) Building retrofitting towards net zero energy: a review. *Energy Build* 322:114707. <https://doi.org/10.1016/J.ENBUILD.2024.114707>
3. Stasi R, Ruggiero F, Berardi U (2025) From energy-intensive buildings to NetPlus targets: an innovative solar exoskeleton for the energy retrofitting of existing buildings. *Energy Build* 333:115416. <https://doi.org/10.1016/J.ENBUILD.2025.115416>
4. Mazzarella L (2015) Energy retrofit of historic and existing buildings. the legislative and regulatory point of view. *Energy Build* 95:23–31. <https://doi.org/10.1016/j.enbuild.2014.10.073>
5. Ruggeri AG, Calzolari M, Scarpa M et al (2020) Planning energy retrofit on historic building stocks: a score-driven decision support system. *Energy Build* 224:110066. <https://doi.org/10.1016/j.enbuild.2020.110066>
6. UNESCO (2013) World heritage centre glossary
7. Bjelland D, Collins D, Gullbrekken L, Hrynyszyn BD (2025) Energy retrofitting of heritage-protected buildings: Establishing representative case studies. *Energy Rep* 13:2752–2763. <https://doi.org/10.1016/J.EGYR.2025.02.010>
8. Vandenbogaerde L, Verbeke S, Audenaert A (2023) Optimizing building energy consumption in office buildings: a review of building automation and control systems and factors influencing energy savings. *J Build Eng* 76:107233. <https://doi.org/10.1016/J.JOBE.2023.107233>
9. Naylor S, Gillott M, Lau T (2018) A review of occupant-centric building control strategies to reduce building energy use. *Renew Sustain Energy Rev* 96:1–10. <https://doi.org/10.1016/J.RSER.2018.07.019>

10. van Roosmale S, Hellinckx P, Meysman J et al (2024) Building automation and control systems for office buildings: Technical insights for effective facility management—a literature review. *J Build Eng* 97:110943. <https://doi.org/10.1016/J.JOBE.2024.110943>
11. Yao Y, Shekhar DK (2021) State of the art review on model predictive control (MPC) in heating ventilation and air-conditioning (HVAC) field. *Build Environ* 200:107952. <https://doi.org/10.1016/J.BUILDENV.2021.107952>
12. Stasi R, Ruggiero F, Berardi U (2024) Assessing the energy saving potential of historical buildings heritage in mediterranean climate. In: 2024 7th IEEE international humanitarian technologies conference, IHTC 2024. <https://doi.org/10.1109/IHTC61819.2024.10855102>

The Assessment of Details of Existing Building Structures with the Addition of a Thermally Conductive Element



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Abstract The process of renovation of historical buildings is a broad topic, which includes various branches of building engineering, such as building physics, life cycle of material and buildings, energy assessment and others. In this paper, the author focuses on the prediction of the internal surface temperature factor, since its assessment is necessary for the design of the building envelope, excluding the effect of surface condensation at the corners. In the simulation program, a 2D detail of the corner in the external perimeter wall of the building structure with and without external thermal insulation composite system (ETICS) was created and a sheet of highly conductive material was added. The effect of a 1 mm thick aluminum sheet on the internal surface temperature over a time period of five years was investigated under unsteady-state conditions. The main objective of the simulation was to investigate, in first phase, the behavior of the internal surface temperature at the corner of an external perimeter wall with ETICS, and in a second phase the behavior of internal surface temperature at the corner of an outer perimeter wall without ETICS. The implementation process was stated due to the time gap, when the external perimeter wall is exposed to climate conditions before re-installation of ETICS. The time gap varies and in the central European region can extend into the winter season. The results were based on comparison of internal surface temperature factor according to the International standard with the results obtained from the simulation. The charts show the development of the curve of internal surface temperature with addition of aluminum sheet over the curve of the critical internal surface temperature factor for most days in the months January, February, November and December. On the other hand, the development shows the curve of the internal surface temperature without addition of aluminum sheet below the curve of the critical internal surface temperature factor, thus surface condensation cannot be excluded in this case. It is also interesting to determine the effect of the materials with different thermal conductivities placed behind the aluminum sheet on the internal surface temperature and the location in the external perimeter wall relative to the thermal bridge.

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Keywords Building envelope • Conductive material • Temperature factor

1 Introduction

Over time, we have been finding different ways of approaching the renovation of existing buildings, but we usually focus on the actual structural and technical survey of the building structures only when there are significant failures of the building structures. Every building is affected by the durability of the building materials, which are under the constant influence of multi-physical phenomena, because in the real world, one physical phenomenon will not occur in isolation without being influenced by others. It is mainly the simultaneous interaction of heat transfer, water movement in porous materials and diffusion flow in building structures.

In any type of building structure (masonry, monolithic reinforced concrete, precast walls) critical details may arise that require increased attention in the design and planning phase of the structure. Professionals and building users alike will think of a 'critical detail' as a location where increased heat flow may occur and this detail is indicated by a thermal bridge in the structure. If the conditions of the technical standards [1] are to be met, the condition of the temperature factor on the internal surface at the thermal bridge location must also be met.

The present work is a continuation of previous research on the problem of internal surface temperature in the corners of structure details with an added element of conductive material (aluminum sheet) installed under the interior plaster [2]. For the evaluation of the building detail was used the patent [3].

In a more complex analysis, the influence of the radiation should be considered, for example polished metal surfaces (Al foils) have a low emissivity to infrared radiation, the heat loss of radiation is reduced [4]. This can lead to the determination of the location in the structure detail and the consideration of the additional heat transfer effect. Options for mitigating thermal bridges are presented. The effect of an added thermal angle with a strip of thermal insulation installed on the internal surface of the external perimeter wall is shown. The addition of this element will increase the internal surface temperature [5].

The thermal resistance of a surface depends on the convention and radiation coefficients, the air movement in the room, the air temperature distribution and the room surface. For the calculation of the internal surface temperature, we should know the most accurate values [6]. In the paper [7], the effect of environmental boundary conditions on the heat transfer through the wall surface was investigated and the convention coefficients were experimentally analyzed and the emissivity of the sample was measured.

The results of this paper can be useful already in the design of buildings, where the durability of building materials will be defined, as well as the method and conditions for the process of building renovation. Furthermore, the results lead to the reduction of effects that may occur during the building renovation process, such as condensation

on the internal surface. These values have so far been experimentally verified using thermographic images for the winter season in the Central European region.

2 Methodology

The methodology for solving the example was divided into two phases. First, a 5-year period with ETICS was simulated to show the temperature field of the external perimeter wall in its original state. A climate analysis from the default settings of the WUFI 2D software was used. The orientation of the example was determined to be north and west Fig. 1.

The results from the first phase time period were included in a further calculation of one year, when the internal surface temperature without ETICS was tested. This case can occur in case when we are renovating or adding to an existing building with ETICS and due to the implementation of building modifications the contact insulation system is exposed. In this place, the internal surface temperature may be lowered and possible structure defects may occur when the building is in full operation.

WUFI 2D 4.6 software, which is designed for the calculation of simultaneous heat and moisture transfer in multilayer building components, was used to simulate the structure detail. The input parameters and the 2D corner layout of the external perimeter wall are given in Tables 1 and 2, Fig. 1. The internal surface temperature shall be tested at a point in the corner on internal surface below the internal plaster.

Indoor conditions were used recommended predefined curves in WTA Guideline 6-2-01/E Simulation of Heat and Moisture Transfer. For the internal surface, a heat transfer coefficient of $8.0 \text{ W/m}^2\text{K}$ was used.

