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Article

Indoor Summer Thermal Comfort in a Changing Climate: The Case of a Nearly Zero Energy House in Wallonia (Belgium) [†]

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Abstract: While the potential impact of climate change mitigation measures is well documented in building sciences literature, there are only relatively sparse studies focusing on the efficiency of adaptation strategies. This paper aims to contribute to this topic by evaluating the extent to which the design of a typical nearly Zero Energy Building (nZEB) house in Wallonia (Belgium), and its current operation, could provide summer thermal comfort in a changing climate. Based on calibrated whole building energy simulations, and on the integration of future climate data directly derived from a high-resolution climate model, this study evaluates the potential evolution of overheating risks in the living room and in the main bedroom of the house. Discussing the compliance with existing overheating criteria, the study shows that the passive strategies currently deployed in the house might not be sufficient to guarantee summer thermal comfort especially in the bedroom, and that other strategies might be necessary in the future to limit the use of active cooling systems and curb their environmental impacts. This study concludes that considering the potential of these strategies to guarantee summer thermal comfort in a changing climate should be a priority for the design of nZEB houses (and their related policies) also in temperate oceanic climates.

Keywords: nearly Zero Energy Buildings; climate change; summer thermal comfort; overheating



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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 its Fifth Assessment Report (AR5) in 2014 [1]. In this context, a drastic reduction of greenhouse gas emissions is needed to mitigate climate change effects. For the building sector, Wallonia (southern part of Belgium), like many other European regions, aims to reach a carbon neutral building stock by 2050 [2]. This implies achieving nearly Zero Energy Buildings (nZEB) standards for all buildings, including existing ones [3]. According to the definition provided in the European Directive 2010/31/EU on the energy performance of buildings [4], nZEB implies that “the very low amount of energy required is covered to a very significant extent by energy from renewable sources”.

In a region such as Wallonia, characterized by a temperate oceanic climate with predominant heating energy use (more than 70% of the energy used in residential buildings [4]), nZEB performance requirements aim first to drastically reduce heating energy needs of buildings. Practically, measures to increase the insulation and airtightness of the thermal

envelope, mechanized hygienic ventilation (with heat exchanger) and the search for a favourable orientation have become essential for the design of nZEBs in Wallonia.

Nevertheless, while undoubtedly allowing for winter comfort conditions with lower energy costs [5], these construction techniques entail other risks of discomfort, and might even require some adaptation/understanding from the part of the occupants [6–8]. Many studies have, for example, 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 under the current climate [9].

Furthermore, there is strong consensus that the frequency and intensity of heatwaves will increase in the future [1]. As a consequence, global warming will have a worsening impact on overheating risk [10] in buildings, potentially compromising comfort, well-being and health, particularly for more sensitive occupants [11].

Today, simple strategies (such as the use of solar shading and the opening of windows) are often seen as key to prevent and guarantee summer thermal comfort in nZEB residential buildings within the considered climatic zone [12]. The use of these passive strategies (as they “do not use or use only small amounts of external energy”, in opposition to active strategies that “use electrical or mechanical systems” [13]) is encouraged by Walloon building standards [3]. It allows, for example, to comply with a specific requirement of nZEB dwellings by lowering an overheating risk indicator [14].

In this context, a question emerges today in the building sector: will the implementation of these passive strategies—which still appears quite limited in practice [15]—be sufficient to avoid in the future a generalised use of active cooling systems, with their energy consumption [16] and environmental impacts [17], in a country with no such tradition?

While the potential impact of climate change mitigation measures is now well documented in the literature of building sciences, studies focusing on the efficiency of these adaptation strategies are only at their infancy for a number of reasons: slow knowledge transfer from climate modelling to building engineering science; stochastic behaviours and uncertainties associated with future climates that induce large datasets and specific methods to deal with; substantial computational time needed; etc. [16]. These studies are, however, crucial to define proper building energy standards that will effectively reduce energy demands without compromising thermal comfort. This paper aims to provide a contribution 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 (Figure 1). In Wallonia, detached houses represent the most frequent type (39%) of single-family housing (approximately 80% of the total housing stock [18]). The house, constructed in 2011, is composed of 2 levels of around 83 m² (net floor area) each and is occupied by 2 adults and 3 children (1 baby). The main thermal characteristics of its building envelope are presented in Table 1.

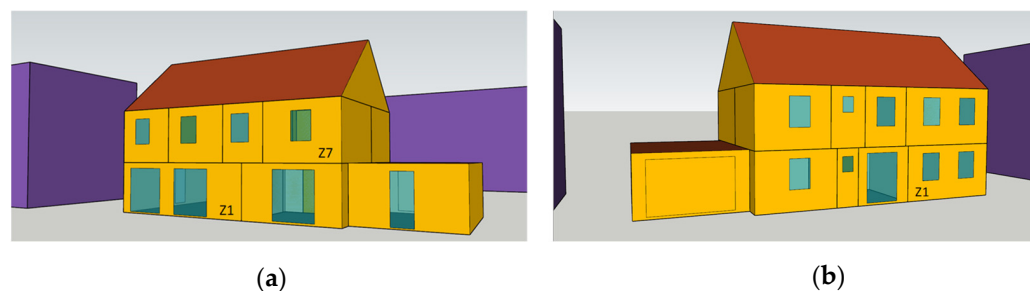


Figure 1. Views of the main facades with indication of the thermal zones considered (Z1: living room, Z7: main bedroom). (a) Rear façade (east oriented). (b) Front façade (west oriented).

