



Environmental effects of urban wind energy harvesting: a review

SYNTHESIS

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ABSTRACT

Transitioning to renewable energy resources is necessary to address the energy and climate crisis and to be in accordance with UN Sustainable Development Goals (SDGs) 7, 11 and 13. Urban wind energy harvesting is still emerging mainly with the use of small wind turbines. Given their implementation challenges, positive and negative effects need to be weighed to make informed policy decisions and regulations. This systematic review evaluates the macro- and micro-scale environmental effects related to implementing small urban wind turbines (SUWTs). Although publications exist on diverse aspects of SUWTs, a review that addresses the broad range of identified environmental effects of SUWT implementations has been lacking until now. This review shows that while the study of the SUWTs' environmental effects can build on the effects associated with large wind turbines, there are also significant differences. Given the heterogeneity of urban conditions, the implementation of SUWTs requires detailed local environmental assessment to characterise accurately most environmental effects, notably the net life-cycle primary energy performance and associated GHG emissions, raw materials depletion, recycling, safety, noise, visual and light pollution, and effects on urban wildlife. Effects that require further investigation and which possibly raise regulatory or social acceptance issues are identified and discussed.

POLICY RELEVANCE

Harvesting urban wind energy can yield multiple environmental, efficiency and resilience benefits. However, several research and policy gaps remain to be addressed before deploying small wind turbines in urban contexts. These include: the need to quantify the net environmental gains of SUWTs based on their performance and life-cycle assessment; the structural implications of deploying SUWTs on existing buildings; the effect of SUWTs on local air quality and microclimates; the potential health and safety risks to those who may pass by; the effects of SUWTs on ecosystems; and the combined effects of SUWTs on people (e.g. noise or light annoyance). Further research and regulation can help to minimise the negative impacts and ensure social acceptability.

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1. INTRODUCTION

1.1 PROBLEM STATEMENT

The energy sector is one of the largest emitters of greenhouse gas (GHG) emissions (Mello *et al.* 2020; Wang *et al.* 2019), driving climate change. In addition, energy demand is projected to rise (US EIA 2021), posing a critical concern as known reserves of oil are anticipated to become depleted by 2055, of natural gas by 2057 and of coal by 2130 (Tasneem *et al.* 2020). Furthermore, driven by recent geopolitical developments, the cost of energy is expected to increase.

In this context, renewable energy resources (RERs) are required. Among RERs, wind energy harvesting, using wind turbines (WTs), is considered one of the most efficient and cost-effective. Prior literature has reported that the environmental footprint of wind energy is low (Mokarram *et al.* 2022), and its economic viability has been proven theoretically and in practice (Guo *et al.* 2021). Between 2010 and 2020 there was a significant rise in investment in wind energy and the use of wind energy for electricity generation (Gil-García *et al.* 2022). In 2020 only, in the European Union (EU), the use of wind power avoided the emission of 333 million tonnes of CO₂e—29% of the GHG reduction target of the EU (Joshi *et al.* 2021).

While WTs are generally installed offshore, or onshore at rural locations where wind is most intense, consistent and unperturbed (Kumar *et al.* 2018), recent attention has been drawn to the prospect of installing small wind turbines (SWTs) within urban areas. Small urban wind turbines (SUWTs) can offer several advantages such as clean energy and fewer grid requirements. However, their environmental effects have only recently started to be examined. In prior literature, the term *impact* has been widely used (and sometimes interchangeably with *effect*) (European Commission 2020). In this review, the term *effect* will be used, given that the focus is not only on addressing the immediate environmental impact driven by SUWT installations but also on their less direct consequences.

In order to identify urban areas where the installation of SUWTs would be most beneficial to maximise wind energy harvesting, while minimising negative effects on the local environment, as well as to assist their regulation and social acceptance, their positive and negative environmental effects must be assessed (Westerlund 2020). This is particularly important given that SUWT investments often depend on urban policymakers who, besides the cost advantages associated with the implementation of RERs (IEA 2022), require the support of citizens. Citizen support is considered a major barrier for the deployment of SUWTs today (Duarte *et al.* 2022).

1.2 AIMS, SCOPE AND STRUCTURE

The aim of this systematic review is to identify, characterise and discuss the environmental effects associated with the implementation of SUWTs for urban wind energy harvesting to assist informed policy decisions and regulations. To date, existing and planned onshore wind farms, located away from cities, have been the subject of in-depth research. In contrast, research on urban wind energy harvesting is more recent. As depicted in Figure 1, research on wind energy has increased by 103% between 2012 and 2022. The research on urban wind energy has increased by 130% in the same period, but still represents a small portion (2%) of wind energy research (Klaeboe & Sundfor 2016; Zhang *et al.* 2021b). Furthermore, prior literature on urban wind energy harvesting has mainly focused on the study of urban wind energy potential and WT technologies (Aravindhan *et al.* 2022), rather than on the formulation of a more comprehensive understanding of the environmental effects of SUWTs.

This paper includes a review and outlook of the environmental effects of installing SUWTs at both macro- and micro-scales. The European Commission has issued guidance documents for onshore (suburban and rural) wind energy developments as part of the EU's nature legislation (European Commission 2020), which enable the environmental impact assessment of non-urban wind farms, but not for SUWT installations. However, while some non-urban WT effects bear similarities to those in an urban context, this is not the case across all environmental effects. As such, it is important to study SUWTs to develop relevant guidelines for their deployment.

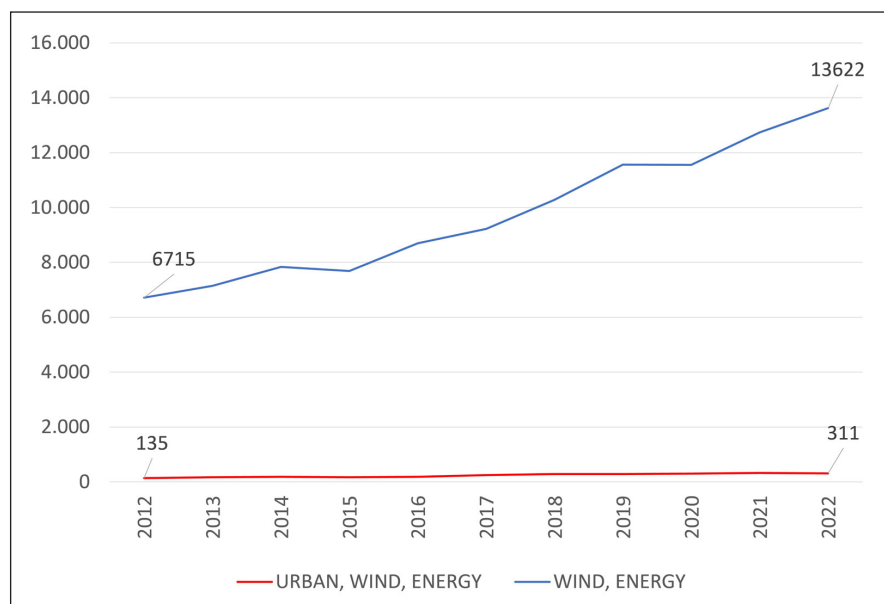


Figure 1: Research publications by year on wind energy (top line) and urban wind energy (bottom line) based on Scopus.

This paper defines effects at the:

- *macro-scale* as those taking place at a planetary scale, e.g. global warming and climate change; and at the
- *micro-scale* as those taking place at the local scale around a particular turbine, e.g. vibrations of a turbine on a building's structure, or noise around the turbine.

The paper is structured as follows. Section 2 presents the environmental effects of large wind turbines (LWTs), which may relate to those of SUWTs. Section 3 presents the review methodology. Section 4 introduces urban wind harvesting, focusing particularly on SUWT technologies and their potential for implementation in urban environments. Section 5 presents the literature review findings. Sections 6 and 7 examine the macro- and micro-scale environmental effects of SUWT implementations, respectively. Section 8 discusses the noteworthy macro- and micro-effects and research directions. Section 9 concludes.

2. LARGE WIND TURBINE (LWT) EFFECTS

Research on LWTs can offer insights into the possible environmental effects of SUWTs. The LWTs exist in large numbers in on- and offshore wind farms and have been studied more extensively. As a result, regulations exist for the LWTs at national and international levels.

The construction, operation and extraction of raw materials produce macro-scale effects. The towers of LWTs are often constructed of concrete, and comprise up to 98% of the total material volume of an LWT (Morini *et al.* 2022). But the materials of the LWTs themselves are generally steel, copper, aluminium, fiberglass and plastic (Crawford 2009; Fleck & Huot 2009; Mello *et al.* 2020), similar to those of SUWTs. The blades are mostly made out of composite materials such as fiberglass or carbon fibre and are not fully recyclable (Jensen & Skelton 2018; Mishnaevsky *et al.* 2017; Xiong *et al.* 2022). The mining of rare-earth materials and the production of neodymium used in some types of generators for LWTs can be responsible for the irradiation of exposed populations in countries of excavation (Bittner *et al.* 2023). Studies on the life-cycle assessment (LCA) of LWTs have reported that the net energy balance would be significantly improved through enhanced lifespan, performance, flexibility for replacement of parts and planned waste management (Teffera *et al.* 2021; Troullaki *et al.* 2019). As such, WT design strategies that consider the second or subsequent life-cycles and repurposing of WT materials/parts are needed (Lichtenegger *et al.* 2020).

Large-scale wind farms affect local atmospheric conditions by taking up kinetic energy from the wind field and creating turbulent fluxes and vertical mixing (Boettcher *et al.* 2015). Wind farms have been reported to reduce the wind speed, mean temperature and specific humidity inside a wind farm and in nearby areas in studies at the meso-scale (Bodini *et al.* 2021; Boettcher *et al.* 2015; Zhu *et al.* 2018). As such, wind farms might affect the local climate.

The effect of LWTs on local wildlife has been examined, especially regarding bird and bat fatalities, ground animal ecosystem disruption, and habitat loss (Dorrell & Lee 2020). Several studies report large birds (Smeraldo *et al.* 2020; Tikkanen *et al.* 2018) and bat (Newson *et al.* 2017) collisions and deaths. There are precedents such as in Norway, where given the numerous bird fatalities, local communities opposed the implementation of LWTs and proposed an alternative renewable energy system (RES) using hydraulic energy (Rygg 2012). In the case of rural and suburban settings, some limited prior literature has also highlighted potential hazards on urban bird species and bats (Haaren & Fthenakis 2011). The rate of mortality by small horizontal-axis wind turbines (HAWTs) in non-urban locations has been estimated using animal carcass findings (as reported by questionnaires), and lies between 0.079 and 0.278 birds per turbine per year, and between 0.008 and 0.169 bats per turbine per year (Minderman *et al.* 2014).

Safety issues arise during the construction, operation and decommissioning of LWTs, which is mostly a concern for construction and maintenance crews (Simos *et al.* 2019). Ice formation and projection is a safety issue for LWTs in cold climates (Vanwijck *et al.* 2021). To mitigate this risk, turbines are blocked at high wind speeds and their production is removed from the grid (Jahromi *et al.* 2022).

Noise produced from WTs has been studied mostly in nearby urban areas. It is perceived as more disturbing in areas where background noise is low (Simos *et al.* 2019). Intermittency and rhythm are reported to be the components of LWT noise that cause most annoyance (Johansson *et al.* 2019; Simos *et al.* 2019). Such noise levels have been reported to be of little or no consequence for health. However, studies have shown that ‘noise annoyance’ depends strongly on non-acoustic factors (Klaeboe & Sundfor 2016). The subjective noise annoyance arises when a sound source is perceived as annoying, irritating or unwanted (Van Renterghem *et al.* 2013). ‘WT syndrome’ is associated with symptoms such as irritableness, fatigue, headaches and decreased performance (Mucci *et al.* 2020; Simos *et al.* 2019). Due to noise, there have been reports of dizziness, migraines, fainting, insomnia and poor sleep quality when living or working in proximity to LWTs (Nakagawa & Singh 2020; Tabrizi *et al.* 2014; Yen & Ahmed 2012). LWT noise may affect self-reported quality of life or health (Mucci *et al.* 2020). Conflicting evidence arises for sleep disturbance, although most of the existing literature agrees that no direct relation exists with LWT noise exposure (Poulsen *et al.* 2018; Qu 2018; Qu & Tsuchiya 2021; Simos *et al.* 2019). Interestingly, the effect of LWT noise on citizen health has been associated with citizens’ attitude towards wind energy (Simos *et al.* 2019).