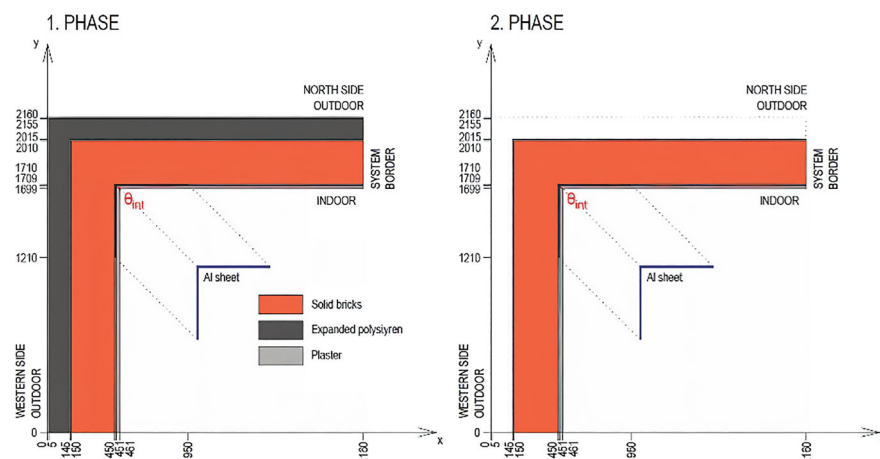


Fig. 1 The structure detail in the two phases of research with the addition conductive material

Table 1 Input boundary conditions for simulation the detail of the structure

	Indoor conditions (sine curves)	Outdoor conditions
Temperature	Medium moisture load	From map/file
Mean value [°C]	21	Hradec Králové
Amplitude [K]	1	Czech Republic
Day of maximum	03.06	
Relative humidity		
Mean value [%]	50	
Amplitude [%]	10	
Day of maximum	16.08	

Table 2 Basic material properties of simulated structure detail

	Bulk density [kg m ⁻³]	Porosity [m ³ / m ³]	Spec. heat capacity [J kg ⁻¹ K ⁻¹]	Thermal conductivity [W m ⁻¹ K ⁻¹]	Water vapour diffusion resistance factor [–]
Solid bricks	1900	0.240	850	0.600	10.0
Expanded polystyrene (ETICS)	15	0.950	1500	0.040	30.0
Interior plaster	1279	0.517	827	0.310	10.2
Exterior plaster	988	0.580	850	0.165	24.0
Aluminum sheet (1 mm thickness)	7800	0.001	800	150.000	1000000.0

The governing equations was used from the Internation standard [1], which describe the relations for the calculation of the internal surface temperature on the internal surface of building structures, the calculated value $f_{R_{si}}$ (1) a critical factor (value $\varphi_i = 50\%$, value $\varphi_{si,cr} = 80\%$) $f_{R_{si,cr}}$ (2). The comparison of the internal surface temperature factor is given by relation (3).

$$f_{R_{si}} = \frac{\theta_{si} - \theta_e}{\theta_i - \theta_e} \quad (1)$$

$$f_{R_{si,cr}} = 1 - \frac{237.3 + 2.1 \cdot \theta_i}{\theta_i - \theta_e} \cdot \frac{1}{1.1 - 17.269 / \ln(\varphi_i / \varphi_{si,cr})} \quad (2)$$

$$f_{R_{si}} \geq f_{R_{si,cr}} \quad (3)$$

where θ_{si} is the internal surface temperature ($^{\circ}\text{C}$), θ_i is the indoor temperature ($^{\circ}\text{C}$), θ_e is the outdoor temperature ($^{\circ}\text{C}$). Value ϕ_i is the relative humidity of indoor air (%), $\phi_{i,cr}$ is the critical indoor surface humidity (%).

3 Results and Discussion

In the evaluation of the results, the author focused on the last year of the 5 year simulation of the internal surface temperature of external perimeter wall using ETICS for phase number 1 with and without aluminum sheet. The chart in Fig. 2 shows the phase 1 with dark and light dashed line. In the next step, the results of the internal surface temperature were taken for the simulation of perimeter wall without ETICS.

The chart in Fig. 2 shows the phase 2 with dark and light solid line. Furthermore, in phase number 2, the internal surface temperature values for the months January, February, November and December were simulated to characterize the constant heating period for the specified location Figs. 3, 4, 5 and 6. Author used Eqs. (1) and (2) to convert the temperature values to the internal surface temperature factors. In Fig. 2, two different material compositions of the external wall are considered, which affect the temperature of the internal surface. The external perimeter wall with ETICS and additional aluminum sheet achieves a higher internal temperature of approximately $0.5\text{--}0.6\text{ }^{\circ}\text{C}$ than the external perimeter wall with ETICS and without aluminum sheet. Compared to this case, the external perimeter wall without ETICS and additional aluminum sheet achieves a higher internal temperature of approximately $1.25\text{--}1.75\text{ }^{\circ}\text{C}$ than the external perimeter wall without ETICS and without aluminum sheet for the months under evaluation (November, December, January, February).

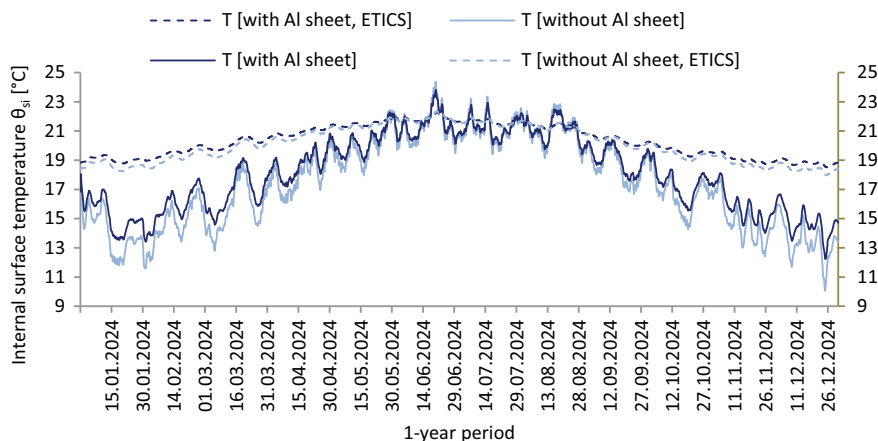


Fig. 2 One-year period of internal surface temperature with first and second phase

