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INDOOR SUMMER THERMAL COMFORT IN A CHANGING CLIMATE: THE CASE OF A NEARLY ZERO ENERGY HOUSE IN WALLONIA (BELGIUM)

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Abstract
Today, facing climate change represents a double challenge for the building sector. On one hand, the sector has to reduce its impact in terms of greenhouse gas emissions and on the other hand designers have to guarantee comfortable indoor climate conditions in a changing climate. In this context, Wallonia (southern part of Belgium) is engaged in a drastic reduction of its greenhouse gas emissions and aims to reach a Carbon Neutral building stock by 2050. This relies on the generalization of the nearly Zero Energy Buildings (nZEB) concept for all buildings, including existing ones. In temperate oceanic climate, it mainly implies a drastic reduction of buildings heating energy demand by high thermal insulation levels and airtightness of the building envelope. Many studies have however shown that indoor summer thermal comfort in nZEB requires specific attention even in current climate. It is also clear that global warming will have a worsening impact on overheating risks in buildings.
The aim of this paper is to evaluate the evolution of overheating risk of a typical nZEB house in Wallonia, in the frame of the changing climate. A whole building energy simulation of the house has been carried out using TRNsys18 simulation engine. The model has first been calibrated based on previous measurements, using ASHRAE guideline 14 indicators, in order to realistically evaluate the indoor summer thermal conditions encountered in the house. Data for current and future climatic conditions have been directly derived from high-resolution climate model. These models, dynamically downscaled from Global Climate Models (GCM), consider local climate variations and anomalies and allow a detailed geographical resolution (horizontal grid spacing <4km). Today, they are available in Belgium within the CORDEX project for the different representative concentration pathways (RCP).
On these bases, the paper discusses the potential evolution of overheating risks in the living room and in the main bedroom of the house. The evaluation of summer thermal comfort is conducted according to CIBSE TM52 and TM59 criteria for historical (1976-2005) and future (RCP2.6 and 8.5) climates. It shows that the passive strategies currently deployed in the house won't be enough to guarantee summer thermal comfort in the future, especially in the bedroom. In this way, the study emphasizes that considering summer thermal comfort and its possible evolution should be a priority for the design of nZEB houses (and related policies) also in temperate oceanic climate.

1. INTRODUCTION
"Warming of the climate system is unequivocal and the effects of anthropogenic greenhouse gas emissions, together with those of other anthropogenic drivers, are extremely likely to have been the dominant cause of the observed warming since the mid-20th century", the Intergovernmental Panel on Climate Change (IPCC) writes in his Fifth Assessment Report (AR5) in 2014 (IPCC 2014). In this context, Wallonia (southern part of Belgium) is engaged in a drastic reduction of its greenhouse gas emissions and aims to reach a Carbon Neutral building stock by 2050 (Gouvernement wallon 2019). This relies on the generalization of the nearly Zero Energy Buildings (nZEB) concept for all buildings, including existing ones (Gouvernement wallon 2020). In a temperate oceanic climate (Cfb zone according to the Köppen–Geiger climate classification system (Peel, Finlayson et al. 2007)) such as in Wallonia, it mainly implies a drastic reduction of buildings heating energy demand by high thermal insulation levels and airtightness of the building envelope.
Many studies have however shown that such techniques (modifying the thermal behaviour of the building) tend to keep the warmth inside and therefore increase the risk of overheating even in current climate (Jones, Goodhew et al. 2016). It is also clear

that the increase of heatwaves frequency and intensity induced by global warming will have a worsening impact on this risk (Ozarisoy and Elsharkawy 2019) and could compromise comfort, well-being and health of sensitive occupants (World Health Organization 2004). In the considered climatic zone, simple passive strategies (such as use of solar shading and windows opening) are often seen as the key to prevent and guarantee summer thermal comfort in nZEB residential buildings (Mlakar and Štrancar 2011). So the question emerges today in the building sector: will the implementation of such strategies - that appears in practice quite limited (Dartevelle and Vanwelde 2018)- be sufficient to avoid the generalisation of active cooling systems and their induced energy consumption (Yang, Javanroodi et al. 2021) and environmental impacts (Brian Ford, Dejan Mumovic et al. 2021) in a country with no such tradition?