The visual effect has been associated with visual and light pollution and has been studied for rural and nearby urban areas. It has been reported that WT visibility seems to be more important for residents than proximity (Langer *et al.* 2018). The light pollution is related to the flickering effects of light projected over the WT blades (Pohl *et al.* 2012). To date there has been insufficient evidence to prove a link between moving shadows produced by WTs and an effect on citizens’ health, besides annoyance (Simos *et al.* 2019).

The visual and auditory dimensions of WTs are closely related, and thus both are often simultaneously tested (Simos *et al.* 2019). Residents who can see a WT installation from their dwelling are known to report higher and more frequent noise levels from that WT (Taylor *et al.* 2013).

While the environmental effects of LWTs have been studied across different scales, findings are not directly transposable to SUWTs due to significant differences in size, technology and context. As such, a comprehensive review of the environmental effects of SUWTs is needed, capitalising on the existing knowledge about LWTs.

3. METHODS

For this systematic review, the 2020 version of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) method was followed (Moher *et al.* 2010). The databases selected for the search were Scopus, Web of Science, PubMed and Google Scholar.

Figure 2 provides an overview of the keywords used to search for papers. The search focused on three thematic areas that characterise the scope. The first thematic area is related to wind energy and WT technologies. The second is related to the geographical area of interest, *i.e.* the urban area. The third is related to the environmental effects associated with urban wind energy harvesting. Three keyword groups were used for the search, one group per thematic area. The keywords, and notably the keywords about the effects, were compiled following an initial exploratory search, which included LWTs to enrich the results. For the first thematic group, the composite keywords *wind energy OR small AND 'wind turbin*' OR vertical AND 'wind turbin*' OR urban AND 'wind turbin** were used, where the keyword *turbin** is used to capture both *turbine* and *turbines*. For the second thematic group, the keywords *urban OR cit** were used, the second keyword to capture both *city* and *cities*. The third group included the general terms *effect* and *impact* without the specification of the word *environmental* to capture papers that do not specify an environmental effect/impact as such. Also, specific effects identified by an indicative literature search were included as they might have not used the general keywords above. The keywords were: *effect OR impact OR 'carbon footprint' OR 'Life Cycle Analysis' OR comfort, OR 'well-being', OR noise, OR sound, OR 'visual pollution', OR visibility, OR climate, OR wildlife, OR vibration, OR bird, OR bat, OR safety*. Given that research on urban wind energy harvesting is generally recent, the search was constrained to the period 2012–23.

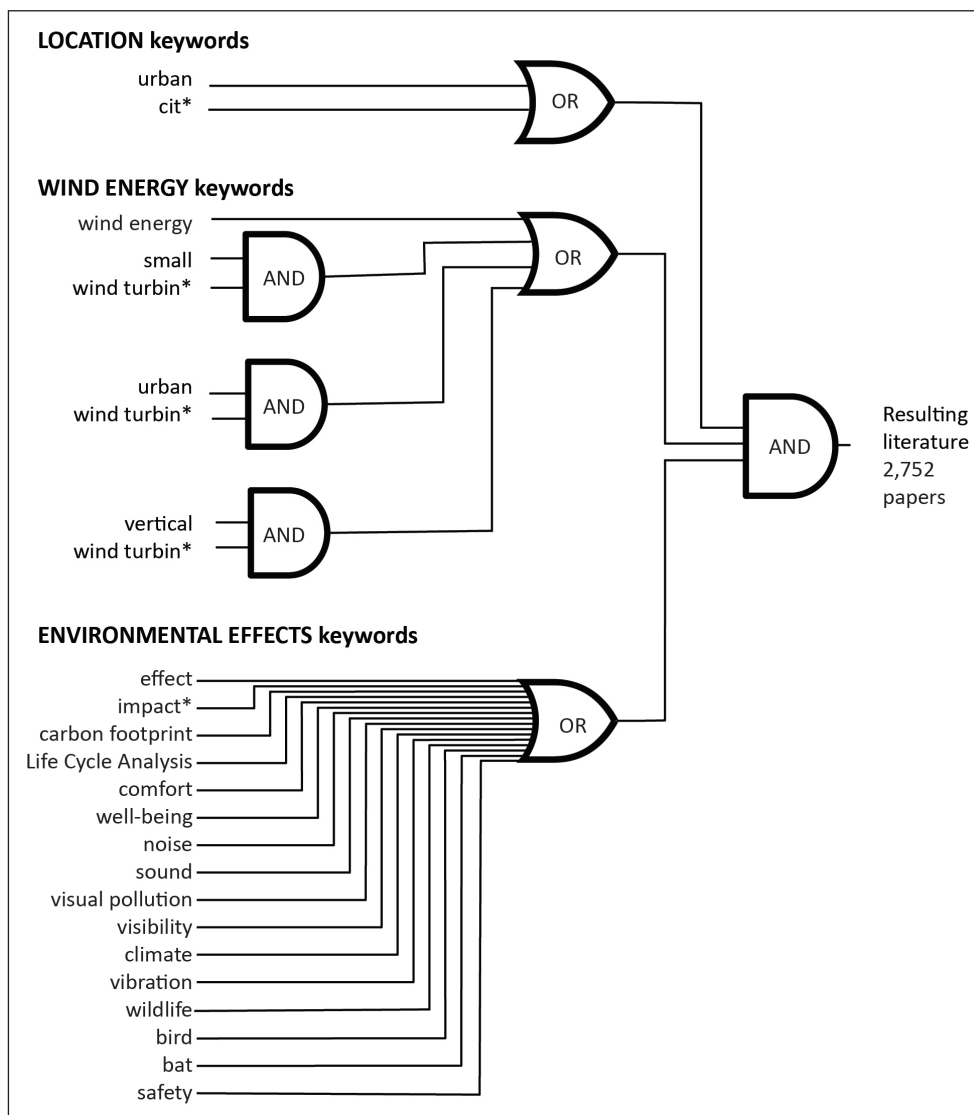


Figure 2: Summary of the search query used to identify the relevant literature.

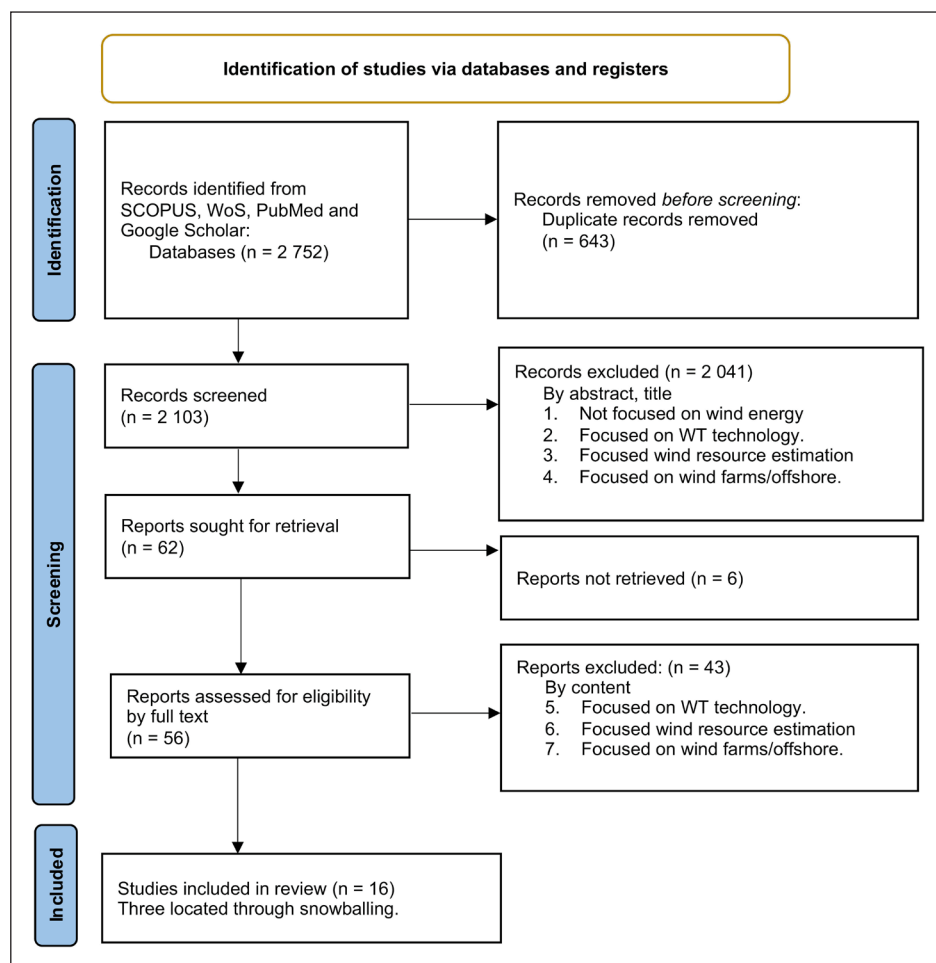


Figure 3: Review process followed in accordance with PRISMA 2020.

Figure 3 depicts the review process. The combined search of all thematic areas in all databases returned a total of 2752 papers. Of these, 643 were duplicates and removed. The exclusion criteria were defined following the PRISMA 2020 (Moher *et al.* 2010) guidelines and applied as follows:

- *Exclusion criterion 1:* Papers not focused on wind energy were considered outside the scope of the review. These papers focused on topics such as urban planning, medical issues, urban noise or visual pollution, addressing concerns not directly related to the implementation of SUWTs.
- *Exclusion criterion 2:* Papers solely focused on WT technologies, such as blade aerodynamic design, blade construction materials, etc., were also excluded.
- *Exclusion criterion 3:* Papers solely focused on the study of wind energy resource mostly through computational fluid dynamic (CFD) simulations, to assess aspects such as the criteria and methods for optimal selection of installation locations, were also excluded.
- *Exclusion criterion 4:* Papers focused on LWTs, such as wind farms, suburban installation of LWTs and offshore installations of WTs, were also excluded.

The exclusion criteria were initially applied through screening by title and abstract, resulting in the exclusion of 2041 papers. The same criteria were applied to a full-text screening stage for the remaining 56 papers. This process yielded 13 papers. With a snowballing technique, three more papers were located, so the final number of papers selected for the review was 16 (Figure 3). This corroborates with the fact that the field under review is indeed a nascent field. Nevertheless, to offer a comprehensive description of all potential environmental effects, data from papers that mostly refer to LWTs and not included in the final literature list are commented on throughout the review.

4. URBAN WIND ENERGY HARVESTING

Cities host most of the global population, a plethora of activities and land uses (Kammen 2016), and are major hubs of energy use. To aim for local energy generation in the city, local wind energy harvesting can be used. It can have several advantages, including reduced local emissions, reduced grid load and fewer energy losses (Gagliano *et al.* 2013; Gil-García *et al.* 2022; Heagle *et al.* 2011; Kumar *et al.* 2018).

The WTs to be installed in cities must be specifically designed for cities. LWTs installed in non-urban areas are generally unsuitable for urban areas. SUWTs are most suitable for urban areas given their reduced size, adaptability to turbulent wind flow conditions and less demanding structural implementation requirements (Kumar *et al.* 2018).