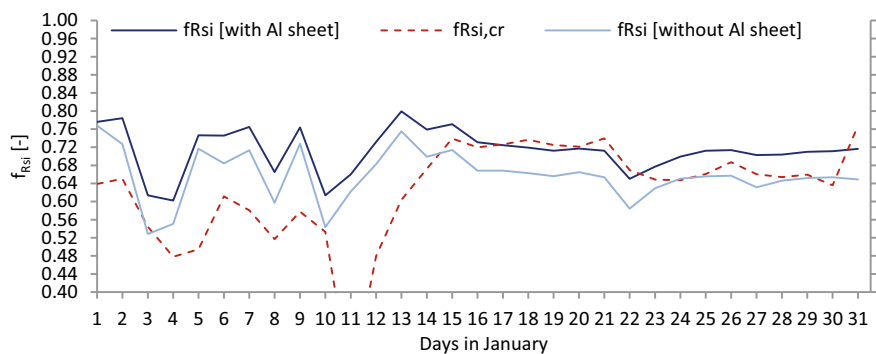


Fig. 3 The course of the internal temperature factor for days in January

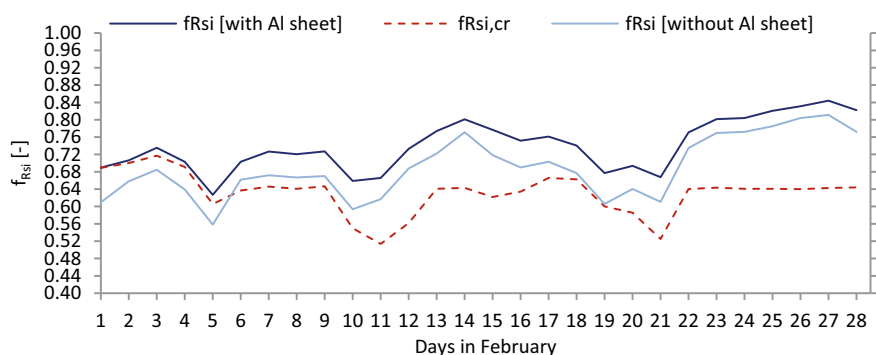


Fig. 4 The course of the internal temperature factor for days in February

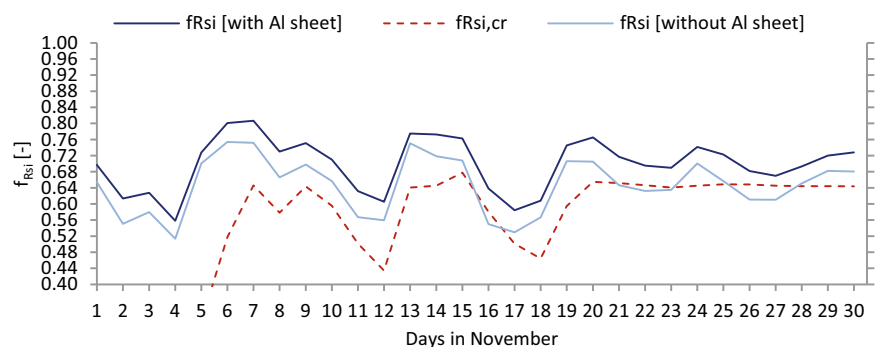


Fig. 5 The course of the internal temperature factor for days in November

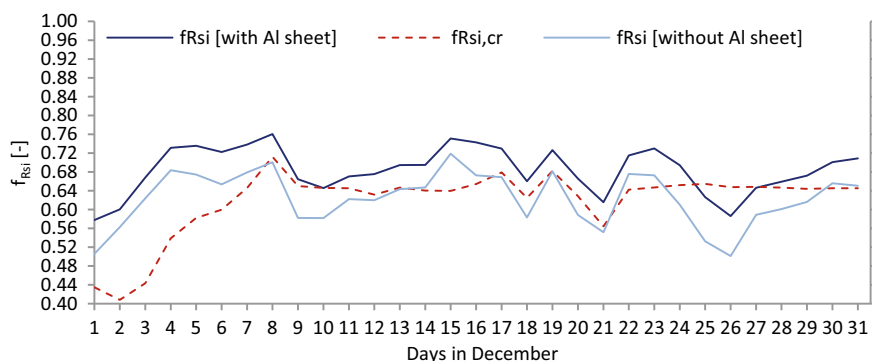


Fig. 6 The course of the internal temperature factor for days in December

Based on the processing of the results of the unsteady-state simulation and steady-state simulation which were solved beyond the scope of this paper, it can be concluded that the material characteristic of the layer behind the aluminum sheet affects the internal surface temperature more than materials on the external surface (ETICS, thermal-insulating plaster).

4 Conclusions

These results lead to the investigation of other influences and other input conditions related to the calculation of the internal surface temperature. The main idea of this paper is to point out a possible defect location that can occur during building modifications and one of the many solutions to eliminate surface condensation.

In December and January, it can be seen that the internal surface temperature with the added element of conductive material is below the level of the critical factor of the internal surface temperature on several days of the month, respectively, 9 days in January and 4 days in December. This implies the need to install an additional support element to ensure that the values of the internal surface temperature are above the critical factor. The solution here is to add an element to provide surface heating for non-compliant days. Another important role is played by the arrangement of the structure detail in the external perimeter wall. In this case, the structure detail consists of two homogenous materials, nevertheless it may be that there is a thermal bridge and also the external perimeter wall may consist of two different materials. These cases may affect the behavior of thermal field with additional aluminum sheet.

The author of the study will further verify the values by simulating the structure details in a 3D temperature field and look for solutions to prevent condensation on the internal surface of the building structures, even in the case of risky thermal bridges. Furthermore, to test the effect of adding a thermally conductive material element to building structure details for different climatic conditions.

References

1. EN ISO 13788 (2012) Hygrothermal performance of building components and building elements—internal surface temperature to avoid critical surface humidity and interstitial condensation—calculation methods, 2nd edn.
2. Vorlíčková P, Kalousek M (2025) Surface condensation on windows of non-insulated buildings and measures before their replacement. *Energy Build* 328:115165
3. Kalousek M (2020) Contact system to suppress thermal bridges in buildings (CZE Patent No. PV2018-179). Licensed to Brno University of Technology, Antonínská 548/1, 602 00 Brno, Veveří, Czech Republic. <https://isdv.upv.gov.cz>
4. Harris DJ (1995) Use of metallic foils as radiation barriers to reduce heat losses from buildings. *Appl Energy* 52(4):331–339
5. Stahl T, Wakili KG (2022) Energy-efficient retrofit of building by interior insulation, materials, methods, and tools, 1st edn. Butterworth-Heinemann, United Kingdom
6. Kalamees T (2006) Critical values for the temperature factor to assess thermal bridges. In: 12th Proceedings of the Estonian academy of sciences engineering. Estonian Academy Publishers, Tallinn, Estonia, pp 218–229
7. Rubeis TD, Evangelisti L, Guattari C, Berardinis PD, Asdrubali F, Ambrosini D (2022) On the influence of environmental boundary conditions on surface thermal resistance of walls: experimental evaluation through a guarded hot box. *Case Stud Therm Eng* 34:101915

A Multi-parameter BIM-Based for Artificial Light Use Assessment: A Food Retail Case Study



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Abstract Artificial lighting represents about 30% of total electricity consumption in food retail buildings. Lighting plays a crucial role in this building typology, as it directly influences the visual perception of food products, affecting customer experience and purchasing behavior. The effective use of natural lighting, combined with solar radiation control, provides an opportunity to reduce electricity consumption due to artificial lighting, while maintaining high-quality illumination and optimal system management. This study investigates the potential reduction in electricity consumption resulting from architectural upgrading scenarios including the incorporation of skylights, use of advanced materials, and the integration of photovoltaic panels in food retail buildings. The analysis focuses on three Key Performance Indicators (KPIs): real energy effectiveness, lighting control, and Life Cycle Assessment (LCA) - to evaluate the impact of some building design upgrades. Results obtained for a retail store in Italy are discussed. A parametric Building Information Model (BIM) and an energy model are implemented and calibrated using real available electricity consumption data. Energy design upgrade scenarios are compared to the baseline condition using KPIs. The results show a reduction of 84% lighting electricity use and 55% annual electricity use. The LCA shows a performance improvement of 85%. This study highlights the effectiveness of parametric design analyses in evaluating multi-criteria decision processes for sustainable energy refurbishment practices.

