Comparison of overheating risk in nearly zero energy dwelling based on three different overheating calculation methods

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Abstract

This study aims to inform building designers about overheating risks in nearly zero energy dwelling and the importance of calculation methods. Three overheating risk indicators are selected and compared, comprising 1) the EPBD overheating indicator, 2) the Passive House overheating indicator, and 3) the ambient warmness degree and indoor overheating degree indicators developed by Hamdy et al. (2017) (Hamdy *et al.*, 2017a). The third overheating calculation method represents the latest state-of-the-art method for overheating assessment. With the help of EnergyPlus energy modeling program, a calibrated building energy model was created. Annual simulations took place for a typical meteorological year comparing overheating risk according to three calculation approaches. Results confirm a 216% difference in the overheated hours between the Energy Performance of Buildings Directive (EPBD) method and the used method of Hamdy et al. 2017. Results emphasize the need to improve the Belgian EPBD calculation method and integrate long-term thermal discomfort indicators to represent climate change and overheating risks in dwellings.

Key Innovations

- Overheating risk estimation is calculated based on three different calculation methods, and results are compared
- One of the overheating calculation method takes into account future climate change scenarios and applies long-term thermal comfort evaluation indicators
- The findings urge the call for a new standardised wat to calculate overheating within the EU Energy Performance of Buildings Directive (EPBD)

Practical Implications

This paper provides a basis to integrate a new overheating calculation method in the EPBD tools in Belgium and other EU member states.

Introduction

This study aims to investigate the vulnerability of dwellings to overheating risk in Belgium. The objectives consist of establishing an energy simulation model of a verified case study within the Walloon Region and assessing its overheating risk based on the three overheating indicators. A five years monitored nearly zero energy house is used as a reference building. A validated building performance simulation model is created and validated in EnegryPlus. By exploring a large body of the literature and standards, we decided to select three overheating assessment methods. The three overheating risk indicators comprise 1) the Belgian Energy Performance of Buildings Directive (EPBD) overheating indicator, 2) the Passive House overheating indicator, and 3) the ambient warmness degree and indoor overheating degree indicators developed by (Hamdy *et al.*, 2017a). The abovementioned methods are applied to a lightweight single-family that has a nearly zero energy annual use with a total surface area of 174 m^2 located in Eupen, Belgium.

This study compares three methods for overheating assessment of new timber construction in Belgium. The innovation lies in the comparative approach that raises the attention to the need to standardise overheating calculation methods.

Our research contributes to overheating evaluation methods in residential buildings (Carlucci and Pagliano, 2012) . The research methodology used in this research is part of the IEA Annex 80 activities on resilient cooling for buildings. The method of Hamdy et al. (2017) is based on CEN 15251 Part 1 and 2 (European Committee for Standardization, 2007). Simultaneously, CEN 16798-1:2019 was consulted. The method runs an aggregated overheating value every time step based on the operative temperature, taking into account the solar radiation and thermal mass effects. The outcomes can help the EU to develop a new approach to assess overheating in residential buildings. Overall, this paper provides an essential basis to improve indoor thermal conditions and climate change resilient design of buildings.

Methodology

The analysis presented in this paper builds on the study of Attia and Fani that investigated the energy performance of a single-family freestanding house in East Belgium (Attia and Gobin, 2020; Fani, 2020). For the study, an integrated modeling approach was developed to analyze the building energy use and thermal comfort conditions, including overheating hours, in a naturally ventilated nearly zero energy building. Figure 2 illustrates the used methodology and the conceptual study framework.

Weather data

The weather information is read from a TMY3 weather data file of a given by the Belgian Royal Meteorological Institute (IRM) for Liege city. The TMY3s are data sets of hourly values of solar radiation and meteorological elements for a 1-year period (2008-2014). Weather data were extracted for Liege Bierset, located at 50.6412° N, 5.4479° E, and 201 m above sea level). The climate file of Liege Bierset is based on Beek weather station, which represents the closest weather station to our case study in Kettenis, Belgium. Our case study is located 51 km east-south of Beek weather station. The weather in Kettenis, Belgium, is known as a temperate oceanic climate.