The implementation of SUWTs must consider the heterogeneous wind flow conditions found in urban environments. The urban morphology and thermal gradients affect the wind flow characteristics within the urban canopy layer where wind flow is highly turbulent and wind speed generally low (Anup *et al.* 2018; Fields *et al.* 2016; Kumar *et al.* 2018; Mead 2017; Tasneem *et al.* 2020). Sudden changes in urban morphology can also produce wind gusts, unusual wind shear and changes in atmospheric stability. To ensure performance and durability, SUWTs must be installed in locations where high wind speeds are consistently present and safety can be guaranteed (Karadag & Yuksek 2020). The height and orientation of buildings, their facades and/or roof geometries affect how the wind can be exploited (Gagliano *et al.* 2013; Yang *et al.* 2016). For example, in the case of roof geometry, gabled roofs usually result in more wind power than flat ones under the same weather conditions (Llaguno 2016; Oliveira *et al.* 2020: 5). Above buildings, areas of high wind velocity may form, but also areas with low wind speed and high turbulence. Furthermore, aside from the geometric characteristics of individual buildings, urban design characteristics can modify urban air flow, creating stagnant air areas, and some locations where wind gusts are recurrent (Zhang *et al.* 2022). Thus, within an urban area, neighbouring locations can exhibit very different mean wind speeds and turbulence. Overall, SUWTs were found to perform better over tall buildings (Balduzzi *et al.* 2012), but wind flow characteristics cannot be generalised. All the aforementioned makes it evident that there are suitable locations in cities where the wind potential and SUWT efficiency are aligned to generate enough energy to recover the environmental or financial investment, alongside other unsuitable locations. It is possible that suitable and unsuitable sites may be located in close proximity to one another. An efficient and precise estimation of the wind resources is required for this purpose. Prior literature generally agrees that tall building rooftops are the most suitable urban sites for SUWT implementation. However, precise locations must still be determined, as significant variations in wind potential can exist even within a single rooftop. In the cases where the resulting energy yield is expected to be low, buildings or even entire urban areas could be considered as unsuitable locations for SUWT installations. SUWTs can be installed freestanding, on existing buildings or integrated into the design of buildings (Anup *et al.* 2018; Gil-García *et al.* 2022). The first choice occupies public urban space, the second can take advantage of existing buildings, while in the third, SUWTs are designed and integrated within the overall architectural form (Karadag & Yuksek 2020).

Few tall buildings have been built to date with project-designed SUWTs at the upper end or beyond the SUWT dimensions. These include the Strata tower in London, Bahrain World Center and Pearl River Tower in Guangzhou, China (Karadag & Yuksek 2020). Strata is equipped with three 18-m HAWTs embedded in the building, rated at 19 kW each. They were anticipated to produce 50 MWh/year; however, despite the favourable location of the WTs at an unobstructed height of 147 m, and optimal orientation relative to wind inflow, the actual performance remains unknown (Škvorc & Kozmar 2021). The turbines remain non-operational, likely due to the failure to account for noise and vibration effects. The two 240-m-high towers of the Bahrain World Center support three HAWTs with a diameter of 29 m each. Design errors related to positioning and orientation concerning air flow are believed to have resulted in inefficient energy harvesting and eventual non-operation (TU/e 2014). The Pearl River Tower is another very tall building (309 m) with four 8-m-high vertical-axis wind turbines (VAWTs) rated at 8 kW each and operating at a speed of 25 m/s. Although their performance has fallen short of expectations, primarily due to lower-than-anticipated wind resources, they remain operational.

When choosing between wind or solar energy harvesting, the preference for one of the two technologies may depend on local climate conditions, as these can vary significantly by location. However, there are synergies and complementarities between the two technologies as their performance may follow distinct time frames. Solar energy harvesting performs in daylight and sunny conditions, whereas wind energy harvesting requires wind, which can occur in cloudy settings or at night. The seasonality of wind and solar energy could also be alternating. Solar energy harvesting does not involve moving parts, thus avoiding potential negative effects (e.g. noise, safety) and probably requiring less maintenance. However, it is more demanding on raw materials and their processing.

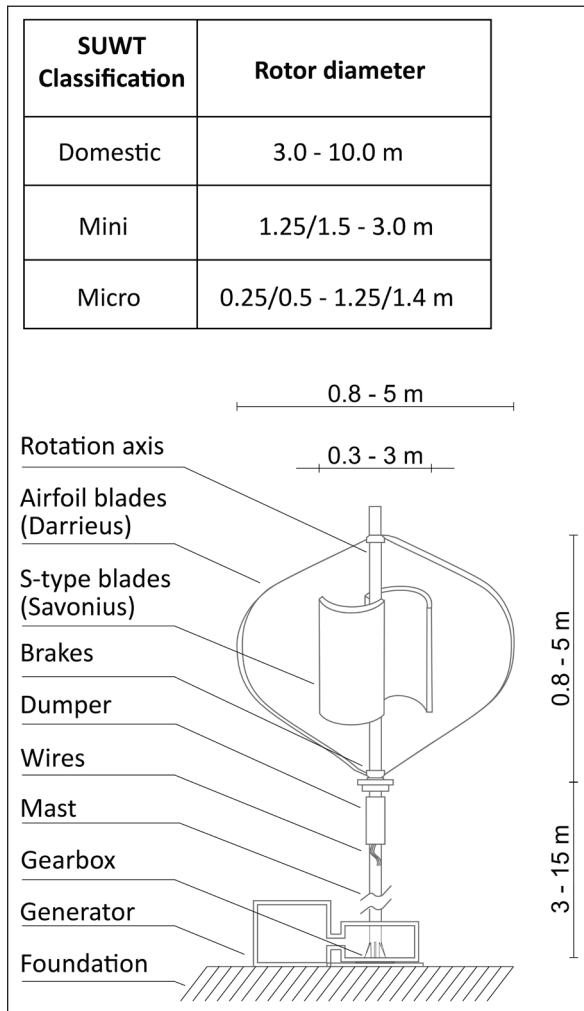


Figure 4: Hybrid (Darrieus and Savonius) vertical-axis wind turbine (VAWT) components with indicative dimensions and their classification by size.

Source: Authors' elaboration.

WTs are mainly divided into two categories based on their axis of rotation: horizontal-axis wind turbines (HAWTs) and vertical-axis wind turbines (VAWT). Most LWTs are HAWTs and most SUWTs are VAWTs.

Figure 4 represents the main types of VAWTs, which are typically deployed in urban settings. These differ from LWTs mainly in terms of size and axis of rotation. SUWTs are considerably smaller. An LWT can be up to 120 m tall with a rotor diameter of 90 m (Hoen *et al.* 2023; Kumar *et al.* 2018). Although there is no universally accepted classification, SUWTs are often grouped based on their rotor diameter size: (1) micro-SUWTs for diameters larger than 1.4 m; (2) mini-SUWTs for diameters between 1.4 and 3.0 m; and (3) domestic SUWTs for diameters between 3 and 10 m (Figure 3). Based on the study of commercially available SUWTs (see the Supplementary Information on Figshare), rotor diameters generally range between 0.35 and 8.30 m, with a median of about 1.40 m. These have a power capacity of about 16–20 kW (Aravindhhan *et al.* 2022; Tummala *et al.* 2016). HAWTs have a higher energy harvesting potential compared to other wind energy technologies; however, their performance is strongly influenced by wind gusts, turbulence

and significant variations in mean wind speeds and directions (Goudarzi *et al.* 2020). A major advantage of VAWTs is that they can exploit wind coming from any direction without the need for a yaw system (for horizontal rotation). Furthermore, VAWTs have a low cut-in wind speed (the speed at which they start to operate) and lower noise levels than HAWTs. Also, VAWTs require less urban space for their installation (Clark *et al.* 2020; Kumar *et al.* 2018).

Depending on whether the rotation is induced by lift or drag forces, VAWTs are divided into lift-based (Savonius), drag-based (Darrieus) and drag–lift-based (Gil-García *et al.* 2022; Kumar *et al.* 2018). The Savonius has the advantage of being simple to design and it performs better at low speeds (Shende *et al.* 2022). On the downside, it usually suffers from negative torques (Tummala *et al.* 2016). The Darrieus type is also suitable for urban environments (Shende *et al.* 2022) and has better aerodynamic performance. A major disadvantage is that it requires an external power source to start spinning. Hybrid SUWTs that incorporate elements from both designs are also starting to be implemented in urban environments (Kumar *et al.* 2018) (Figure 4). There are also other less common designs, such as wind duct turbines which do not require any external moving parts (Grant *et al.* 2008; Nardecchia *et al.* 2021). Furthermore, new urban wind-harvesting technologies include solid-state apparatuses with no moving parts. An example is the solid-state wind energy transformer that creates negative air ions and produces electrical power by harnessing the wind-induced currents and voltages (Richard 2019).

Having introduced the general technology around SUWTs and their differences with LWTs, the following section details the findings of the literature review.

5. LITERATURE REVIEW FINDINGS

A total of 16 papers that focus on SUWT environmental effects were reviewed in depth. The identified environmental effects were categorised into two groups: macro-scale effects (including effects on climate change and raw material depletion) and micro-environmental effects (including effects on urban built structures, air quality and microclimate, urban wildlife, urban health and safety, urban noise pollution, and urban visual and light pollution). Figure 5 summarises all the identified environmental effects of SUWTs. The location of SUWTs is indicative. The tallest building is potentially one of the optimal locations due to its height and unobstructed air flow. The two lower buildings shown with SUWTs on their roofs can benefit from SUWTs depending on their local conditions.

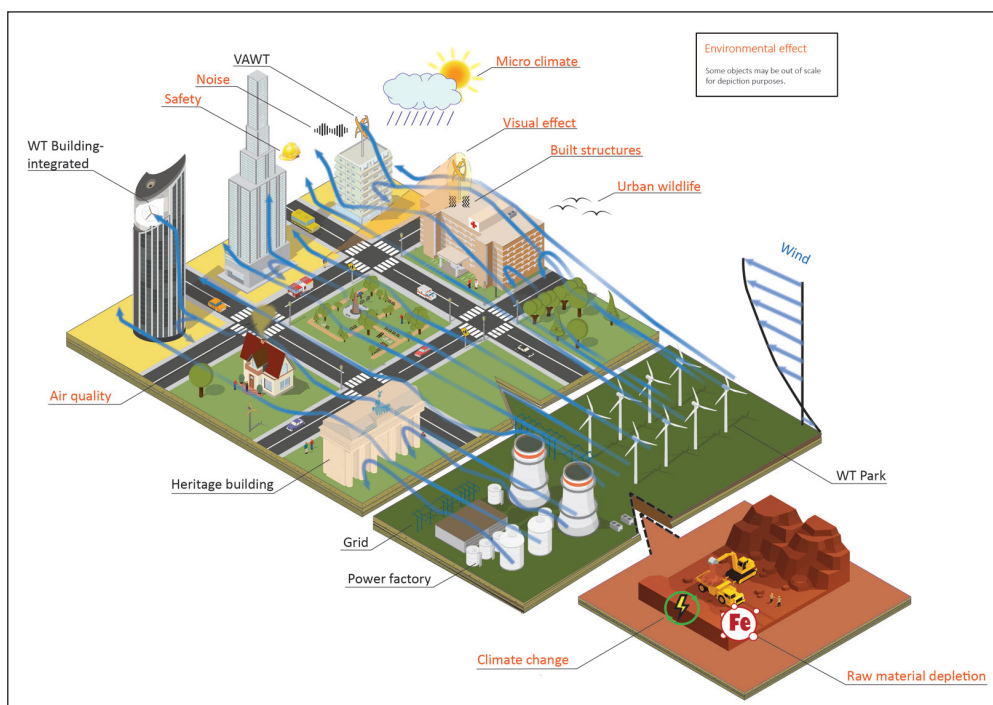
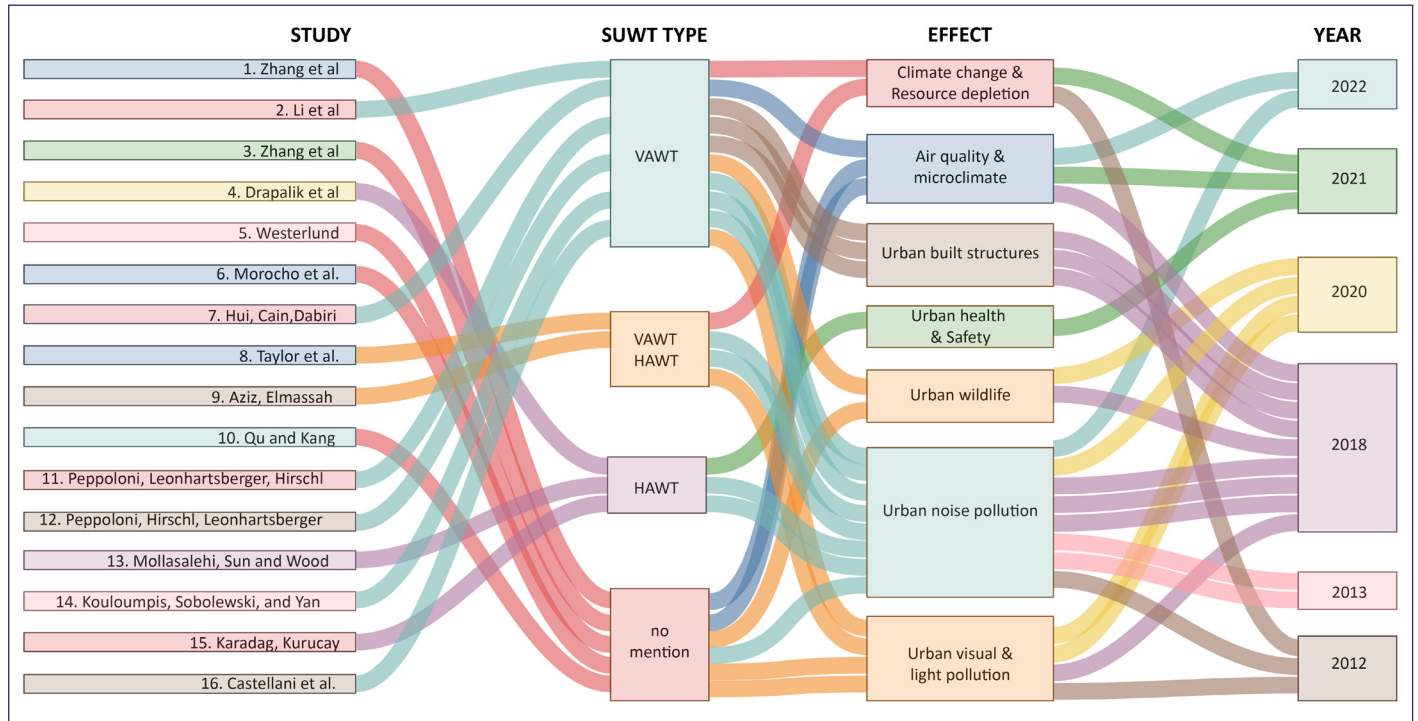