Keywords Natural lighting · Food retail trade building · Energy efficiency

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1 Introduction

The global building sector in Europe is responsible for about 34% of the final energy demand and contributes 37% of global CO₂ emissions [1]. According to the Paris Agreement, non-residential buildings must improve their performance by 16% by 2030 and by 26% by 2033 [2]. Food retail trade buildings play an important role in this energy transition. When considering energy use per unit of floor area, food retail stores are among the most energy-intensive building typologies [3]. Food retail trade buildings have high energy use, primarily due to refrigeration needs of the cold chain (accounting for 30–60% of final energy use), followed by lighting (~ 30%), Heating, Ventilation, and Air-Conditioning (HVAC), food preparation, and transportation [4]. The energy use of the food retail sector underscores the importance of implementing energy efficiency measures.

The rational energy use for lighting can significantly contribute to the reduction of the total energy use in food retail buildings. The energy end-use demand of food retail buildings is usually met by a combination of electricity and natural gas. However, typically natural gas accounts for < 20% of the total energy demand [5]. Furthermore, most food retail buildings have begun the energy transition towards using electricity alone. In prior literature, many solutions have been proposed to optimize energy use for lighting. Galvez-Martos et al. [3] found that optimizing the operation of lamps using advanced controls and daylight can reduce lighting energy use by up to 40%. Kolokotroni et al. [4] showed that increasing the roof glass area reduced lighting energy use. However, when total energy demand was considered, increasing the glass area beyond 10% raised overall energy demand in all cases studied. However, many of these studies were based on the evaluation of energy efficiency using different retrofit solutions without considering real case studies and models calibrated with real energy use data.

The novelty of the proposed method lies in a multi-parameter assessment by integrating three KPIs: real energy effectiveness, lighting control, and LCA. In our study the real energy data are used to validate energy model. As a matter of fact, different buildings and energy upgrades are applied in central Italy case study such as optimal combination between natural and artificial light and advanced materials utilization to minimize electricity use. In particular, the parametric BIM model is implemented to assess the impact of roof retrofit solutions in the overall electricity use and environmental performance to identify the retrofit scenario which best addresses the KPIs.

2 Materials and Methods

The proposed method starts by developing a detailed BIM model of the case study—retail store in Anagni, Italy—and the urban context in which it is located. The BIM model is developed by integrating architectural, structural, and energy data, allowing for detailed simulations of lighting, HVAC performance, and LCA impact.

After constructing the BIM model, its interoperability with RevitToRhino allows for the building roof to be integrated and parameterized using Grasshopper, enabling the exploration of different configuration scenarios. The energy balances were developed by considering the impact of incident solar radiation on the proposed roof upgrading scenarios, using ClimateStudio within Rhino/Grasshopper3D. The project solutions were evaluated to ensure indoor thermal comfort under all the external climate variations, as well as different temporal profiles of use and space occupancy. The energy and environmental performance of the different scenarios were then analyzed using a Building Energy Model (BEM).

2.1 Performance Parameters

For the tested roof upgrading scenarios, and using the BIM model, three KPIs were computed: energy efficiency, lighting control and LCA. As a boundary condition, a value of 1 represents the maximum achievable optimal performance for all parameters, with 100% indicating the optimal performance for the considered parameter.

Real energy effectiveness. This parameter is defined as the ratio of the actual electricity saved to the maximum achievable electricity savings. This parameter provides a quantifiable measure of how effectively energy optimization strategies perform in comparison to their theoretical potential. It is calculated by dividing the real energy saved by the maximum possible energy saved. By analyzing this parameter, the study evaluates the efficiency of architectural upgrading and technological interventions in reducing energy demand while maintaining optimal operative performance.

$$\text{Real energy effectiveness} = \frac{\text{Real electricity saved}}{\text{Maximum possible electricity saved}} \quad (1)$$

Lighting control. The lighting levels in a supermarket are determined based on area function (general sales: 300–750 lx, fresh product areas: 750–1000 lx, cash areas: 500–1000 lx, storage: 200–300 lx...). This parameter is defined as the ratio of lighting energy use after following the retrofit solution to the baseline lighting energy use. It measures the effectiveness of lighting control strategies, including natural lighting control, optimal integration with artificial lighting, LED with DALI systems, and IoT integration. A lower ratio indicates a more efficient lighting system, demonstrating

improved energy performance while maintaining adequate illumination levels for different visual tasks. This parameter also evaluates the impact of smart lighting technologies on overall energy savings.

$$\text{Lighting control} = \frac{\text{Lighting energy saved}}{\text{Baseline lighting energy use}} \quad (2)$$

LCA indicator. This indicator is defined as the ratio of CO₂ saved to the GW_{effect} calculated using the Eco-Indicator 99 [6]. It provides a measure of the environmental benefits associated with the proposed architectural upgrading and technological interventions. A high value indicates a greater reduction in GHG emissions. This indicator enables the assessment of the sustainability of different daylighting and energy efficiency strategies, ensuring that the proposed solutions contribute to lower carbon footprints and improved environmental performance.

$$\text{LCA indicator} = \frac{\text{CO}_2 \text{ saved}}{\text{GWe}} \quad (3)$$

2.2 Case Study

A representative large-scale food retail building with a common design features and functional elements found in many similar structures, based on a thorough typological analysis was selected.

The case study is located in Anagni, Italy (N 41.73, E 13.13, 226 m above sea level). It represents a climatic zone D, characterized by Heating Degree Days (HDD) between 1411 and 2100 according to the Italian Legislation (DPR 412/93 [7] and Law 10/91 [8]). HDDs are used to estimate the energy needed for heating, calculated based on outdoor temperatures below a defined threshold, typically 20 °C. The HDD value for Anagni is 1911. The structure is built with concrete pillars and concrete beams. The roof of the sales area is flat with a concrete structure, while the center features a double-decker roof with a wooden structure spanning 5 m.

2.3 Energy Model Implementation and Calibration

Thanks to the interoperability of BIM with energy modeling software, such as the well-known DesignBuilder, the energy model of the building-plant system is carried out. Then, dynamic numerical simulations are conducted providing a detailed representation of the physical structure and energy systems. Indeed, the model allows for a realistic analysis and combination of refrigeration, HVAC system, lighting, and occupancy patterns, and, therefore, the digital simulation of the effect of potential

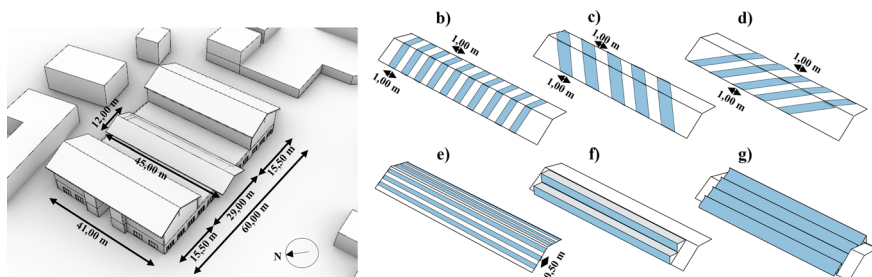


Fig. 1 Different skylights configurations. **a** baseline; **b** scenarios 1, 2, 3, 4, 5 and 6; **c** scenarios 7, 8, 9, 10, 11, and 12; **d** scenarios 13, 14, 15, 16, 17 and 18; **e** 19, 20, 21, 22, 23 and 24; **f** scenarios 25, 26 and 27; **g** scenarios 28, 29 and 30

retrofit strategies (before they are implemented). The BEM model is calibrated using the monthly electricity consumption for the year 2022 data. Weather data from the local regulatory weather station and for the year 2022 is used as boundary conditions.