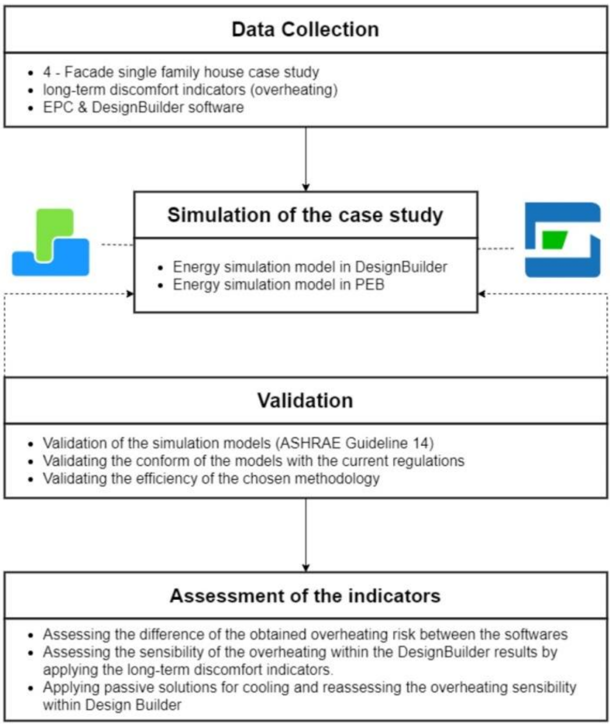

Figure 1: Study conceptual framework describing the key steps of the methodology

Case Study

The case study is a freestanding single-family house constructed in 2008 in Belgium (Attia and Gobin, 2020). The house participated as an exemplary project under the "Construire avec energie" project to stimulate the design and construction of high-performance buildings. The building was chosen as a unique project by the regional government of Wallonia. Besides, the project is an example of sustainable construction advocating for energy neutrality and low embodied carbon (Attia, 2018). The house is occupied by two adults and two children. In this study, assumptions are made for the internal gains induced by equipment and the occupants considering weekdays and weekend occupancy scenarios.

The project is well documented, and its performance is monitored. The case study is located in Eupen (50°37′40″ N, 6°02′11″ E, 298 m) municipality with a temperate oceanic climate (see Figure 2).

Moreover, the building complies with the Belgian Passive House standard requirements and has photovoltaic units mounted on the roof (Mlecnik, Attia and Van Loon, 2011). The external wall conductivity (U-value) is 0.132 W/m^{2}K with 300 mm insulation and net energy requirements for the heating below 150 MJ/m^2 /year.

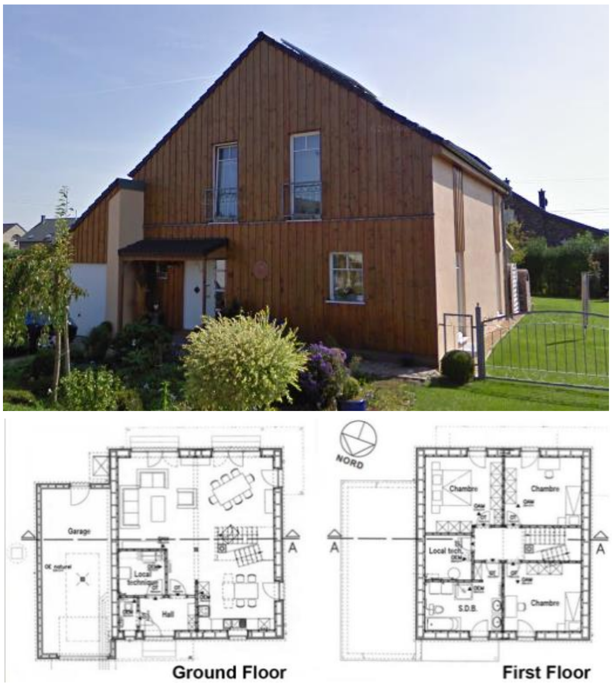

Figure 2: Freestanding single-family house, in Kettenis, Belgium (architect: Leo Michaelis)