Figure 5: Small urban wind turbines (SUWTs) and their effects at the macro- and micro-scales.

As shown in Figure 6, eight of the selected papers examine VAWTs (50%) and five HAWTs (31.25%), possibly indicating the trend for VAWT installation in urban areas, while three papers (31.25%) do not mention the SUWT technology regarding the axis of rotation. VAWTs are examined for all effects except safety. HAWTs are examined for safety, noise and visual effects, as well as for macro-scale effects. Noise is the most examined effect, followed by visual pollution. The other effects are reviewed in two to three papers, except for the urban wildlife effect which is addressed by one paper only.



All selected papers and the effects reviewed are listed in Appendix A in the supplemental data online. Some papers examine more than one effect (e.g. noise with visual effects, built structure and noise, air quality and microclimate, urban wildlife with visual effects).

Figure 6: Sankey diagram analysing the reviewed literature across different dimensions.

6. EFFECTS AT THE MACRO-SCALE

SUWTs utilise circular motion to convert wind energy into electricity, thereby playing a significant role in mitigating GHG emissions resulting from fossil fuel combustion and the resultant global warming and climate change. Simultaneously, SUWTs require a range of finite resources for their manufacturing, contributing to resource depletion. Climate change mitigation and resource depletion are considered macro-scale effects of SUWTs.

Of the 16 papers reviewed, only two report on the macro-scale effects of SUWTs (see Table S2 in Appendix B in the supplemental data online). LCA, which is a method used to assess overall environmental effects, considering the entire life-cycle from production to disposal (cradle to end-of-life), was used for an H-rotor 5 kW Darrieus VAWT in Poland using actual generation data. In this study, the life-cycle inventory was based on primary data (Kouloumpis *et al.* 2020). Two scenarios were examined: one with recycling and the other with incineration as the end-of-life treatment. The review found that most of the environmental effects were linked to the supporting structure—especially the mast and foundations rather than the turbine itself. Also, the environmental performance was very sensitive to fluctuations in the capacity factor, *i.e.* the average power output divided by the maximum power output (Kouloumpis *et al.* 2020). Aziz & Elmassah (2012) compared the effect of LWTs and SUWTs in terms of material needs and associated resource depletion and reported that SUWTs have better environmental performance than LWTs as they

need fewer materials for manufacturing, construction and the grid per output power. Additionally, they noted a reduced environmental impact as these turbines are installed within urban areas, eliminating the need for additional land usage (Aziz & Elmassah 2012).

7. EFFECTS AT THE MICRO-SCALE

The urban environment can host multiple activities in a small area, and the deployment of SUWTs constitutes an addition to that usually dense environment. SUWTs need to be installed in urban locations where urban wind energy can be harvested effectively. Consequently, the choice of location for the installation of an SUWT is dictated by performance considerations. However, there are micro-scale environmental effects to be considered when planning SUWT installations. SUWTs affect the local environment as they add dead loads on buildings, induce vibrations, potentially contribute to visual and sound pollution, and can cause bird fatalities (Mokarram *et al.* 2022). Some of these effects are immediate, and others long term. Furthermore, the implementation of SUWTs may be particularly challenging when in proximity to heritage buildings. These effects influence the social acceptance of SUWTs, which is a complex (Petrova 2013) and crucial factor for the success of their deployment. Environmental costs can be internalised and affect the final cost of SUWTs through material needs, installation specifications, the introduction of additional equipment such as dampers or sound insulators, or requests of relocation leading to implementations at suboptimal sites (Ehyaei & Bahadori 2022). As such, the local environmental effects of SUWTs need to be addressed and justified economically (Rygg 2012).

To assess the environmental effects of implementing SUWTs, local wind resource estimations must be performed. These can be costly for small-scale implementations such as those associated with SUWT projects (Anup *et al.* 2018; Lu *et al.* 2011). Formulating assessment guidelines for SUWTs requires the identification of their micro-environmental effects (city to neighborhood level), which are described in the following subsections.

7.1. URBAN BUILT STRUCTURES

When operating under highly turbulent winds, as is the case in urban environments, SUWT structures need to be strong enough to withstand instantaneous and long-term wind fatigue loads and wind gusts (Anup *et al.* 2018). Due to the wind torque effect, SUWTs can also add intermittent loads to the structure. VAWTs are expected to have less of an effect on the load-bearing structure than HAWTs since the torque is non-directional (Kwok & Hu 2023; Pollino & Huckelbridge 2011), while SUWTs installed in public spaces result in minor structural challenges (Kwok & Hu 2023).

Three of the 16 papers deal with urban built structure effects (see Table S3 in Appendix B in the supplemental data online). To provide solutions for the safe and reliable operation of SUWTs, Peppoloni *et al.* (2018a) recorded oscillations in direct proximity to the generators of two different SUWTs (one HAWT and one VAWT) by using accelerometers. The amplitudes of the oscillation–acceleration and oscillation velocity were measured by sensors. The researchers concluded that the analysis must consider both the SUWT as, and its combination with, the supporting structure. It was deemed unfeasible to assess and compare the oscillation of different SUWT types installed on different supporting structures because each supporting structure, such as a mast or a building, has a particular rigidity and range of natural frequencies which will influence the oscillation spectrum.

In another study, three different roof-mounted SUWT technologies (Savonius, Darrieus-Helix and three-blade horizontal rotor) were examined in CFD simulation environments and also under real-life conditions using three-dimensional (3D) ultrasonic anemometers (Peppoloni *et al.* 2018b). This study concluded that there are many aspects concerning the SUWT type, building height and shape, oscillation modes and resonances, wind inflow conditions, and others that have an influence on the quality of life of nearby inhabitants.

In the third paper, a commercial Darrieus, three-bladed helical shape SUWT, was tested with accelerometers to analyse the vibrations transmitted to the structure. Results confirmed the usefulness of dampers to decrease vibration and increase comfort in the building. The authors found that with the addition of dampers, up to 90% of the vibration frequencies can be absorbed (Castellani *et al.* 2019). In the case of SUWTs integrated within new buildings, the vibration effects are less challenging given that the structural design and dimensioning of the project consider SUWTs from the onset.

7.2. URBAN AIR QUALITY AND MICROCLIMATE

SUWTs can contribute to the improvement of air quality or mitigation of heat exhaust by replacing existing local energy sources such as those using burning coal, oil or gas on a small scale, e.g. boilers (Staudt 2008). SUWTs are not expected to contribute to higher air pollution concentrations, aside from potential construction dust release during the retrofitting works performed on existing buildings (Ali *et al.* 2019; Krasniqi *et al.* 2022). However, they may affect wind flow, and therefore the microclimate, just as LWTs (Boettcher *et al.* 2015).

In this review, three papers dealt with urban air quality and microclimate effects (see Table S4 in Appendix B in the supplemental data online). Through a study using CFD with the large eddy simulation (LES) method, it was found that roof-implemented SUWTs have no effect on pedestrian-level wind, but they may have a significant effect on wind speed and turbulence over rooftops (Zhang *et al.* 2022). Another study using CFD with the Reynolds-averaged Navier–Stokes (RANS) method, showed that rooftop SUWTs weakened the downwash movement of the building and the turbulent kinetic energy behind the rooftop WT was significantly increased, which led to a stronger vertical pollutant dispersion (Zhang *et al.* 2021a). In the third paper, Peppoloni *et al.* (2018b), by using anemometer measurements, found that roof shape influences wind flow velocity and turbulence intensity. It seems that SUWT deployments may affect local wind patterns, thus having a secondary effect on microclimate and pollutant dispersion, but the scale at which this may occur requires further examination.

7.3. URBAN WILDLIFE

Urban wildlife, which is already affected by many human activities, is very likely also to be affected by SUWTs. The extent of this effect may differ depending on the species, as species have different sensitivities. For example, effects due to noise can range from physical damage to the ears to stress responses, changes in foraging, avoidance of noisy areas and subsequent habitat migration, changes in reproductive success, and changes in vocal communication, as have been observed in the case of LWTs (Li *et al.* 2022; Ortega 2012; Zhu *et al.* 2018).

Two papers dealt with the importance of the effect of SUWTs on urban wildlife (see Table S5 in Appendix B in the supplemental data online). However, these mostly report on the significance of the effect rather than studying the disturbance of wildlife per se. Through public opinion polls conducted in California to examine public receptiveness of SUWTs, it was found that the potential risk of SUWTs to kill birds strongly affects their social acceptance (Hui *et al.* 2018). In an examination of four urban sites in Ecuador as implementation possibilities for SUWT installations with multicriteria decision analysis (MCDA), Morocho *et al.* (2020) proposed to include the collision risk of birds and the potential change in animal behaviour along with other technical, economic, environmental and social criteria. As such, the coverage of the effects of SUWTs on urban wildlife seems to be understudied and potentially significant at the same time.

7.4. URBAN HEALTH AND SAFETY

SUWTs are often installed in proximity to pedestrians, therefore safety concerns are critical. LWTs are known to have been designed for safety, durability and performance according to international standards (Anup *et al.* 2018), but these standards have not been adapted to urban conditions (Anup *et al.* 2020: 87; Aravindhan *et al.* 2022).

Only one paper out of the 16 dealt directly with health and safety effects (see Table S6 in Appendix B in the supplemental data online). Drapalik *et al.* (2021) investigated the hazards posed by ice formation on SUWTs in cold climates, as ice can be ejected significant distances by the rotation of the turbine. The size, mass and geometry of thrown ice fragments were evaluated from observations. These data were used to create a representative set of artificial ice specimens which were repeatedly thrown in experiments to approximate real ice throw. It was concluded that the safety concerns associated with falling ice fragments from SUWTs are not negligible (Drapalik *et al.* 2021) and that appropriate safety measures should be deployed.

7.5. URBAN NOISE POLLUTION

Noise as an environmental stressor can lead to increases in heart rate and blood pressure, and changes in blood viscosity, amongst others (Mucci *et al.* 2020). A prolonged exposure to noise, notably for susceptible individuals, can lead to irritability, aggressiveness, decreased cognitive performance and permanent health damage such as hypertension, heart and blood circulatory system diseases, and even stroke (Mucci *et al.* 2020). WT's have moving parts and therefore generate noise issued from mechanical and aerodynamic components (Manyoky *et al.* 2014; Simos *et al.* 2019).