The model calibration is based on the calculation of the Normalized Mean Bias Error (NMBE) and the Coefficient of Variation of the Root Mean Square Error (CV(RMSE)) [9]. The calculated NMBE and CV(RMSE) indices for the calibrated model fall under the tolerance range according to the reference ASHRAE standard. Indeed, when monthly values are considered, the model is considered calibrated when $NMBE < 15\%$ and $-5\% < CV(RMSE) < 5\%$. Calibration results of the BEM are $NMBE = -3.05\% < 15\%$ and $-5\% < CV(RMSE) = 3.03\% < 5\%$.

2.4 Retrofit Scenarios

Ten architectural roof upgrading scenarios (Fig. 1) were considered:

- (1) It includes skylights positioned on the double-pitched roof of the building. These skylights are perpendicular to the rooftop. In this scenario, the skylights are constructed with double glass and, inside the building, a translucent ceiling (e.g., made of a translucent material) is applied to shield direct solar radiation.
- (2) It equals scenario 1 with added photovoltaic (PV) panels on the roof with a peak power of 440 W facing south and inclination 30° .
- (3) It is equal to scenario 2, plus the existing fluorescent lamps are completely replaced with LED and DALI control.
- (4) The skylights on the double-pitched roof (equal to scenario 1) are modelled with a photochromic glass. The internal translucent ceiling is not applied.
- (5) It equals scenario 4, with added PV panels on the roof facing south.
- (6) It is equal to scenario 5, plus the existing fluorescent lamps are replaced with LED and DALI control.
- (7) The skylights with double glass (equal to scenario 1) are rotated to have an east–west orientation.

- (8) It equals scenario 7, with added PV panels on the roof facing south.
- (9) It is equal to scenario 8, plus the existing fluorescent lamps are replaced with LED and DALI control.
- (10) The skylights with double glass (equal to scenario 3) are implemented with photochromic glass.
- (11) It equals scenario 10, with added PV panels on the roof facing south.
- (12) It is equal to scenario 11, plus the existing fluorescent lamps are replaced with LED and DALI control.
- (13) The skylights with double glass (equal to scenario 1) are rotated to have a North–South direction.
- (14) It equals scenario 13, with added PV panels on the roof facing south.
- (15) It is equal to scenario 13, plus the existing fluorescent lamps are replaced with LED and DALI control.
- (16) The skylights with double glass (equal to scenario 13) are implemented with photochromic glass.
- (17) It equals scenario 16, with added PV panels on the roof facing south.
- (18) It is equal to scenario 17, plus the existing fluorescent lamps are replaced with LED and DALI control.
- (19) It includes skylights parallel to the rooftop with double glass positioned on the double-pitched roof of the building. Inside the building the translucent ceiling.
- (20) It equals scenario 19, with added PV panels on the roof facing south.
- (21) It is equal to scenario 20, plus the existing fluorescent lamps are replaced with LED and DALI control.
- (22) The skylights with double glass (equal to scenario 19) are implemented with photochromic glass.
- (23) It equals scenario 22, with added PV panels on the roof facing south.
- (24) It is equal to scenario 23, plus the existing fluorescent lamps are replaced with LED and DALI control.
- (25) Shed roof with double glass positioned on the south surface of the double-pitched roof of the building.
- (26) It equals scenario 25, with added PV panels on the roof facing south.
- (27) It is equal to scenario 26, plus the existing fluorescent lamps are replaced with LED and DALI control.
- (28) Replace the whole existing roof of the building with a shed roof.
- (29) It equals scenario 28, with added PV panels on the roof facing south.
- (30) It is equal to scenario 29, plus the existing fluorescent lamps are replaced with LED and DALI control.

3 Results and Discussion

Table 1 provides the results and comparison of the different proposed parameters.

The results show the energy-environmental potential of each scenario. The best scenarios for real energy effectiveness are scenarios 1, 2, 3, 5, and 7 with PV panels, LED lamps, and the DALI system. As a matter of fact, in these scenarios, this indicator reaches a value of 0.50. This fact shows a 50% total energy reduction.

The best scenarios for the LCA indicator are scenarios 1 and 2 with PV panels, LED lamps and the DALI system. In scenario 2 the LCA performance indicator has a value of 0.85. If scenario 3 is considered, the efficacy of lighting control is more than 70% and real energy effectiveness more than 35%.

In Fig. 2 is shown the dynamic relationship between real energy effectiveness, lighting control, and LCA indicator. Each point of the graph represents one specific scenario. The distribution of points highlights the trade-offs between real energy effectiveness, lighting control, and environmental impact. In Fig. 3 the comparison of real energy effectiveness, lighting control, and LCA is shown.

The best scenario, considering all KPIs, is Scenario 9. This combination achieves maximum energy savings, optimal lighting conditions, and significant environmental benefits.

Table 1 Real energy effectiveness, lighting control, and LCA indicator values for all scenarios

Scenario	Real energy effectiveness	Lighting control	LCA	Scenario	Real energy effectiveness	Lighting control	LCA
1	0.35	0.31	0.18	16	0.08	0.17	0.05
2	0.42	0.31	0.22	17	0.14	0.17	0.07
3	0.55	0.62	0.27	18	0.42	0.58	0.22
4	0.07	0.15	0.14	19	0.34	0.33	0.18
5	0.14	0.15	0.28	20	0.40	0.33	0.19
6	0.53	0.58	0.85	21	0.54	0.62	0.26
7	0.34	0.71	0.55	22	0.08	0.17	0.05
8	0.39	0.71	0.62	23	0.14	0.17	0.07
9	0.53	0.84	0.84	24	0.42	0.58	0.22
10	0.09	0.16	0.05	25	0.10	0.13	0.05
11	0.17	0.16	0.07	26	0.16	0.13	0.08
12	0.41	0.58	0.28	27	0.37	0.57	0.22
13	0.34	0.37	0.28	28	0.05	0.19	0.03
14	0.40	0.37	0.19	29	0.13	0.19	0.06
15	0.54	0.62	0.26	30	0.41	0.59	0.20

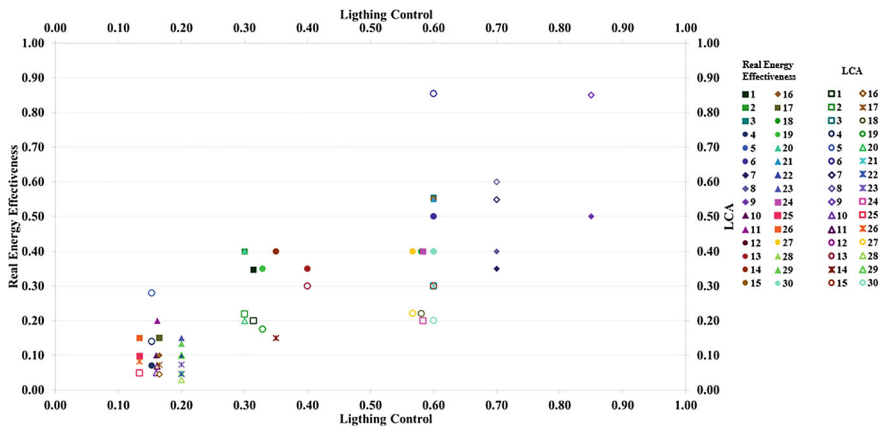


Fig. 2 Relationship between real energy effectiveness, lighting control, and the LCA