While the impact of climate change mitigation measures is now well studied, researches focusing on the efficiency of these adaptation strategies are only at their infancy in the building sector for a number of reasons: slow knowledge transfer from climate modelling to building engineering science, stochastics behavior and uncertainties associated with future climates that induce large datasets and specific method to deal with, computational time needed, etc.(Yang, Javanroodi et al. 2021). These analyses are however crucial to define proper building energy standards that will effectively reduce energy demands without compromising thermal comfort. This paper aims to contribute to answer this question. Based on a real case study, it evaluates the extent to which the design of a typical nZEB house in Wallonia and its current operation could guarantee summer thermal comfort in a changing climate.

2. METHOD

2.1. CASE STUDY

The case study is a real detached single-family house. The house is located in a suburban area of Namur (Erpent, southern part of Belgium, 50° North). In Wallonia, detached houses represent the most frequent type (39%) of single-family housing (approximately 80% of the housing stock (Climact 2017)).
The house, constructed in 2011, is composed of 2 levels of around 83m² (net floor area) each and is occupied by 2 adults and 3 children (1 baby). Regarding its thermal performances, it complies with current requirements for nZEB in Wallonia (Gouvernement wallon 2016) relying on the definition provided in the European Directive 2010/31/EU on the energy performance of buildings (European Parliament 2010). Main thermal characteristics of the envelope of the buildings analysed are presented in Table 1.
The main characteristics and performances of the house have been measured or monitored during one complete year (2016): air temperatures, electricity consumption (internal gains), heating demand, airflows induced by mechanical ventilation, efficiency of the heat recovery system, U values of walls, airtightness. Some weather data have also been monitored on site (dry bulb temperature and relative humidity) and completed with data from the Royal Meteorological Institute of Belgium (RMI) (radiation, cloud cover, etc.). The characteristics of the house presented in Table 1 derive thus from on-site verifications, interviews with the occupants (e.g., about windows opening behaviours) and calculations from the Walloon EPBD (Energy Performance of Buildings) (Gouvernement wallon 2016). In the frame of this study two main rooms were analysed : the living room (Z1) and the main bedroom (Z7). Their spatial characteristics are illustrated in Figure 1.

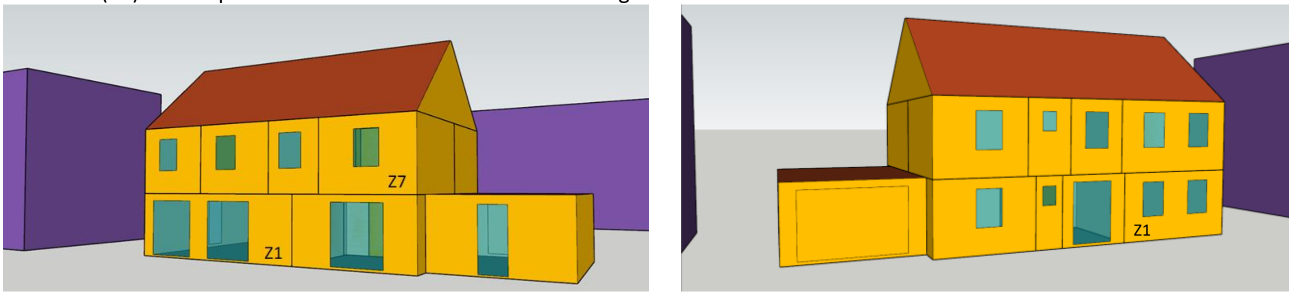

Figure 1: views of the main facades with indication of the considered thermal zones (Z1: living room, Z7: main bedroom). Left: rear façade (east oriented). Right: front façade (west oriented).