Noise is the most studied effect with eight of the 16 papers covering it (see Table S7 in Appendix B in the supplemental data online). One study performed a bibliographic research on the effects of deploying RESs in the city, including SUWTs, and reported that VAWTs are virtually silent (Aziz & Elmassah 2012). Another study combined findings from interdisciplinary research linking noise measurements from SUWT installations with an investigation into the effect of individual personality traits and noise perception. This study combined a survey of households living close to one of 12 micro- or small turbine sites, with environmental noise measurements. The results showed that the individual's level of positive and negative affectivity best explained the variance in attitude to WT's and noise perception. It was recommended to capture survey data before and after installing SUWTs to provide a more detailed understanding of the perception of noise (Taylor *et al.* 2013). A third study investigated noise from the vibrations of the SUWT tower using accelerometers placed on the tower of a HAWT, across different frequencies. The noise pollution from the tower was also simulated computationally (Mollasalehi *et al.* 2013). Noise was detected only when the SUWT operated. Close to the turbine, the computed overall noise level did not exceed 30 dB, a level close to typical urban background noise. The sound pressure level due to the tower vibration was negligible at distances of more than about seven times the tower's height (Mollasalehi *et al.* 2013). Another study examined the relationships between morphological attributes and building facade exposures through regression analyses (Qu & Kang 2018). It concluded that in an urban environment, the sound attenuation over a 400–1000-m range is equivalent to the sound attenuation within 600–1600 m in a free field. This study also found that the shape of buildings can greatly reduce noise exposure, creating a quiet facade that is up to 13 dBA quieter than the most exposed (Qu & Kang 2018). Another study conducted metrological evaluation on the repercussions of roof-mounted SUWTs to residents and the direct environment, among other parameters, also in terms of noise (Peppoloni *et al.* 2018b) in two buildings in the 'Lichtenegg' energy research park in Austria. The study concluded that noise is affected by many factors, such as SUWT type, and building characteristics, such as the type of SUWT, height and shape of the building, oscillation modes and resonances, and inflow conditions. Also in Austria, a commercial Darrieus VAWT was tested to analyse the noise it transmitted to a small, experimental building using sound recording equipment. It was concluded that the noise generated might not be negligible (Castellani *et al.* 2019). In a case study of a tall mixed-use building, the environmental noise distribution due to an HAWT located on the rooftop was simulated. The propagation of SUWT noise was found to be dependent on its location, the distance to it and the built environment arrangement. This study proposed that special acoustic improvement would be necessary for facades and WT-integrated structures (Karadag & Kurucay 2021). SUWTs were also studied by a systematic experimental test campaign for different wind speeds in an anechoic wind tunnel (Li *et al.* 2022). Noise production was mainly within the low-frequency region, below 1000 Hz. The windward side of the VAWTs was identified as an important source of noise. The vortex shedding

noise from the laminar boundary layer was identified as the main noise source. The ratio of the shaft diameter to the rotor diameter of VAWTs was found to be a major factor as the shaft noise was considered of importance (Li *et al.* 2022).

7.6. URBAN VISUAL AND LIGHT POLLUTION

WT installations can produce visual obstructions, visual annoyances or light pollution in urban environments (Gagliano *et al.* 2013; Pohl *et al.* 2021).

Four papers of the 16 dealt with visual effects (see Table S8 in Appendix B in the supplemental data online). One study performed bibliographic research on the effects of the RES deployment, including SUWTs, in the city. It is reported that VAWTs are much less visually intrusive than HAWTs (Aziz & Elmassah 2012). MCDA based on sets of technical, economic, environmental and social criteria was used to classify four sites in Cuenca, Ecuador, for their suitability for micro-SUWT installations. The visual effect that reflects on the aesthetic alteration to the urban environment was proposed as a social criterion (Morochó *et al.* 2020). An online survey conducted in 2015 in Finland to assess the social acceptability of SUWTs found that proximity to heritage sites led to decreased acceptance of SUWTs, likely influenced by the sense of 'place identity' of individuals (Westerlund 2020). A public opinion poll in California to examine public receptiveness was conducted by registering and analysing responses to an experimental design presented to them in pictures in order to assess the willingness to accept VAWT in certain urban settings. Visual differences between the VAWTs and HAWTs were not considered significant (Hui *et al.* 2018).

8. DISCUSSION

8.1 CONTRIBUTION OF THIS REVIEW

The present review examines the nascent field of the environmental effects of SUWTs. It reports and discusses the effects found through a systematic literature review following the PRISMA 2020 method. Prior literature reviews on SUWTs have focused mainly on technology, technical characteristics, performance issues and methods for a more accurate estimation of the wind resource.

Regarding the environmental effects of LWTs, many publications focusing on specific effects that may relate to SUWTs were identified (e.g. Micallef & van Bussel 2018; Mucci *et al.* 2020; Ortega 2012; Reja *et al.* 2022; Shende *et al.* 2022; Simos *et al.* 2019), but no prior review that addresses the effects of SUWTs at both the global and local scales was found. This review identifies and discusses an unprecedented range of environmental effects, identifies associated research gaps and proposes areas of further investigation.

8.2 ENVIRONMENTAL EFFECTS OF SUWTS BASED ON A REVIEW OF THE LITERATURE

The macro-effects of SUWTs in terms of resource depletion, embodied energy and GHG emissions are associated with various life-cycle stages, from raw materials extraction to transport, manufacturing, construction, maintenance and end-of-life (Aziz & Elmassah 2012; Kouloumpis *et al.* 2020). The embodied energy used for these stages typically results in GHG emissions, depending on the energy mix. Each life-cycle stage might occur at different locations and even different countries, so the energy mix used may differ significantly. At this macro-level, it has been suggested that SUWTs have better environmental performance than LWTs (Aziz & Elmassah 2012), as their local energy harvesting reduces grid load and transmission losses. Yet, SUWTs, as LWTs, require rare-earth materials, which are a finite resource (Bittner *et al.* 2023). Also, SUWT blades, as for LWTs, are often made of composite materials, which cannot be efficiently reused or recycled (Tzen 2020).

The much more varied micro-effects of SUWTs tend to be interrelated with many other aspects of the urban environment, such as background noise, urban configuration and perception of the population (Taylor *et al.* 2013).

As SUWTs are generally installed on buildings, the structure of these buildings must be able to support them. The vibrations transmitted to the buildings can cause annoyance and discomfort. These vibrations often are unique to the SUWTs–building system and, as such, accurately predicting these vibrations can be difficult and requires advanced modelling (Peppoloni *et al.* 2018b). Nevertheless, mechanical solutions such as dampers seem largely to compensate this effect (Castellani *et al.* 2019) with additional material requirements, embodied environmental flows and financial cost.

Also at the micro-scale, deploying SUWTs is expected to improve air quality when substituting fossil-fuel-based systems. Effects on wind velocity and turbulence have been observed above rooftops (Peppoloni *et al.* 2018b), which may also affect pollutant dispersion by resulting in stronger vertical pollutant dispersion (Zhang *et al.* 2022). While this dispersion depends on the roof type, wind patterns at street level seem unaffected (Zhang *et al.* 2021a). Any potential effects to the microclimate due to changes in wind patterns have not been determined.

In addition, SUWTs might have potential effects on urban wildlife. Protecting birds and bats has been identified as important for urbanites and for the social acceptance of SUWTs (Hui *et al.* 2018; Morocho *et al.* 2020), but the extent to which SUWTs affect birds and bats has not been studied as compared with the existing body of knowledge for LWTs.

Safety risks associated with SUWTs do exist. These have been studied regarding the formation of ice on blades, which may thereafter be projected over long distances at high speed and pose a significant danger (Drapalik *et al.* 2021). To mitigate this risk, SUWTs may be forced to stop operating beyond certain speeds (cut-out).

SUWTs usually result in a small amount of noise pollution. While SUWTs rotate much faster than LWTs and generate noise at higher frequencies, existing research on SUWTs has consistently found very low noise levels (around 30 dBA) in direct proximity of the revolving turbine. The perception of the noise of SUWTs is further attenuated by the ambient noise pollution in urban environments, notably during daytime. It is important to consider the specific urban form around SUWTs as it either attenuates noise levels or amplifies them.

SUWTs are visible objects in the urban environment and their positioning in the city, *e.g.* in terms of proximity to heritage sites (Westerlund 2020), needs to be carefully considered, on top of the purely performative criteria. VAWTs tend to occupy less volume than HAWTs when regarding visual intrusion (Aziz & Elmassah 2012), but this is also disputed (Hui *et al.* 2018). Importantly, both the physics and the perception of the visual and noise effects tend to be intertwined.

8.3 RESEARCH GAPS AND SUGGESTED RESEARCH DIRECTIONS

The environmental effects of SUWTs identified above and their varying depth of investigation, combined with the very few papers specifically focusing on SUWTs, demonstrate that this research field is still nascent. This is corroborated by existing studies in the field (*e.g.* Gagliano *et al.* 2013; Gil-García *et al.* 2022). As such, there are several research opportunities to fill existing knowledge gaps.

First, it is critical to quantify clearly the net environmental gain of SUWTs based on their performance and LCA, including their potential reuse/remanufacturing after their end-of-life (Jensen & Skelton 2018). Only when an LCA of SUWTs is conducted can their environmental performance be determined, enabling policy decisions. Research into novel materials that are reusable/recyclable is needed to move away from the current reliance on composite materials such as fiberglass which are not usually recyclable (Arwood *et al.* 2023). More standardisation in the design of SUWTs would enable the reuse of parts from one SUWT to another, and across manufacturers. Many lessons could be learned from the aviation (Wu *et al.* 2023) or motor vehicle (Matuszewska & Owczuk 2020) industries in this regard. This is important notably for components with significant value,

such as the generator, gearbox and wires. From a methodological perspective, it is important that the embodied environmental flows of SUWTs are quantified using comprehensive life-cycle inventory approaches, such as hybrid analysis (Crawford *et al.* 2018). Most existing studies rely on process analysis, which is known to underestimate embodied flows significantly by omitting parts of the supply chain from the analysis (Jensen & Skelton 2018; Majeau-Bettez *et al.* 2011; Pomponi & Moncaster 2018). Crawford *et al.* (2022) have compared the coverage of process data for a range of construction materials. For materials currently used in SUWTs, e.g. metals, plastics and fiberglass, they found that process data represented, on average, 52.8%, 48.1% and 80.0% of the embodied energy obtained using hybrid analysis, respectively. This is similar to the findings of Wiedmann *et al.* (2011) who found that the embodied energy of LWTs in the UK was twice as high using a hybrid approach as compared with process data. More research on this aspect is needed to establish more comprehensive life-cycle environmental performance benchmarks for SUWTs, including their material compositions and net mitigation of climate change.

Second, the structural implications of SUWT installations need to be clearly established to enable their deployment on existing buildings. Their high number of rotation cycles necessitates attention on fatigue (Tummala *et al.* 2016) in turbine design, as well as the propagation of vibrations into the structures to which they are attached (e.g. cores of high-rise buildings, slabs, masts) (Hunaidi 2000; Rainer 1982; Turner 1993), or even blade failures that may pose a danger. The latter has been studied from an engineering point of view (Anup *et al.* 2020), but the effect on urban areas remains insufficiently addressed. Studies focused on SUWT safety risks can provide local-level guidelines for structural engineering and the design of SUWTs. This aspect is critical to enable their deployment at scale.

Third, more research is needed to better qualify better the effect of SUWTs on local air quality and microclimate, as their installation on low- or medium-rise buildings might affect wind flow and dispersion of pollutants (Zhang *et al.* 2021a). This effect is likely compounded when arrays of SUWTs are installed. The examination of the effects induced by SUWTs in the local micrometeorology at fine granularity is yet to be developed. Advanced CFD simulations will be needed to evaluate the effect of the installation of SUWTs near to industrial complexes, incinerators, power plants and similar infrastructure that emit gases and pollutants. This would result in zoning and placement guidelines for SUWTs.

Fourth, SUWTs present a health and safety risk for passersby. SUWTs are unique moving structures, as opposed to more typical static structures deployed in urban settings (e.g. antennas, masts, lighting poles), thus urban safety is a critical aspect to consider. During their operation, SUWTs can fail and endanger people, by falling parts, for example (Anup *et al.* 2018). Additionally, in cold climates, ice may accumulate on the blades and be detached at high speeds while in operation, and then reach as far as pedestrians or vehicles (Drapalik *et al.* 2021). Research on safety, and mostly concerning the ice threat in cold climates, is required to enable a safer deployment in urban conditions. Certain WT technologies might need to be prescribed as suitable for urban areas with high levels of affluence.