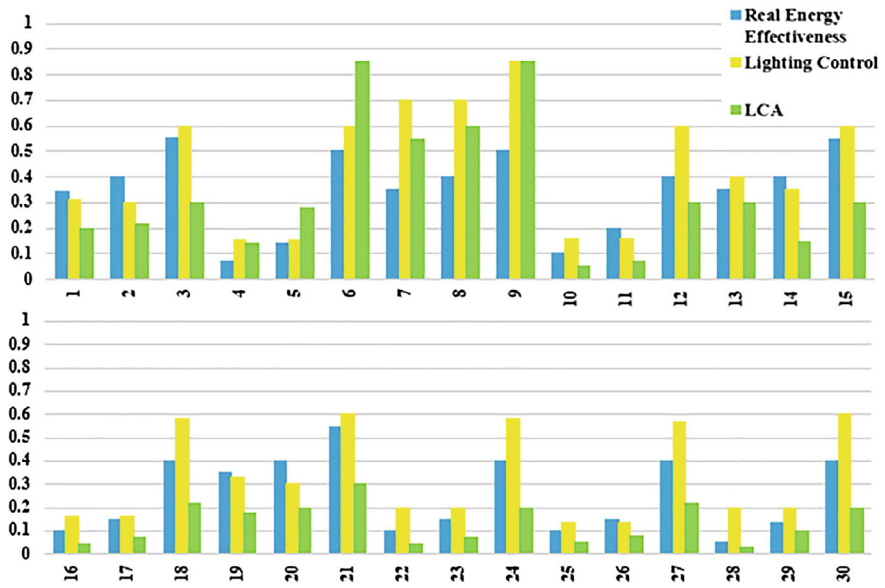


Fig. 3 Performance comparison of real energy effectiveness, lighting control, and LCA

4 Conclusion and Future Developments

This research proposes a multi-parameter method for assessing energy design solutions to reduce energy consumption and environmental impact in large-scale food retail buildings. This method helps identify effective retrofit strategies by comparing three key performance indicators—real energy effectiveness, lighting control, and LCA. The method utilizes BIM interoperability to implement simulation models of

representative buildings based on real data and information, and incorporates integrated dynamic simulations for energy assessment, natural and artificial lighting control, and environmental performance.

Results obtained for a case study—retail store in Anagni, Italy—are discussed. They show that it is possible to reduce 80% of lighting electricity use by means of solar radiation control, applying dedicated skylights on the roof, integrated PV panels, and LED with DALI control system. These energy-architectural upgrade designs are crucial because they provide a reduction on the total electricity use of about 50% with an optimal improved environmental indicator of 85%.

The proposed method lends itself to in-depth analysis and comparisons on multiple case studies located in different geographical and climatic areas, but also urban contexts with different anthropogenic impacts and related heat islands.

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References

1. Global status report for buildings and construction—beyond foundations: mainstreaming sustainable solutions to cut emissions from the buildings sector. <https://wedocs.unep.org/20.500.11822/45095>. Last accessed 20 Feb 2025
2. Energy performance of buildings directive adopted. https://ec.europa.eu/commission/presscorner/detail/en/ip_24_1965. Last accessed 20 Feb 2025
3. Galvez-Martos JL, Styles D, Schoenberger H (2013) Identified best environmental management practices to improve the energy performance of the retail trade sector in Europe. *Energy Policy* 63:982–994
4. Kolokotroni M, Tassou SA, Gowreesunker BL (2015) Energy aspects and ventilation of food retail buildings. *Adv Build Energy Res* 9(1):1–19
5. Spyrou MS, Shanks K, Cook MJ, Pitcher J, Lee R (2014) An empirical study of electricity and gas demand drivers in large food retail buildings of a national organisation. *Energy Build* 68(PART A):172–182
6. Eco-indicator 99 Manual for Designers A damage oriented method for life cycle impact assessment
7. D.P.R. n. 412 del 1993. https://www.bosettiegatti.eu/info/norme/statali/1993_0412.htm. Last accessed 20 Feb 2025
8. Legge n. 10 del 1991. https://www.bosettiegatti.eu/info/norme/statali/1991_0010.htm. Last accessed 20 Feb 2025
9. American society of heating, ventilating, and air conditioning engineers (ASHRAE). Guideline 14-2014 Measurement of energy and demand saving, Atlanta, GA, USA

Sustainable Geometries: A Comparative Analysis of Thermal Performance in Uninsulated 3D Printed Concrete Wall Topologies



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Bárbara Rangel , and Jaime Cunha

Abstract 3D printing has become a leading trend in research and development, playing a crucial role in advancing the Construction 4.0 industry. Aligning with future sustainability goals by increasing productivity and minimising material waste, it is seen as a promising solution for sustainable construction. Concrete, valued for its availability, strength, and adaptability, is a primary material in 3D printing worldwide. However, its high usage of cement-based material, whose production leads to significant CO₂ emissions, drives up its environmental impact substantially. Enhancing the thermal efficiency of 3D printed concrete structures offers a pathway to mitigate this impact. Literature indicates that thermal optimisation can be achieved by modifying structural topology or geometry. This review paper examines thermal optimisation in uninsulated 3D printed concrete walls by comparing 13 topologies referenced in the literature. These configurations were compared based on their geometric properties such as wall thickness and void percentage, as well as their U-values, to identify the primary factors affecting their thermal performance. In the cases analysed, U-values ranged between 0.61 and 3.485 W/m²K. Among them, the diamond, cob, and double-rowed configurations—featuring smaller air cavities, longer heat path distances, and more branches and intermediate barriers—demonstrated the best thermal performances within their respective studies. While findings indicated that majority of

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the studied topologies might need additional insulation to comply with several European U-value standards for new building envelopes, optimising wall geometry should remain to be pursued to reduce dependence on additional insulation measures.

Keywords 3D printed concrete • Thermal performance • Geometry

1 Introduction

3D printing (3DP), one of the key additive manufacturing methods, is a process of developing three-dimensional shapes by sequentially applying material layers [1]. This technology allows the production of complex and non-standard elements, providing flexibility and adaptability to the construction process. The European Commission reports that digital technologies, including 3DP, offer opportunities for the construction industry to assist in the sustainable shift of the built environment. According to the latest statistics, the construction industry generates 37.5% of waste and consumes 40% of the energy in the European Union. Therefore, further construction industrialization is crucial to support the green transition through advancing productivity and resource efficiency [2]. The study of Olsson et al. [3] shows that 3DP reduces the amount of construction waste and carbon footprint, due to the higher optimisation of construction processes and components.

Over the last decade, multiple studies confirm the benefits of 3D printed concrete (3DPC) in efficiency and environmental performance. Study [4] reports that 3DP construction can reduce waste by 30–60%, construction time by 50–70%, and environmental impact by 50%, citing a 3DP modular reinforcement beam that lowered CO₂ emissions by 50%. Alhumayani et al. [5] compare studies on 3DPC performance across six environmental factors, concluding a 24% overall improvement compared to traditional concrete construction.

1.1 Thermal Performance

While considerable research has been developed on 3DP structures like structural and rheological characteristics [4], there is a significant gap in its effective thermal performance [6]. Enhancing the thermal efficiency of construction methods is essential to reducing energy waste in buildings, particularly as nearly 40% of global energy consumption is tied to buildings, with 75% of that energy dedicated to heating and cooling [7]. Achieving climate-neutrality goals requires improved thermal performance, not only to lower energy demand but also to enhance quality of life. For this the building envelope plays a pivotal role, accounting for 50–60% of heat transmission [8], making its improvement an effective way to increase energy efficiency in the construction sector.