According to the information received from the occupant, closure of the white internal curtains to protect from solar radiation and windows opening to dissipate the heat in the living room have been integrated in the thermal model (except during the periods of absence of the occupant). According to the occupant, no such strategies were regularly applied in the main bedroom and, therefore, they have not been integrated for this room in the thermal model.
Globally, no (severe) overheating problem have been measured during the year 2016. The house complied with all the summer thermal comfort criteria defined by CIBSE (see Table 3) even if the occupant perceived the bedroom temperature in summer as slightly too hot. Methods for interviews and data collection are described in (Dartevelle, Moeseke et al. 2020).

Table 1: characteristics of the calibrated thermal model.

Characteristics	Units	Value	Source of value*	Instrumental uncertainties considered	Used uncertainty for calibration
Construction type	[-]	Masonry	1	NA	NA
Number of occupants	[-]	5 <12 y/o: 3	2	NA	NA
Presence during working hours	[-]	Yes	2	NA	NA
Net heated floor area	[m²]	166	3	NA	NA
Window-to-floor surface ratio	[%]	19.9	3	NA	NA
Mean U-value (windows included)	[W/m².K]	0.31	3 (1 for Walls)	[-20%;+20%]	-7%
Air change rate at 50 Pa (n_{50})	[1/h]	1.1	1	[-5%;+5%]	-5%
Mechanical ventilation Airflow (Air change rate)	[1/h]	0.25	1	[-6%;+6%]	-6%
Efficiency of heat recovery (mechanical ventilation)	[%]	85	1	[-6.2%;+6.2%]	-2%
Windows Solar Heat Gain Coefficient (SHGC)	[-]	0.63	3	[-5%;+5%]	-5%
Main windows orientation (living room and main bedroom)	[-]	E	1	NA	NA
Living room total SHGC (glazing+internal shading)	[-]	0.35	2,3	[-5%;+5%]	+5%
Bedroom total SHGC (glazing+internal shading)	[-]	0.35 (usually not used)	2, 3	[-5%;+5%]	+5%
Internal gains (electrical)	[W/m²]	2.2 (mean value)	1	[-3%;+3%]	-3%
Additional thermal capacity of zones (furniture)	[kJ/K.m²]	26.5	4	[-100%;+100%]	+100%
Windows opening for summer thermal control (living room)	[Ach]	3 (Cross ventilation)	2	[-100%;+100%]	+30%
Windows opening for summer thermal control (bedroom)	[Ach]	0 (One side ventilation - Not usual)	2	[0;+6]	+0%
Heating needs	[kWh/m².y]	17.8	1	[-6%;+6%]	-6%
Dry Bulb Outdoor Temperature (annual mean)	[°C]	10.8		[-0.3;+0.3]	-0.3
Radiation (Global Horizontal)	[kWh/m².y]	1035	1	[-10%;+10%]	+0%
Setpoint Temperature Living Room (mean value September to May)	[°C]	20.1	1	[-0.3;+0.3]	+0.3
Setpoint Temperature Main Bedroom (mean value September to May)	[°C]	19.1	1	[-0.3;+0.3]	+0.3

**1 On-site verification/measurements ; 2 Questionnaire-based interviews; 3 Belgian EPBD calculation; 4 Literature.*

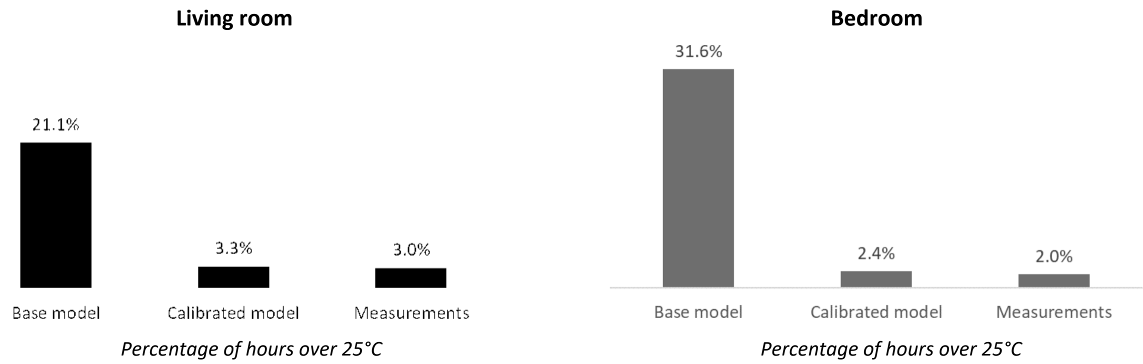

Figure 2: models capability to estimate the time exceeding 25°C in the living room (left) and in the main bedroom (right) compared to the measured values.