The triple glazing has a U-value of 0.81 W/m^{2}K. The triple glazing is composed of three panes of 4 mm separated from each other by 12 mm of a mixture of Argon-Krypton. The measured total energy use is 25 kWh/m^2 /year. The airtightness has been verified through an blower door test and is 0.5 vol/h (n50). The house is a timber construction with a timber truss frame. Its wider geometrical side is oriented perpendicular to the North-South axis, as shown in Figure 2. The roof is gabled with a 35° slope and rises on two floors with the daily activities areas (kitchen, living room, and dining room) on the ground floor and night activities (bedrooms and bathroom) are located upstairs (see Figure 2). A none heated garage is annexed to the house. A detailed energy audit and building characterization took place by De Meester de Betzenbroeck (De Meester de Betzenbroeck , 2008). Windows have internal solar protection. The house occupies an area of 174 m^2 for a heated volume of 536 m^3. The house is highly insulated, i.e., is heated by a pellet heating system. Domestic hot water is produced by a gas water heater, assisted by preheating by solar collectors (6 m^2). This house is equipped with a double-flow mechanical ventilation system (System D) with a heat recovery unit (90%) (*Dispositifs de ventilation dans les bâtiments d'habitation. NBN, Brussels, Belgium.*, 1991). Further details on the building energy efficiency characteristics can be found in the study of De Meester de Betzenbroeck (2008) (De Meester de Betzenbroeck, 2008).

Building Energy Modeling and Calibration

The building energy model was constructed in DesignBuilder (v6.1.5.002). The simulation took place in the dynamic energy simulation program EnergyPlus v9.0. The multizone model included the ground and first floor as heating space (see Figure 3). The garage and the atrium were modeled as nonheated spaces (see Figures 3 and 4). We synthesized several scenarios to represent future weather conditions in the sleeping room and living room, each containing a time series of 8760-time steps. The schedules for occupancy, lighting, and equipment in the sleeping and living rooms are modeled based on the audit of De Meester de Betzenbroeck [19]. The number of household occupants is four people. Mechanical ventilation has a minimum flow rate of 110 m^3/h. The air changes correspond to approximately 30 $m^3/h/person$. This flow rate depends on the function of the room and its surface. Windows are open at night if the indoor temperature is higher than 22 °C, allowing for ventilative cooling. By ventilative cooling we mean mainly diurnal and nocturnal ventilation. The operative temperature is used to control the ideal air loads system. Active heating is assumed all year long. The heating setpoint is set at 21 °C during occupancy and 16 °C for other moments. The summer comfort conditions are explained in the following section. The calibration was based on 3-years energy use monitoring dataset. The calibration protocol respected the recommendations of ASHRAE Standard 140-2017 (Neymark *et al.*, 2017). The calibration details are described in detail in a previous publication by the last author (Fani, 2020).

Figure 3: Multizone building energy model in DesignBuilder

Compared overheating calculation methods

Thermal comfort temperature boundaries reflect within which temperature range the indoor environment is comfortable for occupants. In this study, three overheating calculation methods were tested. Firstly, we used the Passive House Standard static comfort model to set the overheating reference conditions (*PHPP (2010) "Passive house certificate"*, 2020). The methodology assumes a 25ºC threshold to calculate overheating hours. The internal temperature was assessed applying the comfort limits of the Fanger model or PMV model, according to CEN 15251.

Secondly, we tested the building against the Belgian EPBD calculation method for dwellings, which is based on a quasi-steady-state calculation method of the overheating risk. The overheating indicator currently used in Belgium is based on German research performed in the 1990's (Czech Society of Environmental Engineering, REHVA World Congress and International Conference on Indoor Air Quality, 2013). The overheating calculation uses input and calculation parameters part of the CEN 13790 and CEN 15251 calculation method for heating (*Energy performance of buildings. Calculation of energy use for space heating and cooling:*, 2007). The method defines the overheating indicator as the sum of the monthly normalized excess heat gains (1):

$$I_{\text{overh}} = \sum_{m=1}^{12} \frac{\left(1-\eta_{\text{C,gn}}\right) \cdot Q_{\text{C,gn}}}{H_{\text{tr,adj}}+H_{\text{ve,adj,ext}}+H_{\text{ve,adj,hyg}}} \cdot \frac{1000}{3.6} \qquad (1)$$

Where I_{overh} overheating indicator (Kh)

$\eta_{\text{C,gn}}$ utilization factor for heat gains in case of cooling,
possibly taking also passive cooling techniques into account (-)

$Q_{\text{C,gn}}$ monthly internal and solar heat gains (MJ)