While not the sole determinant of a building envelope's thermal performance, especially under non-uniform temperature distributions [4], the thermal transmittance (U-value) serves as a fundamental metric for initial wall topology assessments in the steady state. Representing the heat flux due to a temperature gradient across a multi-layer component [6], the U-value depends on the material's thermal conductivity and its thickness, with a lower value being more insulative and generally preferred. With the freedom and flexibility of 3DP, the aim is to maximize efficiency and optimise performance to reduce the need for extra insulation materials, which affects costs [6]. While additional insulation might still be necessary to meet high energy efficiency standards, particularly for heating which consumes the most energy in buildings [9], the thickness and structure of 3DP walls should be optimised as much as possible.

1.2 Thermal Performance in 3DPC: Topologies

According to [10], there are two main strategies to improve the thermal properties of a building envelope: the first one is through modifying material type, composition, or structure; the second, the focus of this study, is optimising the component's topology by altering its internal geometric configuration. 3DP enables the construction of complex internal topologies that are difficult to achieve with traditional methods. This can result in several benefits, such as (1) reduction of weight; (2) minimising the amount of raw material used; (3) energy saving [11]; (4) enabling designs with special shapes and structures [12]; and (5) facilitation of better adhesion of the mortar to different elements, such as thermal insulation [13].

Besides these, 3DP can enhance thermal performance and energy-efficiency in building envelopes while reducing weight, through the adjustment of infill geometry and proportions [14]. Biomimetic geometries such as cellular or lattice structures, known for their lightness, stiffness, and excellent thermal and acoustic properties, are prime examples of such designs [6]. Literature suggests that the improved thermal performance of these designs is related to different factors, such as: (1) air pockets, which can reduce convective and radiative heat transfer [10] and improve insulation [15]; (2) intricate internal geometry, which can elongate heat conduction paths [15] and prevent overheating caused by radiation [16]; and (3) multiple rows or barriers, which reduce thermal conductivity [4]. Applying these concepts, [17] were able to design an uninsulated 30 cm thick cellular tetrakaidecahedron 3DPC wall with a U-value of 0.58 (W/m²k), which already complies with certain European U-value standards [18]. While topologies need to consider other factors such as mechanical and printability properties, 3DP makes it possible to embed high thermal performance in mono-material components customizable for different climates [15].

2 Methodology

This review paper starts with the selection of 13 3DPC wall topologies from three experimental studies, focused specifically on uninsulated cases. Data related to geometric properties (such as wall thickness, void percentage, and filament width) and thermal performance (U-value) are then gathered from these studies. Afterwards, comparisons are made among the specified variables, which are then analysed and synthesised to identify strengths, limitations, and correlations among the topologies. Finally, conclusions are made through assessment of the schemes against standards, and through recommendations for potential future studies.

3 Analysis of the Samples

Thirteen uninsulated 3DPC wall topologies were analyzed from three studies from Suntharalingam et al. [19], AlZahrani et al. [20] and Chamatete et al. [21].

Study A [19] assessed 16 3DPC wall topologies without cavity insulation, of which five were chosen for this study, through finite element heat-transfer simulations. Results highlighted the impact of wall thickness, number of rows, and intermediate barriers on thermal performance. These uninsulated cavity walls exhibited high U-values, failing standard regulations. Study B [20] analyzed seven 3DPC wall infill structures, selecting five unreinforced ones for comparison. Finite element modeling revealed that increasing the heat path distance and integrating branches reduced thermal conductivity. The U-values of these 3DPC walls were lower than conventional wall constructions, demonstrating enhanced thermal performance. Study C [21] evaluated truss-type, zigzag-type, and cob-like weave lattice geometries, showing how void areas significantly influence heat transfer. Truss-type walls exhibited the poorest performance, while cob-like walls showed superior resistance due to smaller voids and insulative air layers. High U-values were observed across all uninsulated cases.

All three studies used finite element modelling for steady-state heat-transfer analyses, focusing on uninsulated 3DPC wall topologies. U-values were obtained for each topology, to demonstrate the correlation of geometric properties with overall thermal performance.

4 Results Discussion

Studies A and C reported U-values ranging from 3.48 to 1.01 W/m²K, while Study B presented values below 1 W/m²K, likely due to differences in design considerations, simulation parameters, and material properties. While not the focus of this study, mortar material properties can significantly influence the thermal performance of

Table 1 Material properties specified for each study

Study	Material	Density (kg/m ³)	Thermal conductivity (W/mK)	Specific heat (J/gK)	Modelling tool	Source
A	3DPC mix	1522	0.2000	0.7300	Abaqus	Suntharalingam et al. [19]
	Air cavity	Ideal gas	0.0242	1.0064		
B	3DPC mix	1400	0.3708	1.1000	Abaqus	AlZahrani et al. [20]
	Air cavity		0.0260			
C	3DPC mix	1950	0.9790	0.9720	Ansys workbench	Chamatete et al. [21]
	Air cavity	Ideal gas	0.0242	1.0064		

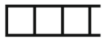
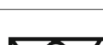
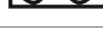
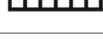
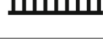
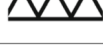
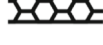
a 3DP wall. Density, while not directly used to calculate U-values, is important as it can impact thermal conductivity, a key component in determining the U-value. Specific heat, though not directly influencing U-value, also offers insight into heat transfer capacity. Table 1 summarizes the material properties extracted from each study. Study C's mix, with the highest density, also possessed the highest thermal conductivity, while Study A used the mix with the lowest specific heat and thermal conductivity.

4.1 Influence of Geometry

Table 2 exhibits how differences in infill geometries can result in thermal performance variations in 3DPC. Diamond, cob, and double-row topologies demonstrated superior thermal performance in their respective studies, while single-row square and triangular configurations exhibited higher U-values. Despite the potential of 3DPC topologies, most configurations failed to meet European thermal transmittance standards (e.g., U values in W/m²K of Germany: 0.28, Spain: 0.37–0.8, Finland: 0.204) [18]. However, Study B walls (0.85–0.61 W/m²K) outperformed red clay brick (2.475), concrete brick (4.88) and insulated red clay brick (1.31). While insulation can enhance performance, optimising wall geometry remains crucial to reduce reliance on insulating materials and minimise environmental impact. Improved thermal efficiency without insulation also benefits interior walls, where performance requirements are lower, aiding in cost-effective building solutions.

In Study A, the single-row 100 mm thick square-type configuration displayed the highest U-value at 3.16 W/m²K. In contrast, 200 mm thick double-row triangular and sinusoidal-shaped topologies resulted in the lowest thermal transmittance among all the configurations, both with a U-value of 1.01 W/m²K. In Study B, the 200 mm thick diamond configuration exhibited the lowest U-value (0.61 W/m²K), followed by hexagonal (0.65 W/m²K) and square (0.655 W/m²K). Study C reported the poorest performance for zigzag/truss-type walls (3.485 W/m²K), whereas the

Table 2 Summary of geometric and thermal properties of studied topologies

Topology picture	Topology/ Geometry	Material	Wall thickness (mm)	Void percentage (%)	Filament width (mm)	U-value (W/m ² K)
 (a)	Single-row square lattice	A	100	64.1	12	3.16
 (a)	Single-row triangular (zigzag)	A	100	52.5	12	2.68
 (a)	Double-row square lattice	A	100	45.6	12	1.89
 (a)	Double-row triangular	A	200	21.7	25	1.01
 (a)	Double-row sinusoidal	A	200	36.4	25	1.01
 (b)	Square	B	200	48	35	0.655
 (b)	Rectangular	B	200	48	35	0.85
 (b)	Triangular	B	200	48	35	0.73
 (b)	Hexagonal	B	200	48	35	0.65
 (b)	Diamond	B	200	48	35	0.61
 (c)	Truss (zigzag)	C	305	58.4	35	3.485
 (c)	Square zigzag	C	305	57.1	35	3.472
 (c)	Cob	C	305	53.2	35	2.77

(a): diagrams based on [19]; (b): diagrams based on [20]; (c): diagrams based on [21]

cob-like weave achieved superior results ($2.77 \text{ W/m}^2\text{K}$). From these results, the key factors influencing thermal performance were identified as:

Wall thickness. U-values of walls generally decreased with increased wall thickness, regardless of cross-sectional configuration, as demonstrated by comparing the topologies within Study A.