Fifth, the effects of SUWTs on ecosystems still suffer from several research gaps. While the existing literature on LWTs and non-urban SWTs has reported collisions with birds and bats (Haaren & Fthenakis 2011), and behavioural changes of animals due to the noise of WTs (Dorrell & Lee 2020: 3; Li *et al.* 2022; Ortega 2012), such research has been proposed (Hui *et al.* 2018; Morocho *et al.* 2020), but has not been conducted for SUWTs. It is critical to understand better the effects of SUWT on local urban ecosystems that are already made more fragile by human activities.

Finally, it is important to understand better the individual and combined visual and noise effects of SUWTs on people. Life-threatening or severe effects on human health do not seem to be substantiated; however, non-severe health conditions such as sleep disturbance, driven mostly by annoyance, from noise needs further addressing. The visual effect also needs to be investigated regarding light and the flickering effect. Besides the possible health issues, there is also the aspect of aesthetic intrusion, especially when heritage buildings are involved. The noise effect also requires further studies to evaluate how the propagation of the sound level and its frequencies may affect not only humans but also the urban fauna.

In summary, several research gaps remain to be addressed for deploying SUWTs in urban settings with minimal negative environmental effects, notably regarding the safety of people and other living beings. Importantly, their net life-cycle environmental performance, which is a prerequisite for their deployment, is highly location specific as the wind resource can vary significantly on a local scale. Regulations can benefit from this research by implementing measures such as licensing SUWTs with a minimum energy return on investment (e.g. 1.2), or a maximum noise level (e.g. 45 dB).

The complex interplay of different effects and performance metrics might result in guidelines that prescribe the deployment of SUWTs to certain urban areas, might limit the use of certain technologies and might prohibit the installation of SUWTs due to structural safety reasons.

8.4 LIMITATIONS

As with any scientific endeavour, this review suffers from certain limitations. The literature search was conducted using only four databases, *i.e.*, Scopus, Web of Science, PubMed and Google Scholar in English. Relevant papers that might appear in other databases or in other languages could have been missed. Furthermore, effects that have not been used as keywords might have been missed in the literature search, especially if they were not discoverable by the general terms *impact* or *effect* and the combination with keywords from the other thematic areas. This appears to be the case with recycling or recovering crucial materials from SUWTs, such as their blades, given that their recycling or recovery methods can probably be identified in the literature based on constituting materials rather than SUWTs. Additionally, specific effects were found by prior research and indicative search for LWTs and used to choose the additional keywords to augment the generic keywords *effect* and *impact*. While indicative search is helpful in locating research, it may add bias.

Despite these limitations, it is estimated that the field of urban wind energy harvesting has been covered in a way that identifies the most examined effects and that relevant research pathways have been established.

9. CONCLUSIONS

Harvesting urban wind energy using small wind turbines (SWTs) can yield multiple benefits, including: from an environmental performance, a more efficient electricity grid with lower transmission losses, and an enhanced protection from potential power plant failures. This can also result in a higher resilience in the power supply, as when installing rooftop solar photovoltaic panels and a combination of the two technologies. The benefits from introducing small urban wind turbines (SUWTs) can contribute to United Nations' Sustainable Development Goals (SDGs) 7, 11 and 13.

However, deploying SUWTs has also been subject to criticism in terms of social acceptance. Environmental assessment guidelines and urban policies are necessary to weight the pros and cons of implementing an SUWT in a specific location, and to avoid situations where SUWTs are underperforming, inducing environmental stressors or health problems, or provoking citizen opposition.

This paper aimed to establish the basis for the formulation of SUWT installation guidelines using a comprehensive systematic review based on four citation databases and in line with the PRISMA 2020 method, focusing on the identification of the environmental effects associated with urban wind energy harvesting. This review has highlighted the global (macro-scale) and local (micro-scale) effects that are most frequently addressed in the existing literature focusing on SUWT installations. Also, lessons from large wind turbines (LWTs) that might need to be examined for SUWTs have been drawn from the relevant literature.

Several environmental effects and research gaps have been identified. At the macro-scale, there is a need to quantify the life-cycle environmental performance of SUWTs, including their potential reuse and remanufacturing, and to tackle resource depletion and end-of-life material recovery.

At the micro-scale, the structural implications of SUWT implementations on existing buildings need to be further assessed, primarily to address potential vibrations. A positive effect is expected on local air quality, but this might be counterbalanced by the increased dispersion of pollutants. The effect on air quality and the local micrometeorology requires further study as the SUWTs seem to affect local wind patterns by altering the wind velocity and inducing turbulence. Urban health and safety concerns are also to be further assessed based on the technologies and climate zones, since the failure of SUWTs may endanger people by falling parts and, in cold climates, by ice shards. The effects of SUWTs on local ecosystems need to be further studied, given the lack of research focused on urban environments, and the stressors to which urban biodiversity and wildlife are already subject. It is critical to understand better the individual and combined visual and noise effects of SUWTs on people. How visual and noise effects may affect non-severe health conditions, such as annoyance or sleep disturbance, is to be further studied. The visual effects of SUWTs are also related to light and the flickering effect, which, besides aesthetics, may compromise pedestrian safety or create discomfort. On historical and cultural sites, the aesthetic concerns can be more crucial than elsewhere.

Social acceptance remains an important barrier related to the aforementioned environmental effects and mostly noise, visual perception and potential danger to urban wildlife. The local acceptance of SUWTs cannot be guaranteed, despite the climate emergency, and might suffer from not-in-my-backyard (NIMBY)-ism. Thus, analysing the macro- and micro-scale environmental effects associated with implementing SUWTs is necessary for the formulation of guidelines for SUWT deployment, along with community participation strategies which reduce possible uninformed negative perceptions and resistance.

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COMPETING INTERESTS

The authors have no competing interests to declare.

DATA ACCESSIBILITY

The data used for this paper comprise a listing of commercially available small urban wind turbines (SUWTs) by private companies. The listing includes the characteristics of various commercially available SUWT models. The data were collected from the websites of the companies, and their technical description are publicly available on Figshare (<https://doi.org/10.6084/m9.figshare.21732173>).

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SUPPLEMENTAL DATA

Supplemental data for this paper can be found at: <https://doi.org/10.5334/bc.491.s1>

- Ali, G., Abbas, S., Pan, Y., Chen, Z., Hussain, J., Sajjad, M., & Ashraf, A. (2019). Urban environment dynamics and low carbon society: Multi-criteria decision analysis modeling for policy makers. *Sustainable Cities and Society*, 51, 101763. <https://doi.org/10.1016/j.scs.2019.101763>
- Anup, K., Whale, J., Evans, S. K., & Clausen, P. D. (2020). An investigation of the impact of wind speed and turbulence on small wind turbine operation and fatigue loads. *Renewable Energy*, 146, 2087–2098. <https://doi.org/10.1016/j.renene.2019.06.124>
- Anup, K. C., Whale, J., & Urmee, T. (2018). Urban wind conditions and small wind turbines in the built environment: A review. *Renewable Energy*, 131, 268–283. <https://doi.org/10.1016/j.renene.2018.07.050>
- Aravindhan, N., Natarajan, M. P., Ponnuvel, S., & Devan, K. P. (2022). Recent developments and issues of small-scale wind turbines in urban residential buildings—A review. *Energy & Environment*, 34(4), 1142–1169. <https://doi.org/10.1177/0958305x221084038>
- Arwood, Z., Cousins, D. S., Young, S., Stebner, A. P., & Penumadu, D. (2023). Infusible thermoplastic composites for wind turbine blade manufacturing: Static characterization of thermoplastic laminates under ambient conditions. *Composites Part C: Open Access*, 11. <https://doi.org/10.1016/j.jcomc.2023.100365>
- Aziz, T. A., & Elmassah, O. (2012). Could renewable energy affect the form of the city? Case study on the wind energy considerations. *Energy Procedia*, 18, 276–290. <https://doi.org/10.1016/j.egypro.2012.05.039>
- Balduzzi, F., Bianchini, A., Carnevale, E. A., Ferrari, L., & Magnani, S. (2012). Feasibility analysis of a Darrieus vertical-axis wind turbine installation in the rooftop of a building. *Applied Energy*, 97, 921–929. <https://doi.org/10.1016/j.apenergy.2011.12.008>
- Bittner, S., Gellermann, R., & Walther, C. (2023). The radioecological footprint of electricity production by wind turbines. *Radiation Protection Dosimetry*, 199(12), 1324–1335. <https://doi.org/10.1093/rpd/ncad168>
- Bodini, N., Lundquist, J. K., & Moriarty, P. (2021). Wind plants can impact long-term local atmospheric conditions. *Scientific Reports*, 11(1), 22939. <https://doi.org/10.1038/s41598-021-02089-2>
- Boettcher, M., Hoffmann, P., Lenhart, H.-J., Schlünzen, K. H., & Schoetter, R. (2015). Influence of large offshore wind farms on north German climate. *Meteorologische Zeitschrift*, 24(5), 465–480. <https://doi.org/10.1127/metz/2015/0652>
- Castellani, F., Astolfi, D., Peppoloni, M., Natili, F., Buttà, D., & Hirschl, A. (2019). Experimental vibration analysis of a small scale vertical wind energy system for residential use. *Machines*, 7(2). <https://doi.org/10.3390/machines7020035>
- Clark, C., Crumpler, C., & Notley, A. H. (2020). Evidence for environmental noise effects on health for the United Kingdom policy context: A systematic review of the effects of environmental noise on mental health, wellbeing, quality of life, cancer, dementia, birth, reproductive outcomes, and cognition. *International Journal of Environmental Research and Public Health*, 17(2). <https://doi.org/10.3390/ijerph17020393>
- Crawford, R. H. (2009). Life cycle energy and greenhouse emissions analysis of wind turbines and the effect of size on energy yield. *Renewable and Sustainable Energy Reviews*, 13(9), 2653–2660. <https://doi.org/10.1016/j.rser.2009.07.008>
- Crawford, R. H., Bontinck, P.-A., Stephan, A., Wiedmann, T., & Yu, M. (2018). Hybrid life cycle inventory methods—A review. *Journal of Cleaner Production*, 172, 1273–1288. <https://doi.org/10.1016/j.jclepro.2017.10.176>
- Crawford, R. H., Stephan, A., & Prideaux, F. (2022). The EPIC database: Hybrid embodied environmental flow coefficients for construction materials. *Resources, Conservation and Recycling*, 180. <https://doi.org/10.1016/j.resconrec.2021.106058>
- Dorrell, J., & Lee, K. (2020). The cost of wind: Negative economic effects of global wind energy development. *Energies*, 13(14). <https://doi.org/10.3390/en13143667>
- Drapalik, M., Zajicek, L., & Purker, S. (2021). Ice aggregation and ice throw from small wind turbines. *Cold Regions Science and Technology*, 192. <https://doi.org/10.1016/j.coldregions.2021.103399>
- Duarte, R., García-Riazuelo, Á., Sáez, L. A., & Sarasa, C. (2022). Analysing citizens' perceptions of renewable energies in rural areas: A case study on wind farms in Spain. *Energy Reports*, 8, 12822–12831. <https://doi.org/10.1016/j.egy.2022.09.173>
- Hythaei, M. A., & Bahadori, M. N. (2022). Internalizing the social cost of noise pollution in the cost analysis of electricity generated by wind turbines. *Wind Engineering*, 30(6), 521–529. <https://doi.org/10.1260/030952406779994114>
- European Commission. (2020). *Guidance document on wind energy developments and EU nature legislation*. European Commission. <https://op.europa.eu/en/publication-detail/-/publication/2b08de80-5ad4-11eb-b59f-01aa75ed71a1>