$H_{\text{tr,adj}}$ heat transfer coefficient for transmission (W/K)

$H_{\text{ve,adj,ext}}$ heat transfer coefficient for ventilation with outside air (W/K)

$H_{\text{ve,adj,hyg}}$ heat transfer coefficient for ventilation with preconditioned air (W/K)

An overheating indicator of 11000 Kh/year would correspond to temperatures higher than 23°C. The use of the limit value allows adopting fictitious cooling in dwellings without mechanical cooling. A fictitious cooling demand calculates if mechanical cooling was installed, and a probability $p_{\text{cool,seci}}$ (-) which depends on the overheating risk (2). This intervention penalizes the contingent installment of mechanical cooling after completing the dwelling as shown in Figure 4 (Czech Society of Environmental Engineering, REHVA World Congress and International Conference on Indoor Air Quality, 2013).

$$p_{\text{cool,seci}} = \max\left\{0, \min\left(\frac{I_{\text{overh,seci}}-I_{\text{overh,tresh}}}{I_{\text{overh,max}}-I_{\text{overh,tresh}}}, 1\right)\right\} \qquad (2)$$

Where $p_{\text{cool,seci}}$ probability that mechanical cooling is installed in energy sector I (-)

$I_{\text{overh,seci}}$ overheating indicator of energy sector I (Kh)

$I_{\text{overh,tresh}}$ minimum overheating indicator above which mechanical cooling possibly is installed in energy sector I (Kh), set equal to 8000 Kh

$I_{\text{overh,max}}$ maximum overheating indicator in energy sector I (Kh), set equal to 17500 Kh

The third overheating methodology is developed by Hamdy et al. (2017) (Hamdy *et al.*, 2017a) and applies a climate change sensitive overheating assessment method. Three metrics are used, namely Indoor Overheating Degree (*IOD*), Ambient Warmness Degree (*AWD*), and Building Climate Vulnerability Factor (*BCVF*). The overheating risk is assessed under four climate scenarios representing historical and future scenarios.

IOD is a multi-zonal indicator that quantifies the indoor overheating risk taking into account both severity and frequency of high indoor temperatures,

$$IOD=\frac{\sum_{z=1}^{Z}\sum_{i=1}^{N_{occ(z)}}[(T_{op,i,z}-T_{op,i,z,comfort})^{+}\times t_{i,z}]}{\sum_{z=1}^{Z}\sum_{i=1}^{N_{occ(z)}}t_{i,z}} \quad (3)$$

Where i is occupied hour counter, z is building zone counter, Z is the number of total building zones, N_{occ} is number of all occupied hours, $T_{op,i,z}$ is the indoor operative temperature, and $T_{op,i,z,comfort}$ is the static or adaptive thermal comfort limit of time step i and zone z (Carlucci *et al.*, 2018). *IOD* enables the implementation of multiple thermal comfort models in different building zones. In this paper, a fixed temperature limit of 26 ℃ based on static comfort model CIBSE Guide A (Butcher, Craig and Chartered Institution of Building Services Engineers, 2015) is assumed for bedrooms. This selection is made since adaptation actions performed by occupants are limited during the sleeping period. For all other living areas, category II of adaptive thermal comfort model EN 16798-1 (CEN, 2019) is considered as one of the most commonly used comfort standards worldwide (Attia *et al.*, 2019).

AWD indicates the severity and frequency of high outdoor temperatures according to a predefined base temperature,

$$AWD_{14\,°C}=\frac{\sum_{i=1}^{N}[(T_{a,i}-T_{b})^{+}\times t_{i}]}{\sum_{i=1}^{N}t_{i}} \quad (4)$$

Where N is the total number of building occupied hours, $T_{a,i}$ is the outdoor air temperature in time step i, and T_b is outdoor base temperature. T_b is determined based on building characteristics and is equal to an outdoor air temperature threshold, which above necessitates the operation of any means of passive or active cooling systems. Due to high insulation levels and overheating risk in Passive Houses, T_b of 14 ℃ is considered.

By assuming a linear correlation between *IOD* and *AWD*, *BCVF* is the slope of the regression line that predicts the vulnerability of the building to overheating risk concerning climate change,

$$BCVF=\frac{IOD}{AWD_{18\,°C}} \quad (5)$$

$BCVF < 1$ shows that the building can suppress the outdoor thermal stress, and $BCVF > 1$ means that the building becomes overheated by increasing outdoor air temperature. The three above metrics help estimate the ability of a building to maintain an acceptable indoor thermal environment in a warming climate.