2.2. CALIBRATED THERMAL MODEL

A whole building energy simulation of the house has been carried out (Figure 1) using TRNsys18 simulation engine (Solar Energy Laboratory 2018). In order to ensure a realistic evaluation of the indoor summer thermal conditions, a calibration process of the model was performed. The calibration consisted in two main steps. First, measured values (thermal properties, weather data, etc.) (cf. Table 1) were introduced in the model (= base model). Then a variation of the entries data within the range of their estimated instrumental uncertainties (obtained from manufacturers) was performed in order to minimise the deviation of simulated temperatures (hourly values) from measured values according to the, widely used (see for example (Aparicio-Fernández, Vivancos et al. 2019)), indicators defined by ASHRAE guideline 14 (ASHRAE 2014). These indicators are based on the Coefficient of Variation of the Root Mean-Square Error (CV-RMSE) and the Mean Bias Error (MBE). This last calibration step was performed using an optimisation algorithm (Particle Swarm Optimization (PSO) (M. Juneja and S. K. Nagar 2016)) and has involved more than 900 simulations.

Table 2 presents the compliance of the final model with ASHRAE indicators. The last column of Table 1 details the related entries data.

Table 2: final model compliance with calibration criteria defined in Ashrae guideline 14.

	Living room temperature	*Bedroom temperature*	*Calibration criteria*
NMBE [%]	**0.64**	**0.68**	+/- 10
CV-RMSE [%]	**3.39**	**3.41**	30

2.3. CLIMATE CHANGE MODEL

Data for current and future climatic conditions (temperature, humidity, radiation, wind speed and direction, etc.) have been directly derived from high-resolution climate model. These models, dynamically downscaled from Global Climate Models (GCM), consider local climate variations and anomalies and allow a detailed temporal and geographical resolution (horizontal grid spacing <4km). Compared with the classical use of morphed weather data (Shen and Malkawi 2016), this method allows for accounting the variability in occurrence and intensity of heatwaves phenomena throughout the years. Today, they are available in Belgium within the CORDEX project for the different representative concentration pathways (RCP) (Giot, Termonia et al. 2016). For the purpose of this paper, two future climates scenarios (Representative Concentration Pathway (RCP) 2.6 and 8.5) for the period 2071-2100 were considered and compared with historical data (1976-2005) (also derived from the same climate model) for the city of Uccle (main meteorological station in Belgium). These two RCPs scenarios were chosen since they represent opposite (and extreme) perspectives regarding the deployment of mitigation strategies and, in consequence, the severity of induced climate change : a stringent mitigation scenario (RCP2.6) that would keep global warming likely below 2°C above pre-industrial temperatures which is in line with the objectives of the Paris agreement (United Nations / Framework Convention on Climate Change 2015) and a very high Green House Gas (GHG) emissions scenario (RCP 8.5) leading to an increase of global mean temperature comprised between 2.6°C to 4.8°C (95% confidence interval) by the end of the 21st century (2081–2100) relative to 1986–2005 (IPCC 2014). It is recognised that these scenarios will impact the frequency and the duration of heat waves (IPCC 2014).