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	n.a.**	n.a.	
Number of occupants	[-]	5 (<12 y/o: 3)	2	n.a.	n.a.	
Presence during working hours	[-]	Yes	2	n.a.	n.a.	
Net heated floor area	Total	[m ²]	166	3	n.a.	n.a.
	Living room	[m ²]	42.3	3	n.a.	n.a.
	Main bedroom	[m ²]	14.2	3	n.a.	n.a.
Window-to-floor surface ratio	Total	[%]	19.9	3	n.a.	n.a.
	Living room	[%]	29.2	3	n.a.	n.a.
	Main bedroom	[%]	7.9	3	n.a.	n.a.
Mean U-value (windows included)	[W/m ² K]	0.31	³ (Walls: 1)	[-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	[%]	85	1	[-6.2%; +6.2%]	-2%	
Solar Heat Gain Coefficient (SHGC) (windows)	[-]	0.63	3	[-5%; +5%]	-5%	
Main windows orientation (living room and main bedroom)	[-]	E	1	n.a.	n.a.	
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/m ²]	2.2 (mean value)	1	[-3%; +3%]	-3%	
Additional thermal capacity of zones (furniture)	[kJ/K.m ²]	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 (Not usual) (One side ventilation)	2	[0; +6]	+0%	
Heating needs	[kWh/m ² ·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/m ² ·y]	1035	1	[-10%; +10%]	+0%	
Setpoint temperature (mean value September to May)	Living Room	[°C]	20.1	1	[-0.3; +0.3]	+0.3
	Main Bedroom	[°C]	19.1	1	[-0.3; +0.3]	+0.3
Primary energy use (Mainly heating and domestic hot water —PV production)	[kWh/m ² ·y]	61 kWh/m ² ·y	3	n.a.	n.a.	

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

** n.a.: not applicable.

In terms of thermal performances, the house complies with the current requirements for nZEB in Wallonia [19] relying on the definition provided in the European Directive 2010/31/EU on the energy performance of buildings [20]. These requirements imply a primary energy use of a maximum 85 kWh/m²·year (mainly including heating, domestic hot water consumption as well as on site electricity production, here supplied by photovoltaics cells covering the roof). The nZEB standard also requires compliance with a simplified overheating risk indicator based on a static thermal calculation under the current climate [14].

Following an initial measurement of its main characteristics, the performance of the house has been monitored during one full year (2016), including: air temperatures, electricity use (internal gains), heating demands, airflows induced by mechanical ventilation, efficiency of the heat recovery system, U values of the walls and airtightness. Some weather data have also been monitored on site (dry bulb temperature and relative humidity) and complemented by 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) tool [19]. In the framework of this study, two main rooms were analysed: the living room (Z1) and the main bedroom (Z7). A description of their spatial characteristics is included in Table 1 and illustrated in Figures 1 and 2.

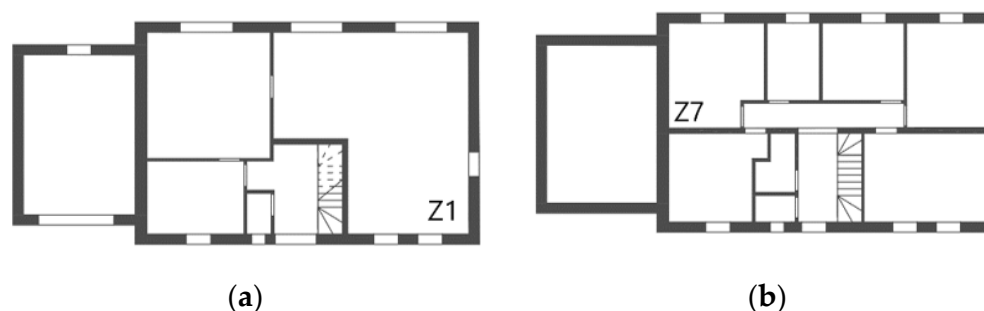


Figure 2. Plans of the house with indication of the considered thermal zones (Z1: living room, Z7: main bedroom). (a) Floor plan. (b) First floor.

Based on the behaviours reported by the occupants, the closure of the white internal curtain to protect from solar radiation and the opening of windows to dissipate the heat in the living room have been integrated in the thermal model (except during the periods of absence of the occupants). According to the occupants, 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 problems have been measured during the year 2016. The house complied with all the summer thermal comfort criteria (see Section 2.4) defined by the Chartered Institution of Building Services Engineers (CIBSE) (UK), even if the occupants perceived the bedroom temperature in summer as slightly too hot. The methodologies implemented for interviews and data collection are described in more detail in a previous publication [21].