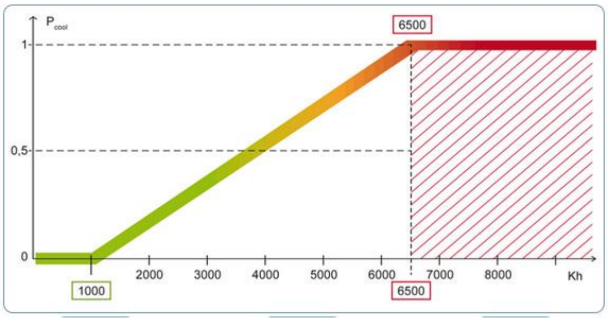

Figure 4: Belgian EPBD Overheating indicator thresholds

The applied method requires two historical and two future weather datasets. For this aim, we used (i) average scenario representing historical climate using the weather data for the moderate year of 1965, (ii) extreme scenario that is the extreme data recorded in 2003, (iii) future normal scenario that is the normal climate projection of the year 1976 to 2100 with an increase of 2 ℃ in average temperature due to global warming effect, (iv) future extreme scenario that is the extreme climate projection of the year 1976 to 2100 with an increase of 4 ℃ in average temperature due to global warming effect and 1.4 ℃ due to the urban heat island effect (Hamdy *et al.*, 2017b). The annual distribution of daily mean outdoor temperature under four climate scenarios is shown in Figure 5.

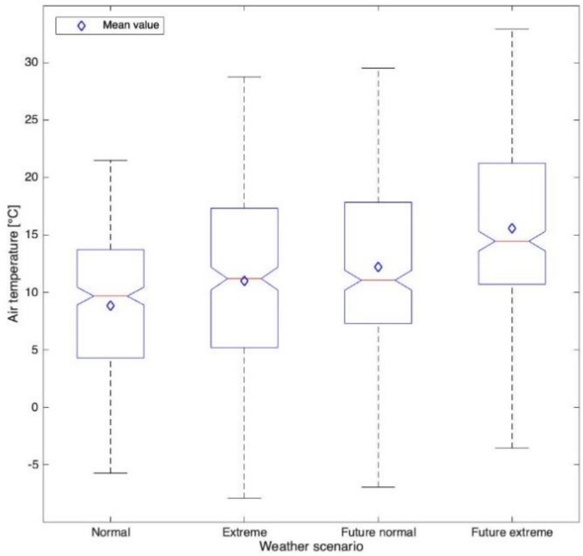

Figure 5: Annual distribution of daily mean outdoor air temperature under four climate scenarios.

Results

Figure 6 presents the overheating hours calculations results based on the three overheating calculation approaches. The Passive House Platform Package estimates an overheating risk of 400 hours annually in the living and sleeping room. According to the Belgian EPBD method, the risk is slightly increased to 430 hours annually. However, Hamdy's calculation method shows a remarkable difference reaching 1348 hours of overheating in the sleeping room.

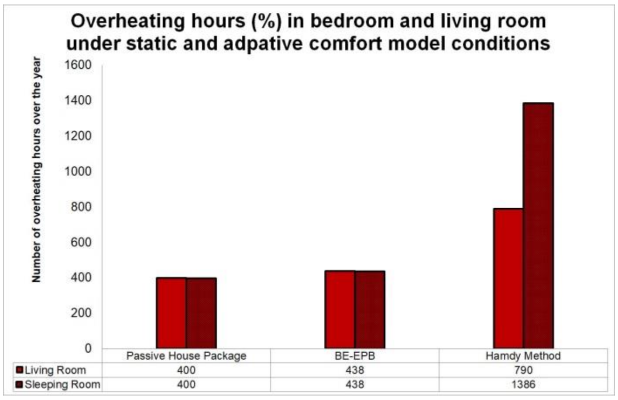

Figure 6: Overheating hours using the three calculation methods

Figure 7 illustrates the overheating hours, which represent almost 16% of the years. The overheating occurs mainly during July and August and is calculated based on a 26ºC thermal comfort upper limit threshold. Figure 8 shows the ambient warmth degree that reaches 3.5ºC. Since the building is a timber construction with low to medium thermal mass, the cooling degree hours were calculated for a base temperature of 18ºC.