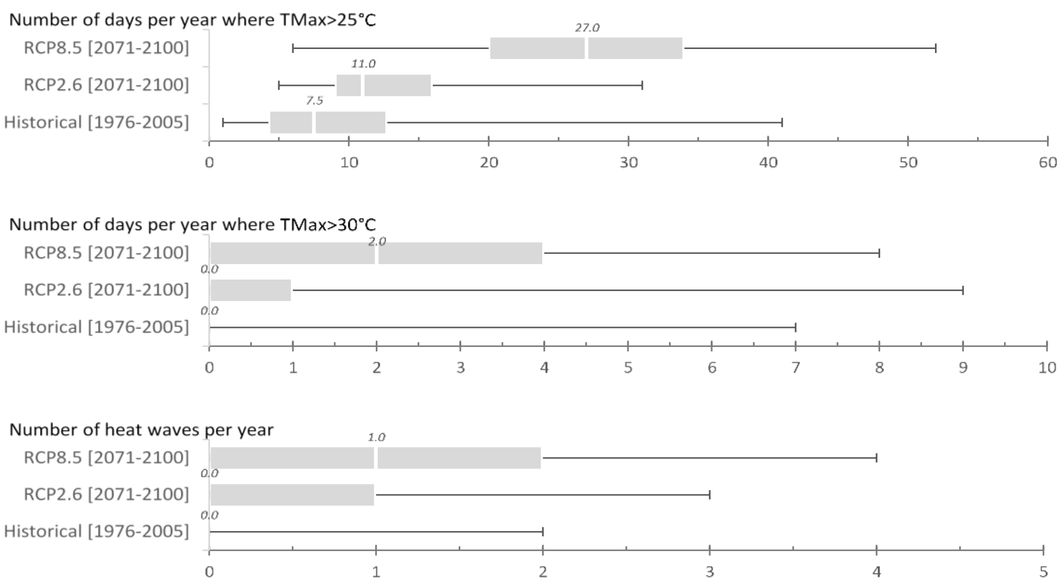

Figure 3 : evolution of the number of days reaching 25°C, 30°C and the number of heatwaves per year according to historical (1976-2005), RCP2.6 (2071-2100) and RCP8.5 (2071-2100) scenarios in Uccle (Belgium).

In climatology, heatwaves can be defined as a period of minimum 5 consecutive days with air temperature reaching at least 25°C and more than 30°C during at least 3 days (Royal Meteorological Institute of Belgium 2021). Figure 3 presents the evolution of the number of heat waves per year as well as the number of days reaching 25°C and 30°C according to RCP 2.6 and 8.5 for the end of the century (2071-2100) compared to the historical period (1976-2005) for Uccle. Standard boxplot representation has been used to illustrate the distribution (min, percentile 25, median, percentile 75, max) of the encountered values for the considered period. Median values have also been specified to ease the readability of these graphs. These sets of data, covering a period of 30 years each, were directly introduced in TRNsys simulation software with an hourly resolution (using an IWEC format (ASHRAE 2001)) in order to provide a detailed overview of their implication on the building indoor climate.

2.4. SUMMER THERMAL COMFORT EVALUATION

The evaluation of summer thermal comfort has been conducted according to CIBSE Technical Memoranda TM52 (CIBSE 2013) and TM59 (CIBSE 2017) as they offer a comprehensive and widely used method for overheating risk analysis in buildings (see for example (Gamero-Salinas, Monge-Barrio et al. 2020)). The first document (TM52) presents three criteria based on the frequency, duration and intensity of the deviations of operative temperature from the EN15251 comfort categories (NBN 2007): *Adaptive hours of exceedance* (Tmax+1), *Daily weighted exceedance* (We), and *Upper limit temperature* (Tupp) (CIBSE 2013). In homes, CIBSE only imposes compliance with the first criterion (*Adaptive hours of exceedance*) for living rooms, kitchens and bedrooms (CIBSE 2017). Nevertheless, all these criteria have been considered in this study with respect to the limit of the comfort Category II (NBN 2007), recommended for new buildings and major refurbishments in absence of very sensitive and fragile persons (Olesen 2007). For bedrooms, a criterion based on an absolute threshold of 26°C was also considered as suggested by TM59 (CIBSE 2017). This static criterion is based on the fact that thermal adaptation is considerably reduced during the sleep (Peeters, de Dear et al. 2009). Table 3 details the application of these criteria. Occupied hours were considered for the living room from 7am to 10pm and from 10pm to 7am for the bedroom in accordance with TM59 (CIBSE 2017).