The house is located in a suburban area of Namur (the capital city of Wallonia), in the city of Erpent in the southern part of Belgium (50° North) (see Figure 3) and is exposed to a temperate oceanic climate (Cfb zone according to the Köppen–Geiger climate classification system [22]). Section 2.3 presents an overview of the current and potential future characteristics of this climate.



Figure 3. Localisation of the city of Erpent (Wallonia, south part of Belgium) (Reprinted from Ref. [23]).

2.2. Calibrated Thermal Model

A whole building energy simulation of the house has been carried out (Figure 1) using the TRNsys18 simulation engine [24]. 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 [25]) indicators defined by ASHRAE guideline 14 [26]. 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) [27]) 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 illustrates in detail 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

Figure 4 illustrates the capability of the calibrated model to estimate the time exceeding 25 °C in the living room and in the main bedroom compared to the values that were measured in 2016. The year 2016 can be considered broadly in line with the average of the last 30 years, both in terms of solar radiation and of temperatures [28] (for an overview of climatic historical data, see Figure 5).

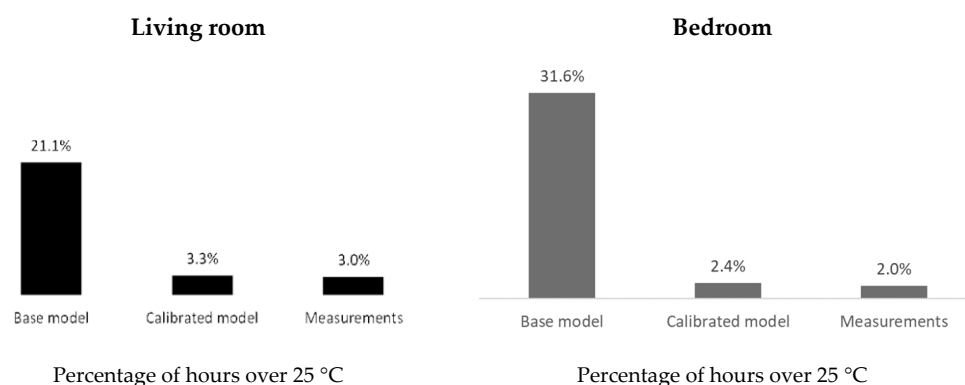


Figure 4. Models' capability to estimate the time exceeding 25 °C in the living room (**left**) and in the main bedroom (**right**) compared to the measured values.

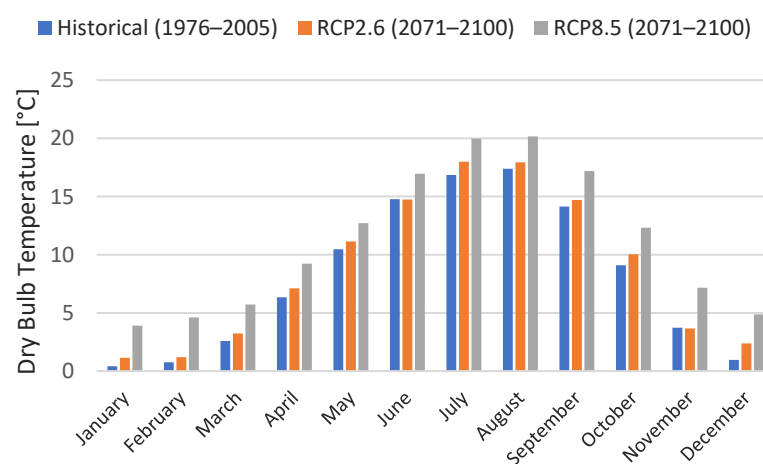


Figure 5. Monthly mean dry bulb temperature evolution under historical, RCP2.6 (2071–2100) and RCP8.5 (2071–2100) scenarios according to ALARO Model [29].

2.3. Climate Change Model

Data for future and historical (here intended as similar to current) climatic conditions (temperature, humidity, radiation, wind speed and direction, etc.) have been directly derived from high-resolution climate modelling. These models, dynamically downscaled from Global Climate Models (GCMs), consider local climate variations and anomalies and allow a detailed temporal and geographical resolution (horizontal grid spacing <4 km). Compared to the classical use of morphed weather data [30], this method allows for accounting the variability in occurrence and intensity of heatwaves phenomena throughout the years. Today, these data based on the ALARO model are available in Belgium for different representative concentration pathways (RCP) [29]. 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 to historical data (1976–2005) (also derived from the same climate model) for the city of Uccle (the main meteorological station of Belgium, located in the southern part of Brussels, about 50 km from Namur). These two RCPs scenarios were chosen since they represent opposite (and extreme) perspectives with respect to the deployment of mitigation strategies and, consequently, 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 [31], 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 [1]. Figure 5 shows the monthly mean outdoor temperature evolution according

to these scenarios compared to the historical one (yearly global horizontal radiation remains stable—around 1040 kWh/m²·year—under these different scenarios).