- Fields, J., Oteri, F., Preus, R., & Baring-Gould, I.** (2016). *Deployment of wind turbines in the built environment: Risks, lessons, and recommended practices*. US Department of Energy Office of Energy Efficiency & Renewable Energy. https://www.google.com/url?sa=t&source=web&rct=j&opi=89978449&url=https://www.nrel.gov/docs/fy16osti/65622.pdf&ved=2ahUKEwjRnufQsLGKAXUtUqQEHTpOAMAQFnoECBYQAQ&usq=AOvVaw2xMADjYf7UAgb7xZ_Cal
- Fleck, B., & Huot, M.** (2009). Comparative life-cycle assessment of a small wind turbine for residential off-grid use. *Renewable Energy*, 34(12), 2688–2696. <https://doi.org/10.1016/j.renene.2009.06.016>
- Gagliano, A., Nocera, F., Patania, F., & Capizzi, A.** (2013). Assessment of micro-wind turbines performance in the urban environments: an aided methodology through geographical information systems. *International Journal of Energy and Environmental Engineering*, 4(1), art. 43. <https://doi.org/10.1186/2251-6832-4-43>
- Gil-García, I. C., García-Cascales, S. M., & Molina-García.** (2022). Urban wind: An alternative for sustainable cities. *Energies*, 15, 4759. <https://doi.org/10.3390/en15134759>
- Goudarzi, N., Mohammadi, K., St. Pé, A. S., Delgado, R., & Zhu, W.** (2020). Wind resource assessment and economic viability of conventional and unconventional small wind turbines: A case study of Maryland. *Energies*, 13(22). <https://doi.org/10.3390/en13225874>
- Grant, A., Johnstone, C., & Kelly, N.** (2008). Urban wind energy conversion: The potential of ducted turbines. *Renewable Energy*, 33, 1157–1163. <https://doi.org/10.1016/j.renene.2007.08.005>
- Guo, Y., Ling, Z., Zheng, J., Li, Z., Xiang, M., Gao, M., Xiao, Z., & Gang, W.** (2021). Economic performance of 100% renewable energy system for residential community in China, Paper presented at the 6th International Conference on Power and Renewable Energy (ICPRE). <https://ideas.repec.org/a/gam/jsusta/v13y2021i19p10590-d642174.html>
- Haaren, R. van, & Fthenakis, V.** (2011). GIS-based wind farm site selection using spatial multi-criteria analysis (SMCA): Evaluating the case for New York State. *Renewable and Sustainable Energy Reviews*, 15(7), 3332–3340. <https://doi.org/10.1016/j.rser.2011.04.010>
- Heagle, A. L. B., Naterer, G. F., & Pope, K.** (2011). Small wind turbine energy policies for residential and small business usage in Ontario, Canada. *Energy Policy*, 39, 1988–1999. <https://doi.org/10.1016/j.enpol.2011.01.028>
- Hoen, B., Darlow, R., Haac, R., Rand, J., & Kaliski, K.** (2023). Effects of land-based wind turbine upsizing on community sound levels and power and energy density. *Applied Energy*, 338. <https://doi.org/10.1016/j.apenergy.2023.120856>
- Hui, I., Cain, B. E., & Dabiri, J. O.** (2018). Public receptiveness of vertical axis wind turbines. *Energy Policy*, 112, 258–271. <https://doi.org/10.1016/j.enpol.2017.10.028>
- Hunaidi, O.** (2000). Traffic vibrations in buildings. *Construction Technology Update*, 39.
- IEA.** (2022). *World energy outlook*. International Energy Agency (IEA). <https://www.iea.org/reports/world-energy-outlook-2022>
- Jahromi, S., Moosavian, S. F., Yaghoobirad, M., Azizi, N., & Ahmadi, A.** (2022). 4E analysis of the horizontal axis wind turbine with LCA consideration for different climate conditions. *Energy Science & Engineering*, 10(10), 4085–4111. <https://doi.org/10.1002/ese3.1272>
- Jensen, J. P., & Skelton, K.** (2018). Wind turbine blade recycling: Experiences, challenges and possibilities in a circular economy. *Renewable and Sustainable Energy Reviews*, 97, 165–176. <https://doi.org/10.1016/j.rser.2018.08.041>
- Johansson, A., Bolin, K., & Alvarsson, J.** (2019). Annoyance and partial masking of wind turbine noise from ambient sources. *Acta Acustica*, 105(6), 1035–1041. <https://doi.org/10.3813/aaa.919382>
- Joshi, N., Rohit, S., Noriega, L., Gokarn, K., Mwendia, A., & Rivera, E.** (2021). Urban wind power. *Renewable and Sustainable Energy Reviews*, 13640321. <https://doi.org/10.1016/j.rser.2005.08.004>
- Kammen, D. M.** (2016). City-integrated renewable energy for urban sustainability. *Urban Planet*, 352(6288), 922–928. <https://doi.org/10.1126/science.aad9302>
- Karadag, İ., & Kurucay, E.** (2021). Noise emission from building integrated wind turbines: A case study of a tall building. *Sakarya University Journal of Science*, 25(2), 563–570. <https://doi.org/10.16984/saufenbilder.884517>
- Karadag, İ., & Yuksek, I.** (2020). Wind turbine integration to tall buildings. In Al Qubeissi, M., El-kharouf, A., & Serhad, H. S. (Eds.), *Renewable energy—Resources, challenges and applications*. InTech. <https://doi.org/10.5772/intechopen.91650>
- Klaeboe, R., & Sundfor, H. B.** (2016). Windmill noise annoyance, visual aesthetics, and attitudes towards renewable energy sources. *International Journal of Environmental Research and Public Health*, 13(8). <https://doi.org/10.3390/ijerph13080746>
- Kouloumpis, V., Sobolewski, R. A., & Yan, X.** (2020). Performance and life cycle assessment of a small scale vertical axis wind turbine. *Journal of Cleaner Production*, 247. <https://doi.org/10.1016/j.jclepro.2019.119520>

- Krasniqi, G., Lajqi, S., Durin, B., & Kranjcić, N.** (2022). Impact of installing small wind turbines in urban areas on reducing pollution—A case study. *International Energy Journal*, 22(1), 49–60.
- Kumar, R., Raahemifar, K., & Fung, A. S.** (2018). A critical review of vertical axis wind turbines for urban applications [Review]. *Renewable and Sustainable Energy Reviews*, 89, 281–291. <https://doi.org/10.1016/j.rser.2018.03.033>
- Kwok, K. C. S., & Hu, G.** (2023). Wind energy system for buildings in an urban environment. *Journal of Wind Engineering and Industrial Aerodynamics*, 234. <https://doi.org/10.1016/j.jweia.2023.105349>
- Langer, K., Decker, T., Roosen, J., & Menrad, K.** (2018). Factors influencing citizens' acceptance and non-acceptance of wind energy in Germany. *Journal of Cleaner Production*, 175, 133–144. <https://doi.org/10.1016/j.jclepro.2017.11.221>
- Li, S., Chen, Q., Li, Y., Pröbsting, S., Yang, C., Zheng, X., Yang, Y., Zhu, W., Shen, W., Wu, F., Li, D., Wang, T., & Ke, S.** (2022). Experimental investigation on noise characteristics of small scale vertical axis wind turbines in urban environments. *Renewable Energy*, 200, 970–982. <https://doi.org/10.1016/j.renene.2022.09.099>
- Lichtenegger, G., Rentizelas, A. A., Trivyza, N., & Siegl, S.** (2020). Offshore and onshore wind turbine blade waste material forecast at a regional level in Europe until 2050. *Waste Management*, 106, 120–131. <https://doi.org/10.1016/j.wasman.2020.03.018>
- Llaguno, M.** (2016). *Airflow analysis in the architectural design process*. ETH.
- Lu, X., Tchou, J., McElroy, M. B., & Nielsen, C. P.** (2011). The impact of production tax credits on the profitable production of electricity from wind in the U.S. *Energy Policy*, 39(7), 4207–4214. <https://doi.org/10.1016/j.enpol.2011.04.034>
- Majeau-Bettez, G., Hawkins, T. R., & Stromman, A. H.** (2011). Life cycle environmental assessment of lithium-ion and nickel metal hydride batteries for plug-in hybrid and battery electric vehicles. *Environmental Science and Technology*, 45(10), 4548–4554. <https://doi.org/10.1021/es103607c>
- Manyoky, M., Wissen-Hayek, U., Heutschi, K., Pieren, R., & Grêt-Regamey, A.** (2014). Developing a GIS-based visual-acoustic 3D simulation for wind farm assessment. *ISPRS International Journal of Geo-Information*, 3(1), 29–48. <https://doi.org/10.3390/ijgi3010029>
- Matuszewska, A. W. P., & Owczuk, M.** (2020). Vehicles recycling Part 2—Recycling of selected vehicle components. *Studia Ecologiae et Bioethicae*. <https://doi.org/10.21697/seb.2020.4.09>
- Mead, I.** (2017). *International energy outlook 2017*. Center for Strategic and International Studies. https://www.google.com/url?sa=t&source=web&rct=j&opi=89978449&url=https://www.eia.gov/pressroom/presentations/mead_91417.pdf&ved=2ahUKEwjS3KrpsbGKAxXGRKQEHRqKngEQFnoECBYQAQ&usq=AOvVaw1X3Q4U19TmppsYQxl98S1M
- Mello, G., Dias, M. F., & Robaina, M.** (2020). Wind farms life cycle assessment review: CO₂ emissions and climate change. *Energy Reports*, 6(6), 214–219.
- Micallef, D., & van Bussel, G.** (2018). A review of urban wind energy research: Aerodynamics and other challenges. *Energies*, 11(9). <https://doi.org/10.3390/en11092204>
- Minderman, J., Fuentes-Montemayor, E., Pearce-Higgins, J. W., Pendlebury, C. J., & Park, K. J.** (2014). Estimates and correlates of bird and bat mortality at small wind turbine sites. *Biodiversity and Conservation*, 24(3), 467–482. <https://doi.org/10.1007/s10531-014-0826-z>
- Mishnaevsky, L. B. K., Petersen, H. N., Beauson, J., McGugan, M., & Sorensen, B. F.** (2017). Materials for wind turbine blades: An overview. *Materials*, 10(11), 1285. <https://doi.org/10.3390/ma10111285>
- Moher, D., Liberati, A., Tetzlaff, J., Altman, D. G., & Group, P.** (2010). Preferred reporting items for systematic reviews and meta-analyses: The PRISMA statement. *International Journal of Surgery*, 8(5), 336–341. <https://doi.org/10.1016/j.jisu.2010.02.007>
- Mokarram, M., Pourghasemi, H. R., & Mokarram, M. J.** (2022). A multi-criteria GIS-based model for wind farm site selection with the least impact on environmental pollution using the OWA-ANP method. *Environmental Science and Pollution Research*, 29(29), 43891–43912. <https://doi.org/10.1007/s11356-022-18839-2>
- Mollasalehi, E., Sun, Q., & Wood, D.** (2013). Contribution of small wind turbine structural vibration to noise emission. *Energies*, 6(8), 3669–3691. <https://doi.org/10.3390/en6083669>
- Morini, A. A., Hotza, D., & Ribeiro, M. J.** (2022). Embodied energy and carbon footprint comparison in wind and photovoltaic power plants. *International Journal of Energy and Environmental Engineering*, 13(2), 457–467. <https://doi.org/10.1007/s40095-021-00450-9>
- Morocho, E., Morocho, W., Barragán, & Zalamea, E.** (2020). Optimal location decision of wind generators in urban areas using multi criteria techniques. *Renewable Energy and Power Quality Journal*, 18, 109–115. <https://doi.org/10.24084/repqj18.242>
- Mucci, N., Traversini, V., Lorini, C., De Sio, S., Galea, R. P., Bonaccorsi, G., & Archangeli, G.** (2020). Urban noise and psychological distress: A systematic review. *International Journal of Environmental Research and Public Health*, 17(18). <https://doi.org/10.3390/ijerph17186621>