Table 3 : used criteria for summer thermal comfort evaluation.

Name	Thresholds	Benchmark (maximum)	Source
Static hours of exceedance	T_{op} >26°C	1% of annual occupied hours (10pm-7am) (bedrooms only)	TM59, CIBSE 2017
Adaptive hours of exceedance	T_{op}- T_{max}> 1K with T_{max} *= EN15251 Cat II upp. limit*	3% of occupied hours (May to September inclusive)	TM52, CIBSE 2013 TM59, CIBSE 2017
Daily weighted exceedance	We= ∑he x WF *with WF=max (0; Top-Tmax)* *and he: corresponding time [h]*	6 in any one day during occupied hours	TM52, CIBSE 2013
Upper limit temperature	Tupp=Tmax + 4K	Absolute maximum value during occupied hours	TM52, CIBSE 2013

3. RESULTS

Figure 4 and Figure 5 present the summer thermal comfort evaluation under historical (1976-2005), RCP2.6 (2071-2100) and RCP8.5 (2071-2100) scenarios resulting from the application of the criteria presented in Table 3 for the living room (Figure 4) and for the main bedroom (Figure 5) of the house.

For the living room, Figure 4 shows that the *Adaptive hours of exceedance* criteria (not more than 3% of occupied hours where Top-Tmax> 1K) is met under the 3 climatic scenarios. The *Daily weighted exceedance* criterion is met for 75% of years between 1976 and 2005, but this result could drop under 50% of the years between 2071-2100 (38% under RCP8.5 scenario). Moreover, this criterion is not met for more than 2 days per year for half the years between 2071 and 2100 under the RCP8.5 while it is only exceeded once per year in 25% of the years between 1976 and 2005. The *Upper limit temperature* criteria is only exceeded under the RCP8.5 scenario (3 times and up to 6K). For the main bedroom Figure 5 shows that the *Static hours of exceedance* criteria (max 1% of occupied hours per year where Top>26°C) is only exceeded 25% of the years during the historical period. The non-compliance with this criterion could however become usual: 25 years are exceeding the criteria over the period 2071-2100 under the RCP8.5 scenario. On the contrary, the *Adaptive hours of exceedance* criteria (not more than 3 % of occupied hours where Top-Tmax> 1K) is exceeded only one year out of four under this scenario (while it is met under the other scenarios). The median value of the number of days exceeding the *Daily weighted exceedance* reaches 4 between 2071-2100 (under RCP8.5 scenario) while it is 0 for the historical period. The *Upper limit temperature* criteria is not frequently exceeded but reaches higher frequencies per year under the RCP8.5 scenario (up to 39 times per year).