As mentioned in the introduction, there is wide consensus that these scenarios will impact the frequency and the duration of heat waves [1]. In Belgium, heatwaves are defined as a period of minimum 5 consecutive days with air temperature reaching at least 25 °C and more than 30 °C for at least 3 days [32]. Figure 6 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. A standard boxplot representation has been used to illustrate the distribution (min, 25th percentile, median, 75th percentile, max) of the encountered values for the considered period. Median values have also been specified to increase the readability of these graphs. These sets of data, covering a period of 30 years each, were directly introduced in the TRNsys simulation software with an hourly resolution (using an IWEC format [33]) in order to provide a detailed overview of their implications on the building indoor climate.

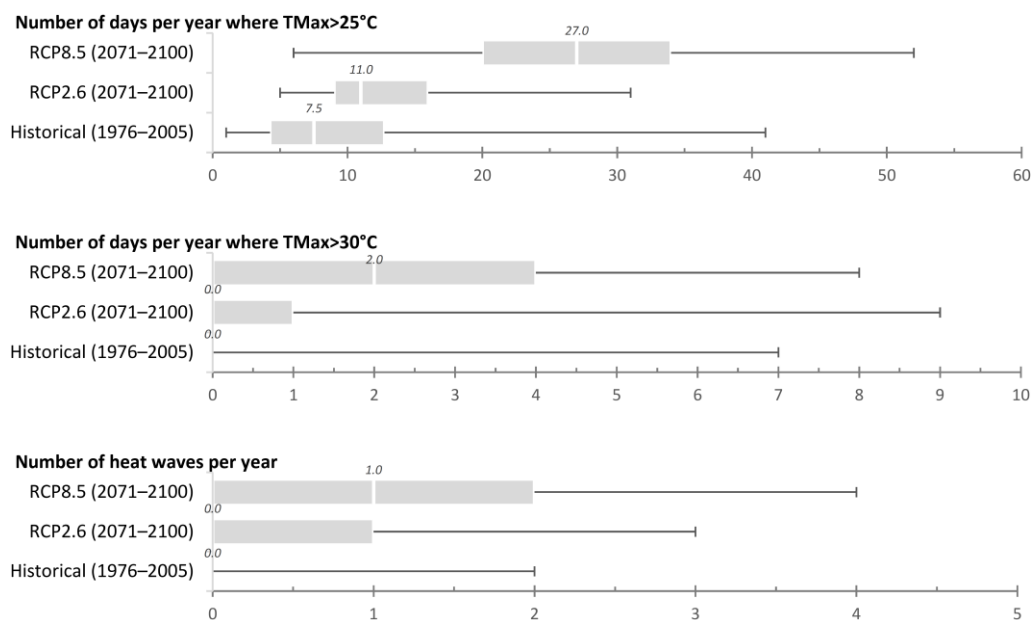


Figure 6. Evolution of the number of days reaching 25 °C or 30 °C and the number of heatwaves per year according to historical (1976–2005), RCP2.6 (2071–2100) and RCP8.5 (2071–2100) scenarios in Uccle (Belgium).

2.4. Summer Thermal Comfort Evaluation

The evaluation of summer thermal comfort has been conducted according to CIBSE Technical Memoranda TM52 [34] and TM59 [35], as they offer a comprehensive and widely-used method for overheating risk analysis in buildings (see for example [36]). 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 [37]: *Adaptive hours of exceedance* ($T_{\max} + 1$); *Daily weighted exceedance* (W_e) and *Upper limit temperature* (T_{upp}) [34]. In the context of climate change scenarios, these criteria—based on the theory of adaptive comfort—seem particularly appropriate as they already imply a physiological, behavioural and psychological adaptive capacity of humans [38,39]. In homes, CIBSE only imposes compliance with the first criterion (*Adaptive hours of exceedance*) for living rooms, kitchens, and bedrooms [35]. Nevertheless, all these criteria have been considered in this study with respect to the limit of the comfort Category II [37], recommended for new buildings and major refurbishments in the absence of very sensitive and fragile persons [40]. For bedrooms, a criterion based on an absolute threshold of 26 °C was also considered as suggested by TM59 [35]. This static criterion is based on the fact that thermal adaptation

is considerably reduced during sleep [41]. Table 3 illustrates in detail the application of these criteria. In accordance with TM59, occupied hours were considered to be from 7 am to 10 pm for the living room and from 10 pm to 7 am for the bedroom [35].

Table 3. Criteria for summer thermal comfort evaluation.