Number of intermediate rows or barriers. Double-row configurations significantly reduced U-values compared to single-row designs. In Study A, double-row triangular and sinusoidal designs exhibited a 42.10% and 40.72% decrease respectively, in 200 mm thick walls. The study reports that more intermediate barriers correlate to reduced material conductivity, improving thermal efficiency.

Heat path. Longer heat paths, like in Study B's diamond configuration, decreased thermal bridging by increasing resistance to heat transfer. Conversely, shorter, direct paths like in the rectangular design, resulted in higher U-values. Branching patterns in hexagonal and diamond shapes, which provide more ways for energy to travel, also reduced heat transfer and lowered U-values.

Void percentage, size, and distribution. Study C highlighted that lower void percentages could correlate with decreased U-values, with cob-like weaves (53.2%) outperforming zigzag/truss designs (58.4%). However, Study B showed that thermal performance is not governed by void percentage alone, and that void size and distribution are also crucial factors. Larger voids increase heat flux due to convection currents, while smaller, evenly distributed voids enhance insulation. Even at equal void percentages, Study B illustrated that designs with smaller voids, such as hexagonal, exhibited lower U-values.

While these factors contribute to thermal performance, their combined effects determine overall efficiency. Likewise, a future goal of this study is to execute a more robust, global analysis that includes pertinent thermal performance parameters such as mass and thermal capacity per unit area, as well as performing experimental validation to complement the numerical models and to account for dynamic state conditions. Investigating combined geometries could yield more energy-efficient solutions, while incorporating holistic evaluations (structural, acoustic, fire, moisture, and sustainability aspects) through academia-industry collaboration could aid in their standardization and facilitate widespread adoption in diverse climates and economies.

5 Conclusions

Focusing on geometric factors and U-values, this review paper compares the thermal performance of 13 3DPC wall topologies and concludes that thermal performance can be improved through combined geometric strategies. The diamond, cob, and double-rowed topologies demonstrated improved performance, facilitated by reducing void sizes and increasing wall thickness, number of intermediate barriers, heat path length, and branching. While majority of the topologies require additional insulation for

European standards, optimising wall geometry remains crucial to reduce dependence on additional measures. Future research should prioritize global analyses that consider dynamic conditions and pertinent thermal performance parameters, such as mass and thermal capacity, as well as experimental validation to complement these findings.

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References

1. Mohamed RA, Mohamed AFA (2024) Exploring the environmental benefits of 3D printing technology in concrete construction; a review. *Prog Addit Manuf* 1–11
2. Papadaki I, Moseley P, Staelens P, Horvath R, Sanz ON, Lipari M, Velayos PG, Vaananen H (2023) Directorate-general for internal market, industry, entrepreneurship and SMEs. Transition pathway for construction. European Commission
3. Olsson NO, Arica E, Woods R, Madrid JA (2021) Industry 4.0 in a project context: introducing 3D printing in construction projects. *Proj Leadersh Soc* 2:100033
4. Sovetova M, Calautit JK (2024) Thermal and energy efficiency in 3D-printed buildings: review of geometric design, materials and printing processes. *Energy Build* 114731
5. Alhumayani H, Gomaa M, Soebarto V, Jabi W (2020) Environmental assessment of large-scale 3D printing in construction: a comparative study between cob and concrete. *J Clean Prod* 270:122463
6. Pessoa S, Guimarães AS, Lucas SS, Simões N (2021) 3D printing in the construction industry—a systematic review of the thermal performance in buildings. *Renew Sustain Energy Rev* 141:110794
7. United Nations Environment Programme: 2023 Global status report for buildings and construction: beyond foundations—mainstreaming sustainable solutions to cut emissions from the buildings sector. United Nations Environment Programme (2024)
8. Yılmaz Z (2007) Evaluation of energy efficient design strategies for different climatic zones: comparison of thermal performance of buildings in temperate-humid and hot-dry climate. *Energy buildings* 39(3):306–316
9. Papadopoulos AM, Giama E (2007) Environmental performance evaluation of thermal insulation materials and its impact on the building. *Build Environ* 42(5):2178–2187
10. de Rubeis T, Ciccozzi A, Giusti L, Ambrosini D (2024) On the use of 3D printing to enhance the thermal performance of building envelope—a review. *J Build Eng* 95:110284
11. Ntintakis I, Stavroulakis G, Plakia N (2020) Topology optimization by the use of 3D printing technology in the product design process. <https://doi.org/10.28991/HIJ-2020-01-04-03>
12. Feng J, Fu J, Lin Z, Shang C, Li B (2018) A review of the design methods of complex topology structures for 3D printing. *Vis Comput Ind Biomed Art* 1(1)
13. Kaszynka M, Olczyk N, Techman M, Skibicki S, Zielinski A, Filipowicz K, Wroblewski T, Hoffmann M (2019) Thermal-humidity parameters of 3D printed wall. *IOP Conf Ser Mater Sci Eng* 471:082018

14. Ganobjak M, Carstensen JV (2019) Topology-optimized insulating facebrick with aerogel filling. *J Phys Conf Ser* 1343:012195
15. Curth A, Alvarez EG, Sass L, Norford L, Mueller C (2023) Additive energy: 3D printing thermally performative building elements with low-carbon earthen materials. <https://doi.org/10.13140/RG.2.2.14662.65600>
16. Mihalache A, Hrițuc A, Boca M, Oroian B, Condrea I, Botezatu C, Slătineanu L (2021) Thermal insulation capacity of a 3D printed material. *Macromol Symp* 396(1)
17. Briels D, Kollmannsberger S, Leithner F, Matthäus C, Nouman AS, Oztoprak O, Rank E (2022) Thermal optimization of additively manufactured lightweight concrete wall elements with internal cellular structure through simulations and measurements. *Buildings* 12(7):1023
18. Congedo PM, Baglivo C, D'Agostino D, Albanese PM (2024) Overview of EU building envelope energy requirement for climate neutrality. *Renew Sustain Energy Rev* 202:114712
19. Suntharalingam T, Upasiri I, Gatheeshgar P, Poologanathan K, Nagaratnam B, Santos P, Rajanayagam H (2021) Energy performance of 3D-printed concrete walls: a numerical study. *Buildings* 11(10):432
20. AlZahrani AA, Alghamdi AA, Basalah AA (2022) Computational optimization of 3D-printed concrete walls for improved building thermal performance. *Buildings* 12(12):2267
21. Chamatete K, Yalçinkaya Ç (2024) Numerical assessment of thermal bridging effects in 3D-printed foam concrete walls. *Mater Res Express* 11(10):105702