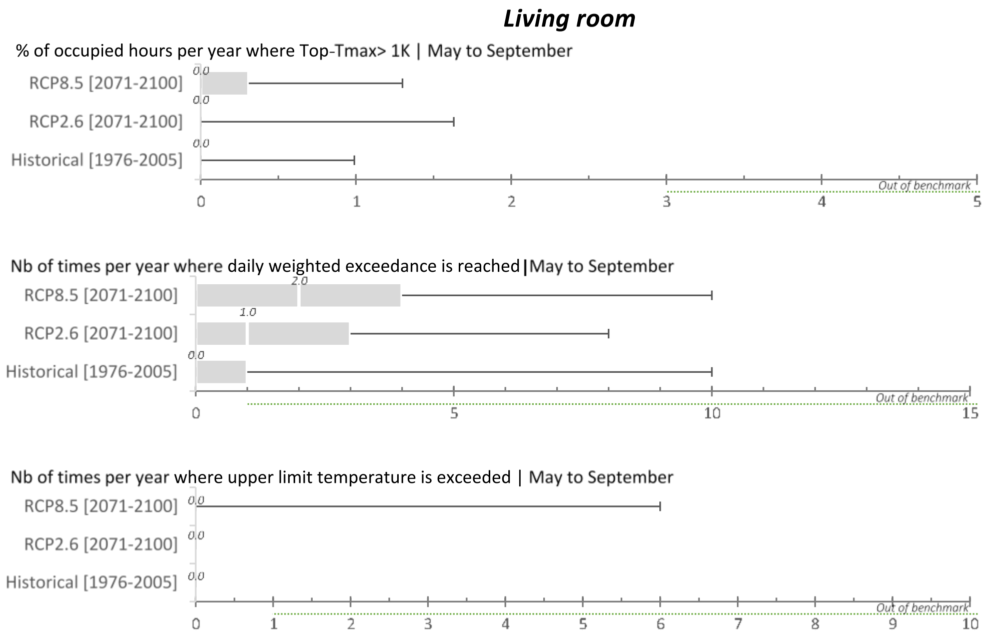

Figure 4: summer thermal comfort evaluation under historical (1976-2005), RCP2.6 (2071-2100) and RCP8.5 (2071-2100) scenarios resulting from the application of the criteria presented in Table 3 for the living room.

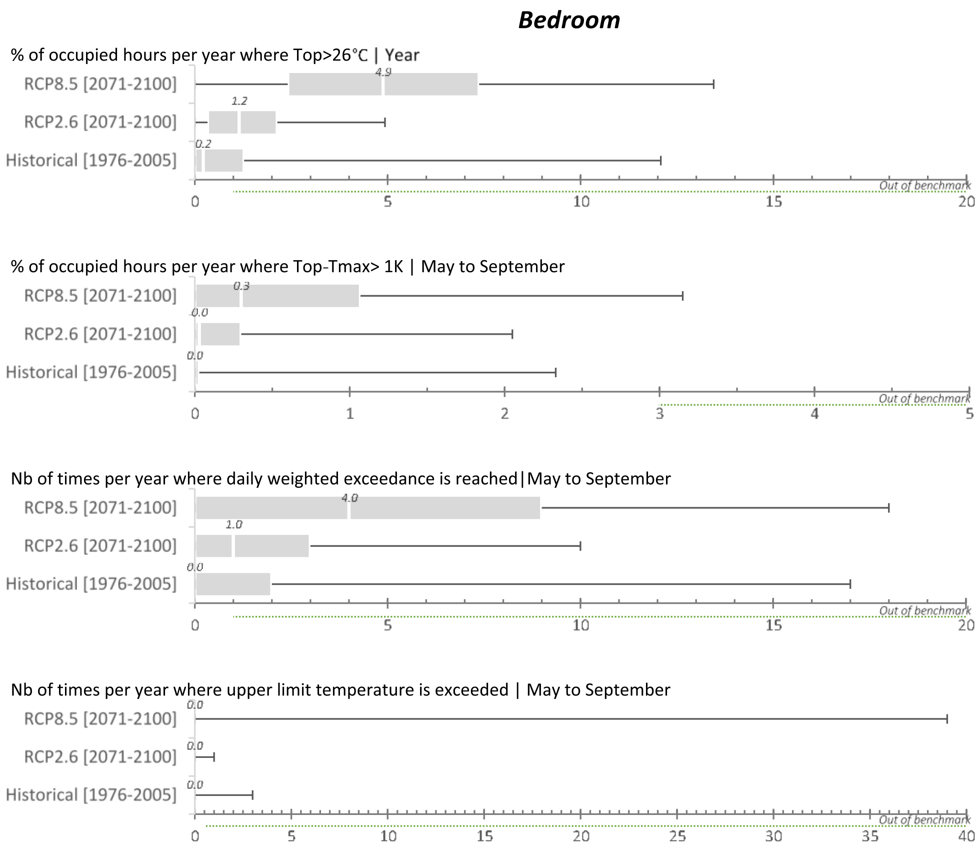

Figure 5: summer thermal comfort evaluation under historical (1976-2005), RCP2.6 (2071-2100) and RCP8.5 (2071-2100)

scenarios resulting from the application of the criteria presented in *Table 3* for the bedroom.