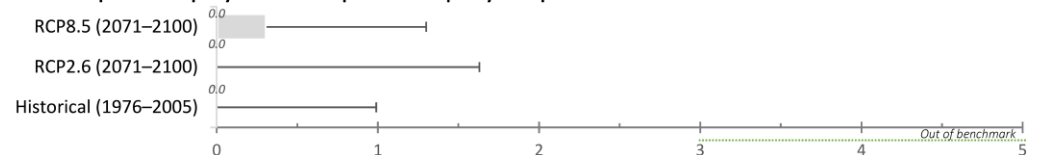
Name	Thresholds	Benchmark (Maximum)	Source
Static hours of exceedance	$T_{op} > 26 \text{ }^{\circ}\text{C}$	1% of annual occupied hours (10 p.m.–7 a.m.) (bedrooms only)	TM59, CIBSE 2017
Adaptive hours of exceedance	$T_{op} - T_{max} > 1 \text{ K}$ $T_{max} = \text{EN15251 Cat II upp. limit}$	3% of occupied hours (May to September inclusive)	TM52, CIBSE 2013 TM59, CIBSE 2017
Daily weighted exceedance	$W_e = \sum h_e \times WF$ $WF = \max(0; T_{op} - T_{max})$ h_e : corresponding time [h]	6 in any one day during occupied hours	TM52, CIBSE 2013
Upper limit temperature	$T_{upp} = T_{max} + 4 \text{ K}$	Absolute maximum value during occupied hours	TM52, CIBSE 2013

3. Results

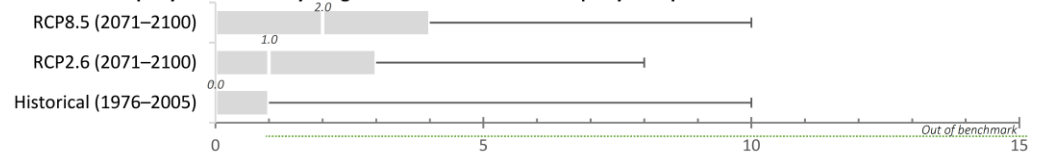
Figures 7 and 8 present the summer thermal comfort evaluation under historical (1976–2005), RCP2.6 (2071–2100) and RCP8.5 (2071–2100) scenarios resulting from the application of the criteria presented in Table 3 for the living room (Figure 7) and for the main bedroom (Figure 8) of the house.

Living room

% of occupied hours per year where $T_{op} - T_{max} > 1 \text{ K}$ | May to September



Nbre of times per year where daily weighted exceedance is reached | May to September



Nbre of times per year where Upper limit temperature is exceeded | May to September

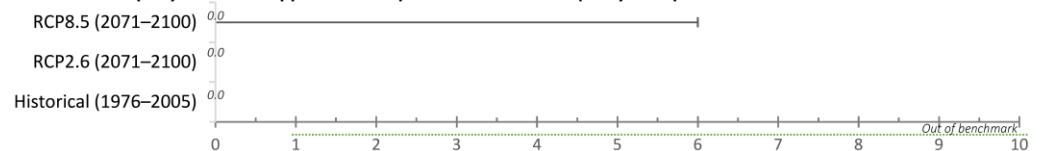


Figure 7. Summer thermal comfort evaluation under historical (1976–2005), RCP2.6 (2071–2100) and RCP8.5 (2071–2100) scenarios resulting from the application of the criteria presented in Table 3 for the living room.