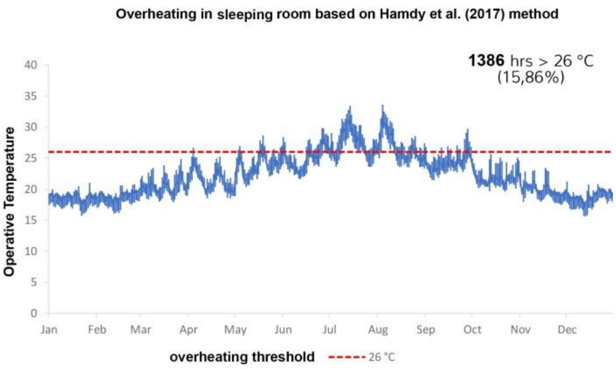

Figure 7: Overheating hours in the sleeping room calculated based on Hamdy et al. method.

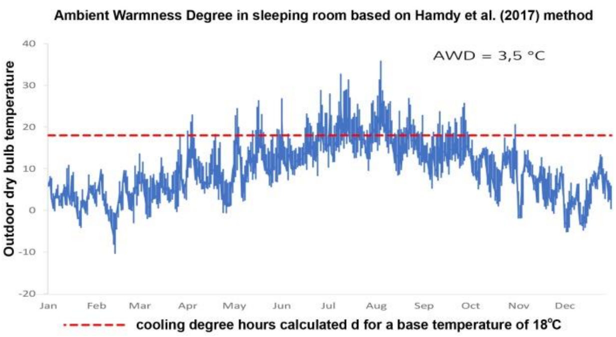

Figure 8: The ambient warmness degree annual temperature profile.

Finally, Figure 9 illustrates the Indoor Overheating Degree temperatures obtained for temperatures exceeding the 26ºC threshold. Thus, overheating risk's intensity and frequency have a value of 1.95ºC, quantified by the temperature difference between the free-running indoor operative temperature and a chosen thermal comfort temperature limit. In contrast, the frequency is calculated by integrating the intensity of overheating during the occupied period to present the overall overheating in the building. In other words, the investigated case study suffers from an average overheating temperature increase of 2 ºC in the long term under the influence of climate change. Consequently, the dwelling's escalation factor or sensitivity to overheating is 0.56, which means that the dwelling can suppress outdoor thermal stress. If the value were higher than one, the building would be characterized as weak regarding its ability to curb the climate change overheating effect.

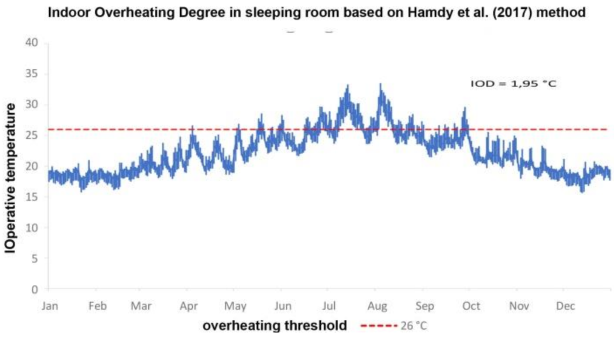

Figure 9: Indoor operative temperature profile with an average overheating risk increase of almost 2ºC.

Discussion

Overheating in buildings is a problem that is gaining attention worldwide under the accelerating effect of climate change (Tian *et al.*, 2020). In this study, we compared three overheating calculation methods using a nearly zero energy dwelling as a case study. The study findings and implications are discussed in the following sections.

Findings and recommendations

The Belgian Passive House Standard calculation package assumed an overheating risk of 400 hours annually. The calculation method is based on a static model representing all building zones in one zone. The Belgian EPB tool assumed an overheating risk of 430 hours. The method is based on a quasi-dynamic model representing the climate through monthly average temperatures. The building is modelled as one single zone and relies on a static thermal comfort model. Remarkably, the third calculation method estimates a remarkable overheating risk is reaching 1348 hours. The methodology takes into account long-term climate change sensitive indicators and allows for multizonal modeling distinguishing sleeping and living spaces.