4. DISCUSSION

As shown in Figure 3, days over 25°C and heat waves will become quite common in the future in Belgium: around 27 days reaching 25°C and one heatwave (until four) on average per year should be excepted under the RCP8.5 scenario while these phenomena were very exceptional in Historical data (only one year with heatwaves and a mean value of less than 11 days per year reaching 25°C).

The analysis of the historical period shows that the passive strategies implemented in the building (internal shading devices and natural cooling by windows opening only practiced in the living room) generally allow compliance with *the CIBSE overheating criteria*. It should also be remembered here that the configuration of the building (east oriented, limited glazing area, sub urban area, etc.) helps not to exacerbate overheating phenomena.

The climate evolution could have however a clear impact on the encountered indoor climate conditions as shown in *Figure 4* and *Figure 5.* The severity of this evolution depends on the criterion and on the studied room. In this way, the results confirm the observation made in a previous study (Attia and Gobin 2020).

More specifically, the CIBSE *Daily weighted exceedance* criterion appears to be difficult to meet in the future (more than 50% of the years during the period 2071-2100 under RCP2.6 do not comply with this criterion for both the living room and the bedroom). This shows an increasing difficulty in dissipating the heat accumulated inside the building probably linked to higher external temperatures. The bedroom suffers particularly from this phenomenon (median value of 4 days per year where the daily weighted exceedance criteria is reached under the RCP8.5 scenario (vs. 2 for the living room)). The *static hours of exceedance* (Top>26°C) criterion in the bedroom appears to be the most difficult to comply with in the future (criterion exceeded more than 50% of the years during the period 2071-2100 under the RCP2.6 scenario and more than 75% of the years under the RCP8.5).

The *Adaptive hours of exceedance* and *Upper limit temperature* criteria are however rarely exceeded. The CIBSE criteria based on adaptive comfort appear thus easier to meet than the criteria based on a fixed static value. However, it has been already shown that these criteria based on a significant deviation from the comfort limits set by EN15251 are not very restrictive for this type of building and are not always representative of the number of complaints reported by the occupants (Dartevelle, Moeseke et al. 2020). It is therefore crucial to properly (re)consider (and probably depending on the room type) the applicability and the limits of adaptive thermal comfort in residential buildings (EN15251 has been established in offices).

More generally, the passive strategies currently deployed (internal solar shading and natural cooling by windows opening in the living room only) will not be sufficient in the future. The widespread use of solar shadings (which could be replaced by external solar shadings) and natural cooling by windows opening in all rooms (including bedrooms) could certainly contribute to improve the summer thermal comfort of the house and probably limit the use of active cooling systems in the future. In this context, the the potential decrease of (night)ventilative cooling efficiency due to higher (night)temperature induced by climate evolution should be explored in details.

Further research focusing on the potential of such strategies in a global warming context are thus needed. This understanding appears crucial to limit the potential global increase in cooling energy consumption (Yang, Javanroodi et al. 2021) and properly define policies and standards aiming at a better resilience of the building stock to heat waves (Attia, Levinson et al. 2021).

5. CONCLUSION

Based on a whole building energy simulation, this paper has investigated the potential evolution of summer thermal comfort in a typical nZEB house under different climate evolution scenarios (RCP2.6 and RCP8.5).

The study, based on compliance with CIBSE TM52 and TM59 summer thermal comfort criteria analysis, has shown that the passive strategies currently used in the case study (internal solar shading and intensive natural ventilation in the living room only) will not be sufficient in the future (especially in the bedroom) and that other strategies will be necessary to guarantee summer thermal comfort.

It has also been noticed that CIBSE criteria based on adaptive thermal comfort are much less restrictive in a context of changing climate than the criterion based on a fixed static value. It is therefore crucial to verify the applicability of adaptive thermal comfort defined in EN15251 to the residential sector and its limits in a changing climate context.

More generally, the paper shows that considering summer thermal comfort and its possible evolution should be a priority for the design of nZEB houses (and related standards and policies) to avoid the generalisation of active cooling system in temperate oceanic climate and its induced environmental impacts. Therefore, the potential of passive design strategies to ensure summer thermal comfort under future temperate oceanic climate have to be analysed more in depth.

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