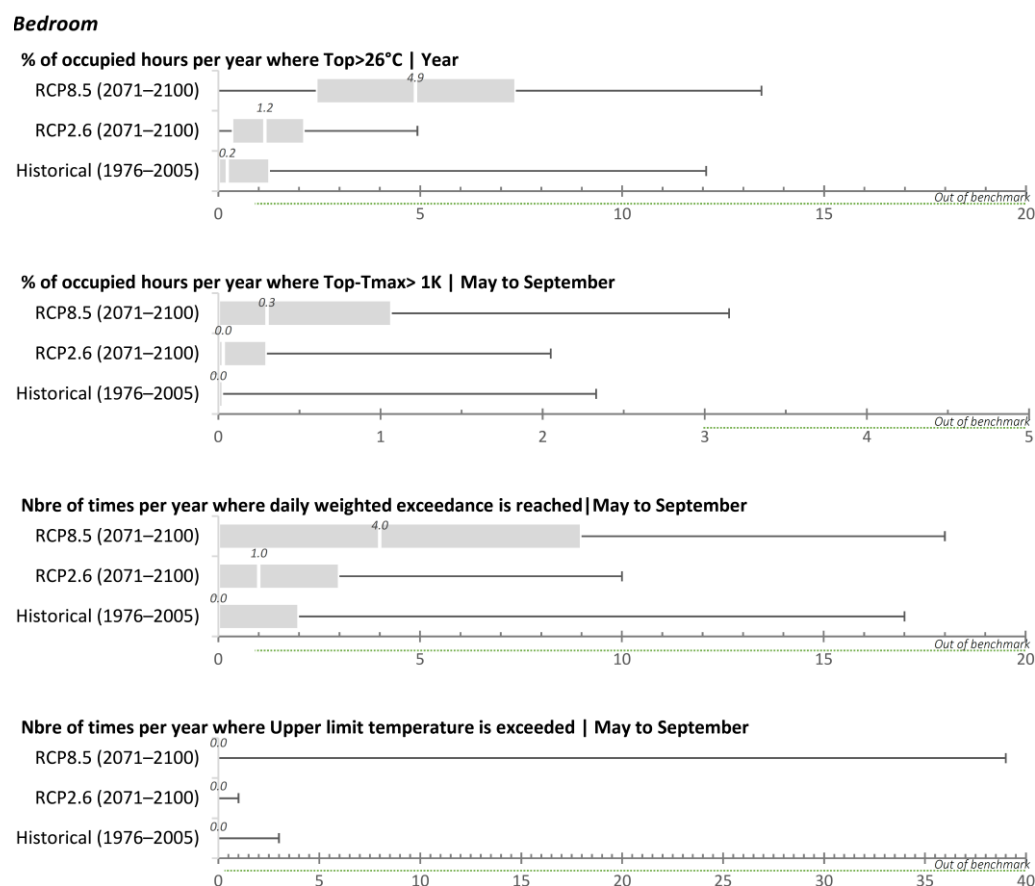


Figure 8. Summer thermal comfort evaluation under historical (1976–2005), RCP2.6 (2071–2100) and RCP8.5 (2071–2100) scenarios resulting from the application of the criteria presented in Table 3 for the bedroom.

For the living room, Figure 7 shows that the *Adaptive hours of exceedance* criteria (not more than 3% of occupied hours where $T_{op} - T_{max} > 1$ K) is met under the three 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 and 2100 (38% under RCP8.5 scenario). Moreover, this criterion is not met for more than 2 days per year for half of 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 (three times and up to 6 K). For the main bedroom, Figure 8 shows that the *Static hours of exceedance* criterion (max 1% of occupied hours per year where $T_{op} > 26$ °C) is only exceeded 25% of the years during the historical period. The non-compliance with this criterion could, however, become systematic: 25 years are exceeding this criterion over the period 2071–2100 under the RCP8.5 scenario. On the contrary, the *Adaptive hours of exceedance* criterion (not more than 3% of occupied hours where $T_{op} - T_{max} > 1$ K) 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* criterion is not frequently exceeded but it reaches higher frequencies per year under the RCP8.5 scenario (up to 39 times per year).

4. Discussion

As shown in Figure 6, 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 (up to four) on average per year should be expected under the RCP8.5 scenario. Conversely, these

phenomena were very exceptional in the 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 implementation of passive strategies in the building (e.g., internal shading devices and natural cooling by windows opening only practiced in the living room) generally allows compliance with the CIBSE overheating criteria. It should also be remembered here that the configuration of the building analysed for this study (east oriented, limited glazing area, suburban area, etc.) allowed to reduce the occurrence of overheating phenomena.

The evolution of the climate could have, however, a clear impact on future indoor climate conditions, as shown in Figures 7 and 8. 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 [42].

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* criterion is reached under the RCP8.5 scenario, versus 2 for the living room). The *Static hours of exceedance* ($T_{op} > 26$ °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. These CIBSE criteria based on adaptive comfort appear, thus, easier to meet than benchmarks based on a fixed static value. 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 [21]. It is, therefore, crucial to properly (re)consider (this also probably depending on the room type) the applicability and the limits of adaptive thermal comfort principles and strategies in residential buildings (EN15251 was originally established from data collected in offices) [43,44].

More generally, the passive strategies currently deployed (internal solar shading and natural cooling by windows opening in the living room only) might not be sufficient in the future. The widespread use of window curtains (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 need of active cooling systems in the future. In this context, the potential decrease of (night)ventilative cooling efficiency due to higher (night)temperatures induced by climate evolution (as illustrated by Figure 5) should be explored in detail.

Further research focusing on the potential of such strategies in a global warming context is, therefore, needed. A more thorough understanding appears crucial to limit the potential global increase in cooling energy consumption [16] and to properly define policies and standards aiming at a better resilience of the building stock to heat waves [45].

5. Conclusions

Based on a whole building energy simulation, this paper 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 analyses, has shown that the passive strategies currently used in the selected 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 the theory of adaptive thermal comfort are much less restrictive in a context of changing climate than criteria 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 the context of a changing climate.

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 generalised use of active cooling systems, with their induced environmental impacts, in temperate oceanic climates. Therefore, the full potential of passive design strategies to ensure summer thermal comfort under future climate scenarios have to be analysed more in depth.