We recommend the use of Hamdy et al. overheating the calculation approach. A post-occupancy evaluation and long term thermal comfort monitoring is essential to assess occupant's real thermal sensation, perception, and adaptation potential regarding thermal comfort (Attia, 2020b). Belgium must update its EPB calculation methods and represent the climate more accurately. The new EPB calculation approach should allow for multizonal modeling while distinguishing the sleeping room. Adaptive thermal comfort models can be used in living spaces, while sleeping rooms must have a static comfort model.

Strengths and limitations

This is the first study that focuses on comparing overheating evaluation methods involving future climate change scenarios based on the 2014 Intergovernmental Panel on Climate Change (IPCC) reports and projections is a novel approach.

The study aimed at comparing three different overheating assessment methods. But how the comparison is applied cannot be accepted from scientific point of veiw. The three methods have different purposes which seems to be not comparable. The first indicator (the Passive House overheating indicator) is proposed to assess only the number of overheating hours. The second indicator (EPBD overheating indicator) is proposed to check the probability that mechanical cooling is installed. The third indicator (Hamdy et al., 2017a) is proposed to quantify the overheating vulnerability to the climate change.

The study's main limitation remains in the difficulty to compare the three calculation methods and the assumptions made to estimate the Ambient Warmth Degree and the used weather files' accuracy. The *AWD* is mainly assumed based on the air temperature threshold at which cooling will be needed. Thus, *AWD*'s estimation is subjective to the building state and does not consider solar radiation or building geometry. On the other hand, several global and regional climate change models neglect increasing solar radiation phenomena and do not accurately represent the sky conditions. Using global or regional climate change scenarios and models can lead to a remarkable difference compared to real observation and local weather files in cities. Moreover, the study focused on only one indicator, which is namely overheating hours. Including additional indicators such as the cooling energy needs and the associated carbon emission could have extended the study findings. Oour study used weather files from the Dutch Beek Airport, which is not sensitive to the urban heat island effect because it is located in a suburban context. However, the overheating calculation methods are not sensitive enough to solar radiation and local conditions such as the urban heat island effects and air pollution.

Implication on practice and future research

The study proves that the Passive House and EPBD calculation methods should go through major revisions (Attia, 2020a). The new version of the EPB must build on these study findings and address overheating risks more profoundly (Brücker, 2005). Adding, other indicators to assess the impact of overheating, such as the cooling energy needs or the associated carbon emissions can be very beneficial. Moreover, humidity must be addressed too.

Finally, designers should pay more attention to buildings that fall in the EN 15251 or EN 16798 Category I, including nursing homes and residents with assisted living help for seniors. The design or renovation of senior dwellings with assisted-living or long-term care homes requires assessing overheating rigorously. Future research should further explore the utility of Hamdy's method and better represent the urban heat islands effect, outdoor solar radiation, and sky conditions and adapt them to the local climate of Belgian cities. At the same time, the learned lessons from this study can be applied universally. For example, the European Union should develop a standardized method to calculate overheating risks under climate change in Europe (Attia and Rahif, 2021). There is a need for accurate overheating indicators that take into account the effects of climate change.

Conclusion

A multizonal model was created and calibrated based on 5-year monitoring data for a timber single-family house in Belgium. The house represents the latest construction technologies for timber construction and is labeled as a nearly zero energy building. The study used a comparative approach to assess overheating risk. Two commonly known calculation methods, namely the Passive House Standard Package and the Belgian EPBD failed to estimate overheating risk accurately. The Belgian Passive House Standard calculation package assumed an overheating risk of 400 hours annually. The Belgian EPB tool assumed an overheating risk of 430 hours. The third calculation method estimates a remarkable overheating risk is reaching 1348 hours, which is more than three times more than what the Passive House and EPBD methods estimate. The long term monitoring and iterative calibration of the dynamic multizonal model confirm the results and indicate a serious threat for all residential buildings in Belgium under the current climate change conditions and based on the IPCC 2014 future climate change scenarios. The study presents a set of recommendations to policymakers and building professionals to update the EPBD calculation method and standardise the way overheating is estimated and calculated in Europe. Also the study, draw more attention to overheating risks in the residential sector and the importance to develop reliable indicators that can estimate the savings in terms of cooling energy need

Acknowledgment

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