- Nakagawa, K., & Singh, A.** (2020). Troubles with a wind project. In Proceedings of International Structural Engineering and Construction. https://www.google.com/url?sa=t&source=web&rct=j&opi=89978449&url=https://www.isec-society.org/ISEC_PRESS/ASEA_SEC_05/pdf/LDR-03.pdf&ved=2ahUKEwjSoO6OsrGKAXvbkvsDHYWoNkMQFnoECBsQAQ&usq=AOvVaw1p2tiHRTY3Q9Ie8Ea64yPC
- Nardecchia, F., Groppi, D., Garcia, D. A., Bisegna, F., & Santoli, L. D.** (2021). A new concept for a mini-ducted wind turbine system. *Renewable Energy*, 175, 610e624.
- Newson, S. E., Evans, H. E., Gillings, S., Jarrett, D., Raynor, R., & Wilson, M. W.** (2017). Large-scale citizen science improves assessment of risk posed by wind farms to bats in southern Scotland. *Biological Conservation*, 215, 61–71. <https://doi.org/10.1016/j.biocon.2017.09.004>
- Oliveira, C., Baptista, J., & Cerveira, A.** (2020). Wind energy exploitation in urban environment: the effect of roof shape. In Second Edition of the International Conference on Innovative Applied Energy. https://www.researchgate.net/publication/347914036_Wind_energy_exploitation_in_urban_environment_the_effect_of_roof_shape
- Ortega, C. P.** (2012). Effects of noise pollution on birds: a brief review of our knowledge. *American Ornithological Society*.
- Peppoloni, M., Hirschl, A., & Leonhartsberger, K.** (2018b). Operational behaviour of SWT. In Proceedings of Wind Energy Exploitation in Urban Environment. <https://doi.org/10.1007/978-3-319-74944-0>
- Peppoloni, M., Leonhartsberger, K., & Hirschl, A.** (2018a). Environmental influences on SWT vibrations and oscillations. In Proceedings of Wind Energy Exploitation in Urban Environment. <https://doi.org/10.1007/978-3-319-74944-0>
- Petrova, M. A.** (2013). NIMBYism revisited: Public acceptance of wind energy in the United States. *WIREs Climate Change*, 4(6), 575–601. <https://doi.org/10.1002/wcc.250>
- Pohl, J., Hübner, G., & Mohs, A.** (2012). Acceptance and stress effects of aircraft obstruction markings of wind turbines. *Energy Policy*, 50, 592–600. <https://doi.org/10.1016/j.enpol.2012.07.062>
- Pohl, J., Rudolph, D., Lyhne, I., Clausen, N.-E., Aaen, S. B., Hübner, G., Kørnøv, L., & Kirkeg, J. K.** (2021). Annoyance of residents induced by wind turbine obstruction lights: A cross-country comparison of impact factors. *Energy Policy*, 156. <https://doi.org/10.1016/j.enpol.2021.112437>
- Pollino, M. C., & Huckelbridge, A. A.** (2011). *Initial observations from monitoring the in-situ performance of a community-scale wind turbine support structure*. ENERGYTECH.
- Pomponi, F., & Moncaster, A.** (2018). Scrutinising embodied carbon in buildings: The next performance gap made manifest. *Renewable and Sustainable Energy Reviews*, 81, 2431–2442. <https://doi.org/10.1016/j.rser.2017.06.049>
- Poulsen, A. H., Raaschou-Nielsen, O., Pena, A., Hahmann, A. N., Nordsborg, R. B., Ketznel, M., Brandt, J., & Sorensen, M.** (2018). Long-term exposure to wind turbine noise and redemption of antihypertensive medication: A nationwide cohort study. *Environment International*, 121(1), 207–215. <https://doi.org/10.1016/j.envint.2018.08.054>
- Qu, F.** (2018). Impacts of wind turbine noise on health and well-being from the perspective of urban morphology (dissertation, WoS). <https://etheses.whiterose.ac.uk/19188/>
- Qu, F., & Kang, J.** (2018). Impacts of wind turbine noise on health and well-being from the perspective of urban morphology. *Renewable Energy*, 156. <https://doi.org/10.1016/j.enpol.2021.112437>.
- Qu, F., & Tsuchiya, A.** (2021). Perceptions of wind turbine noise and self-reported health in suburban residential areas. *Frontiers in Psychology*, 12. <https://doi.org/10.3389/fpsyg.2021.736231>
- Rainer, J. H.** (1982). Effect of vibrations on historic buildings: An overview. *Bulletin of the Association for Preservation Technology*, 14(1), 2–10.
- Reja, R. K., Amin, R., Tasneem, Z., Ali, M. F., Islam, M. R., Saha, D. K., Badal, F. R., Ahamed, M. H., Moyeen, S. I., & Das, S. K.** (2022). A review of the evaluation of urban wind resources: challenges and perspectives. *Energy and Buildings*, 257. <https://doi.org/10.1016/j.enbuild.2021.111781>
- Richard, E.** (2019). Ion thrusters for electric propulsion: Scientific issues developing a niche technology into a game changer. *Applied Physics Letters*, 115. <https://doi.org/10.1063/5.0010134>
- Rygg, B. J.** (2012). Wind power—An assault on local landscapes or an opportunity for modernization? *Energy Policy*, 48, 167–175. <https://doi.org/10.1016/j.enpol.2012.05.004>
- Shende, V., Patidar, H., Baredar, P., & Agrawal, M.** (2022). A review on comparative study of Savonius wind turbine rotor performance parameters. *Environmental Science and Pollution Research*, 29(46), 69176–69196. <https://doi.org/10.1007/s11356-022-22399-w>
- Simos, J., Cantoreggi, N., Christie, D., & Forbat, J.** (2019). Wind turbines and health: A review with suggested recommendations. *Environnement, Risques & Santé*, 18, 149–159. <https://doi.org/10.1684/ers.2019.1281>
- Škvorc, P., & Kozmar, H.** (2021). Wind energy harnessing on tall buildings in urban environments. *Renewable and Sustainable Energy Reviews*, 152. <https://doi.org/10.1016/j.rser.2021.111662>

- Smeraldo, S., Bosso, L., Fraissinet, M., Bordignon, L., Brunelli, M., Ancillotto, L., & Russo, D.** (2020). Modelling risks posed by wind turbines and power lines to soaring birds: the black stork (*Ciconia nigra*) in Italy as a case study. *Biodiversity and Conservation*, 29(6), 1959–1976. <https://doi.org/10.1007/s10531-020-01961-3>
- Staudt, L.** (2008). Wind energy. In Letcher, T. M. (Ed.), *Future energy: Improved, sustainable and clean options for our planet* (pp. 93–110). Elsevier. <https://doi.org/10.1016/B978-0-08-054808-1.00006-5>
- Tabrizi, A. B., Whale, J., Lyons, T., & Urmee, T.** (2014). Performance and safety of rooftop wind turbines: Use of CFD to gain insight into inflow conditions. *Renewable Energy*, 67, 242–251. <https://doi.org/10.1016/j.renene.2013.11.033>
- Tasneem, Z., Noman, A. A., Das, S. K., Saha, D. K., Islam, R., Ali, F., R Badal, F., Ahamed, H., Moyeen, S. I., & Alam, F.** (2020). An analytical review on the evaluation of wind resource and wind turbine for urban application: Prospect and challenges. *Developments in the Built Environment*, 4. <https://doi.org/10.1016/j.dibe.2020.100033>
- Taylor, J., Eastwick, C., Lawrence, C., & Wilson, R.** (2013). Noise levels and noise perception from small and micro-wind turbines. *Renewable Energy*, 55, 120–127. <https://doi.org/10.1016/j.renene.2012.11.031>
- Teffera, B., Assefa, B., Björklund, A., & Assefa, G.** (2021). Life cycle assessment of wind farms in Ethiopia. *International Journal of Life Cycle Assessment*, 26(1), 76–96. <https://doi.org/10.1007/s11367-020-01834-5>
- Tikkanen, H., Balotari-Chiebao, F., Laaksonen, T., Pakanen, V.-M., & Rytönen, S.** (2018). Habitat use of flying subadult white-tailed eagles (*Haliaeetus albicilla*): implications for land use and wind power plant planning. *Ornis Fennica*, 95, 137–150.
- Troullaki, A., Latoufis, K., Marques, P., Freire, F., & Hatzigiorgiou, N.** (2019). Life cycle assessment of locally manufactured small wind turbines and pico-hydro plants. Paper presented at SEST—2nd International Conference on Smart Energy Systems and Technologies. <https://ieeexplore.ieee.org/document/8849074>
- TU/e.** (2014, October 29). Bahrain World Trade Center is exactly the wrong way round. <https://www.tue.nl/en/news/news-overview/bahrain-world-trade-center-is-exactly-the-wrong-way-round>
- Tummala, A., Velamati, R. K., Sinha, D. K., Indrāja, V., & Krishna, V. H.** (2016). A review on small scale wind turbines. *Renewable and Sustainable Energy Reviews*, 56, 1351–1371. <https://doi.org/10.1016/j.rser.2015.12.027>
- Turner, J. D.** (1993). Assessing the damaging effect of continuous vibration in brittle structures. *International Journal of Mechanical Engineering Education*, 21(4), 327–336. <https://doi.org/10.1177/030641909302100403>
- Tzen, E.** (2020). Small wind turbines for on grid and off grid applications. In IOP Conference Series: Earth and Environmental Science. <https://iopscience.iop.org/article/10.1088/1755-1315/410/1/012047>
- US EIA.** (2021). *International energy outlook*. US Energy Information Administration (EIA). <https://pubmed.ncbi.nlm.nih.gov/23624007/>
- Van Renterghem, T., Bockstael, A., De Weirt, V., & Botteldooren, D.** (2013). Annoyance, detection and recognition of wind turbine noise. *Science of the Total Environment*, 456–457, 333–345. <https://doi.org/10.1016/j.scitotenv.2013.03.095>
- Vanwijck, X., Geerinck, P., Cobbaert, J., & Ghene, T.** (2021). TRiceR, a web-application for supporting risk-based decisions associated with ice falling from wind turbine blades. Paper presented at WindEurope Electric City 2021—WindEurope’s Annual On- and Offshore Wind Energy Event.
- Wang, S., Lib, G., & Fang, C.** (2019). Urbanization, economic growth, energy consumption, and CO₂ emissions: Empirical evidence from countries with different income levels. *Renewable and Sustainable Energy Reviews*, 81, 2144–2159.
- Westerlund, M.** (2020). Social acceptance of wind energy in urban landscapes. *Technology Innovation Management Review*, 10(9), 49–62. <https://doi.org/10.22215/TIMREVIEW/1389>
- Wiedmann, T. O., Suh, S., Feng, K., Lenzen, M., Acquaye, A., Scott, K., & Berrett, J. R.** (2011). Application of hybrid life cycle approaches to emerging energy technologies—The case of wind power in the UK. *Environmental Science and Technology*, 45(13). <https://doi.org/10.1021/es2007287>
- Wu, M., Sadhukhan, J., Murphy, R., Bharadwaj, U., & Cui, X.** (2023). A novel life cycle assessment and life cycle costing framework for carbon fibre-reinforced composite materials in the aviation industry. *International Journal of Life Cycle Assess*, 28(5), 566–589. <https://doi.org/10.1007/s11367-023-02164-y>
- Xiong, X., Li, L., Chen, F., Zhang, J., & Houzhang, T.** (2022). Typical pollutant species evolution behaviors study in retired wind turbine blade and coal thermal conversion process. *Journal of Analytical and Applied Pyrolysis*, 168. <https://doi.org/10.1016/j.jaap.2022.105771>
- Yang, A. S., Su, Y. M., Wen, C. Y., Juan, Y. H., Wang, W. S., & Cheng, C. H.** (2016). Estimation of wind power generation in dense urban area. *Applied Energy*, 171, 213–230. <https://doi.org/10.1016/j.apenergy.2016.03.007>

- Yen, J., & Ahmed, N. (2012). Improving safety and performance of small-scale vertical axis wind turbines. *Procedia Engineering*, 49, 99–106. <https://doi.org/10.1016/j.proeng.2012.10.117>
- Zhang, S., Du, B., Ge, M., & Yingtao, Z. (2022). Study on the operation of small rooftop wind turbines and its effect on the wind environment in blocks. *Renewable Energy*, 183, 708–718. <https://doi.org/10.1016/j.renene.2021.11.059>
- Zhang, S., Yang, H., Du, B., & Ge, M. (2021a). Effects of a rooftop wind turbine on the dispersion of air pollutant behind a cube-shaped building. *Theoretical and Applied Mechanics Letters*, 11(5). <https://doi.org/10.1016/j.taml.2021.100296>
- Zhang, W., Li, B., Xue, R., Wang, C., & Cao, W. (2021b). A systematic bibliometric review of clean energy transition: Implications for low-carbon development. *PLoS One*, 16(12). <https://doi.org/10.1371/journal.pone.0261091>
- Zhu, R., Shi, W., Wang, Y., Wang, W., Huang, Q., 石文辉, 王阳, 王伟胜, & 黄其励. (2018). Research suggestions for ecological and climatic environmental effects of wind power development in China. *Strategic Study of CAE*, 20(3), 39–43.

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