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References

1. IPCC. *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*; Core Writing Team, Pachauri, R.K., Meyer, L.A., Eds.; IPCC: Geneva, Switzerland, 2014; p. 151.
2. Gouvernement Wallon. *Déclaration de Politique Régionale pour la Wallonie 2019–2024*; Gouvernement Wallon: Namur, Belgium, 2019.
3. Gouvernement Wallon. *Stratégie Wallonne de Rénovation Énergétique à Long Terme du Bâtiment*; Gouvernement Wallon: Namur, Belgium, 2020.
4. ICEDD. *Bilan Énergétique de la Wallonie: Secteur Domestique et Équivalents*; ICEDD: Namur, Belgium, 2014.
5. Deltour, J.; Vanwelde, V.; Darteville, O. *MEsures de Performances Réelles et de Satisfaction des occupants dans les Bâtiments Résidentiels à Hautes Performances Energétiques: Rapport de Synthèse sur les Performances Énergétiques Réelles*; Architecture et Climat—Université catholique de Louvain, Centre Scientifique et Technique de la Construction: Louvain-la-Neuve, Belgium, 2018; p. 100.
6. Rohdin, P.; Molin, A.; Moshfegh, B. Experiences from nine passive houses in Sweden—Indoor thermal environment and energy use. *Build. Environ.* **2014**, *71*, 176–185. [[CrossRef](#)]
7. Mlecnik, E.; Schütze, T.; Jansen, S.J.T.; de Vries, G.; Visscher, H.; van Hal, A. End-user experiences in nearly zero-energy houses. *Energy Build.* **2012**, *49*, 471–478. [[CrossRef](#)]
8. Ortiz, M.; Itard, L.; Bluysen, P.M. Indoor environmental quality related risk factors with energy-efficient retrofitting of housing: A literature review. *Energy Build.* **2020**, *221*, 110102. [[CrossRef](#)]
9. Jones, R.V.; Goodhew, S.; de Wilde, P. Measured Indoor Temperatures, Thermal Comfort and Overheating Risk: Post-occupancy Evaluation of Low Energy Houses in the UK. *Energy Procedia* **2016**, *88*, 714–720. [[CrossRef](#)]
10. Ozarisoy, B.; Elsharkawy, H. Assessing overheating risk and thermal comfort in state-of-the-art prototype houses that combat exacerbated climate change in UK. *Energy Build.* **2019**, *187*, 201–217. [[CrossRef](#)]
11. World Health Organization. *Health and Global Environmental Change. Heat-Waves: Risks and Responses*; WHO: Geneva, Switzerland, 2004.
12. Mlakar, J.; Štrancar, J. Overheating in residential passive house: Solution strategies revealed and confirmed through data analysis and simulations. *Energy Build.* **2011**, *43*, 1443–1451. [[CrossRef](#)]
13. Chan, H.Y.; Riffat, S.B.; Zhu, J. Review of passive solar heating and cooling technologies. *Renew. Sustain. Energy Rev.* **2010**, *14*, 781–789. [[CrossRef](#)]

14. Gouvernement wallon. *Arrêté du Gouvernement Wallon Déterminant la Méthode de Calcul et les Exigences, les Agréments et les Sanctions Applicables en Matière de Performance Énergétique et de Climat Intérieur des Bâtiments*; Gouvernement Wallon: Namur, Belgium, 2008.
15. Dartevelle, O.; Vanwelde, V. *MESures de Performances Réelles et de Satisfaction des Occupants dans les Bâtiments Résidentiels à Hautes Performances Énergétiques: Rapport de Synthèse sur le Climat Intérieur*; Architecture et Climat—Université catholique de Louvain, Centre Scientifique et Technique de la Construction: Louvain-la-Neuve, Belgium, 2018; p. 80.
16. Yang, Y.; Javanroodi, K.; Nik, V.M. Climate change and energy performance of European residential building stocks—A comprehensive impact assessment using climate big data from the coordinated regional climate downscaling experiment. *Appl. Energy* **2021**, *298*, 117246. [[CrossRef](#)]
17. Ford, B.; Mumovic, D.; Rawal, R. Call for Papers: Alternatives to Air Conditioning: Policies, Design, Technologies, Behaviours. Available online: <https://www.buildingsandcities.org/media/pdf/BCCFPAltCooling.pdf> (accessed on 10 February 2022).
18. BPIE. *Stratégie Wallonne de Rénovation Énergétique à Long Terme du Bâtiment*; Service public de Wallonie: Namur, Belgium, 2017.
19. Gouvernement wallon. *Arrêté du Gouvernement Wallon Modifiant L'arrêté du Gouvernement Wallon du 15 Mai 2014 Portant Exécution du Décret du 28 Novembre 2013 Relatif à la Performance Énergétique des Bâtiments*; Gouvernement Wallon: Namur, Belgium, 2019.
20. European Parliament. *Directive 2010/31/UE of the European Parliament and of the Council of 19 May 2010 on the Energy Performance of Buildings*; European Parliament: Strasbourg, France, 2010.
21. Dartevelle, O.; van Moeseke, G.; Mlecnik, E.; Altomonte, S. Long-term evaluation of residential summer thermal comfort: Measured vs. perceived thermal conditions in nZEB houses in Wallonia. *Build. Environ.* **2021**, *190*, 107531. [[CrossRef](#)]
22. Peel, M.C.; Finlayson, B.L.; McMahon, T.A. Updated world map of the Köppen-Geiger climate classification. *Hydrol. Earth Syst. Sci.* **2007**, *11*, 1633–1644. [[CrossRef](#)]
23. Alexrk2. File:Europe Blank Laea Location map.svg under CC-BY-SA-3.0 Licence. Available online: https://commons.wikimedia.org/wiki/File:Europe_blank_laea_location_map.svg (accessed on 10 February 2022).
24. Solar Energy Laboratory. *TRNSYS: A Transient Simulation Program*; University of Wisconsin: Madison, WI, USA, 2018.
25. Aparicio-Fernández, C.; Vivancos, J.-L.; Cosar-Jorda, P.; Buswell, R.A. Energy Modelling and Calibration of Building Simulations: A Case Study of a Domestic Building with Natural Ventilation. *Energies* **2019**, *12*, 3360. [[CrossRef](#)]
26. ASHRAE. *Guideline 14-2014: Measurement of Energy, Demand, and Water Savings*; ASHRAE: Atlanta, GA, USA, 2014.
27. Juneja, M.; Nagar, S.K. Particle swarm optimization algorithm and its parameters: A review. In Proceedings of the 2016 International Conference on Control, Computing, Communication and Materials (ICCCCM), Allahbad, India, 21–22 October 2016; pp. 1–5. [[CrossRef](#)]
28. Royal Meteorological Institute of Belgium. *Bilan Climatologique Annuel 2016*; RMI: Uccle, Belgium, 2017.
29. Giot, O.; Termonia, P.; Degrauwe, D.; De Troch, R.; Caluwaerts, S.; Smet, G.; Berckmans, J.; Deckmyn, A.; De Cruz, L.; De Meutter, P.; et al. Validation of the ALARO-0 model within the EURO-CORDEX framework. *Geosci. Model Dev.* **2016**, *9*, 1143–1152. [[CrossRef](#)]
30. Shen, P. Impacts of climate change on U.S. building energy use by using downscaled hourly future weather data. *Energy Build.* **2017**, *134*, 61–70. [[CrossRef](#)]
31. United Nations. *Framework Convention on Climate Change Adoption of the Paris Agreement*; United Nations: Paris, France, 2015.
32. Royal Meteorological Institute of Belgium. *Vague de Chaleur: A Definition*. Available online: <https://www.meteo.be/fr/infos/dico-meteo/vague-de-chaleur> (accessed on 10 February 2022).
33. ASHRAE. *International Weather for Energy Calculations (IWEC Weather Files) Users Manual and CD-ROM.*; ASHRAE: Atlanta, GA, USA, 2001.
34. CIBSE. *TM 52: The Limits of Thermal Comfort: Avoiding Overheating in European Buildings*; CIBSE: London, UK, 2013.
35. CIBSE. *TM59: Design Methodology for the Assessment of Overheating Risk in Homes*; CIBSE: London, UK, 2017.
36. Salinas, J.C.G.; Monge-Barrio, A.; Sánchez-Ostiz, A. Overheating risk assessment of different dwellings during the hottest season of a warm tropical climate. *Build. Environ.* **2020**, *171*, 106664. [[CrossRef](#)]
37. NBN. *EN15251:2007 Critères pour l'Environnement Intérieur et Évaluation des Performances Énergétiques des Bâtiments Couvrant la Qualité d'air Intérieur, la Thermique, l'Éclairage et l'Acoustique*; NBN: Brussels, Belgium, 2007.
38. De Dear, R.; Brager, G.S. Developing an adaptive model of thermal comfort and preference. In *ASHRAE Winter Meeting*; ASHRAE: San Francisco, CA, USA, 1998; Volume 104.
39. Nicol, F.; Humphreys, M. Derivation of the adaptive equations for thermal comfort in free-running buildings in European standard EN15251. *Build. Environ.* **2010**, *45*, 11–17. [[CrossRef](#)]
40. Olesen, B.W. The philosophy behind EN15251: Indoor environmental criteria for design and calculation of energy performance of buildings. *Energy Build.* **2007**, *39*, 740–749. [[CrossRef](#)]
41. Peeters, L.; de Dear, R.; Hensen, J.; D'Haeseleer, W. Thermal comfort in residential buildings: Comfort values and scales for building energy simulation. *Appl. Energy* **2009**, *86*, 772–780. [[CrossRef](#)]
42. Attia, S.; Gobin, C. Climate Change Effects on Belgian Households: A Case Study of a Nearly Zero Energy Building. *Energies* **2020**, *13*, 5357. [[CrossRef](#)]
43. De Dear, R.; Kim, J.; Parkinson, T. Residential adaptive comfort in a humid subtropical climate—Sydney Australia. *Energy Build.* **2018**, *158*, 1296–1305. [[CrossRef](#)]

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44. Jeong, B.; Kim, J.; Chen, D.; de Dear, R. Comparison of residential thermal comfort in two different climates in Australia. *Build. Environ.* **2021**, *211*, 108706. [[CrossRef](#)]
 45. Attia, S.; Levinson, R.; Ndongo, E.; Holzer, P.; Kazanci, O.B.; Homaei, S.; Zhang, C.; Olesen, B.W.; Qi, D.; Hamdy, M.; et al. Resilient cooling of buildings to protect against heat waves and power outages: Key concepts and definition. *Energy Build.* **2021**, *239*, 110869. [[CrossRef](#)]