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Comparative Analysis of Overheating Risk for Typical Dwellings and Passivhaus in the UK

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Abstract: There is growing concern that airtight and well-insulated buildings designed to limit heat loss in temperate and cold climates could unintentionally elevate the risk of overheating in summers. Existing literature primarily uses dynamic simulation to investigate this problem due to the difficulty of obtaining large-scale in-performance data. To address this gap, we undertake a meta-analysis of large-scale indoor air temperature data for 195 UK dwellings, as a study of performance in a temperate climate. Of these, 113 are baseline (i.e., typical existing dwellings) and the rest designed to the high-performance Passivhaus standard. Using both Passivhaus and the well-known CIBSE TM59 overheating standards, this study found that there were few overheated cases for any building type. However, the average summer nighttime temperature of Passivhaus bedrooms was 1.6 °C higher than baseline, with 20 out of 31 measured bedrooms exceeding the overheating criterion, and the average overheating hours constituting approximately 19% of the total summertime observation period. These findings suggest that bedrooms in highly insulated dwellings may pose an overheating risk although whole-dwelling overheating risk is low.

Keywords: overheating risk; thermal comfort; Passivhaus; climate change; global warming

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1. Introduction

1.1. Background

The UN Framework Convention on Climate Change (UNFCCC) previously announced that efforts to reduce the rise in global mean surface temperature (GMST) and limit the global temperature increase to 1.5 °C based on temperatures before the industrial revolution must be made to mitigate the recent intensification of global warming [1]. In particular, the International Panel on Climate Change (IPCC) has predicted that the GMST will increase by approximately 5 °C until 2100 [2], and the degree and frequency of abnormal climates are expected to increase gradually [3]. As the interiors of buildings are directly affected by outdoor environmental conditions, an increase in outdoor temperature may also affect the thermal comfort of rooms. In addition, with the increasing penetration of home appliances [4,5], the internal heat gain that may occur in the rooms of a building is increasing. Therefore, due to such factors as an increase in outdoor temperature and internal heat gain, occupants are living with a risk of temperature increase that will decrease comfort and gradually increase exposure to overheating risk. Overheating refers to a phenomenon in which the excessive temperature rise caused by internal or external factors affects the thermal comfort, productivity, and health condition of building occupants [6]. In particular, overheating in buildings is closely related to indoor mortality and morbidity as it involves health risks [7,8]. Since overheating negatively affects the health of occupants through stress and sleep disturbances, more than 800 deaths occur in the UK every summer due to overheating, while more than 2000 deaths have occurred in years with abnormally high outdoor temperatures, such as 2003 [9,10].

As people usually spend more than 90% of their lifetime indoors, comfortable indoor conditions are very important [11,12]. In the UK, because the penetration rate of domestic air-conditioning is still as low as 3% [13], if natural ventilation is not achieved successfully indoors, it is challenging to cope with the resultant overheating. In addition, because it takes a long time to change indoor temperatures without using mechanical equipment, the occurrence of overheating in a residential building may cause the high indoor temperature to be maintained for an extended period of time, thereby adversely affecting the health of the occupants. As the influence of overheating varies depending on the insulation and airtightness of a building, it is important to achieve an appropriate building performance in these aspects [14,15].

1.2. Literature Review

In general, residential buildings are classified into typical residential buildings with normal performances that satisfy legal regulations and buildings with higher performances to achieve energy efficiency such as Passivhaus. Various studies have been conducted over the last few years to evaluate the influence of overheating on such building types. In order to assess the overheating risk of residential buildings, the time-integrated overheating evaluation methods (such as EN 16798, ISO 7730, IS1772, ASHRAE 55, etc.) are utilized [16,17]. In this subsection, previous studies analyzing typical dwellings and high-performance dwellings were reviewed, respectively.

To evaluate the overheating that occurs in typical residential buildings, there are studies that involved conducting experiments in real conditions. Li et al. performed simulations to evaluate overheating occurring in a loft and reported that overheating occurred frequently in the bedroom that exhibited a normal performance during summertime [18]. To assess overheating risk for a long-term period, other research collected the measured data in a typical building over 12 months. They analyzed the overheating frequency using two overheating thresholds of 24 and 25 °C to evaluate overheating and found that approximately 52% of the measured indoor temperature exceeded 25 °C in 6 zones [19]. In addition, in the case of typical dwellings, there is a lot of research presenting many case studies with empirical measured data to statistically analyze the exact risk of overheating. A study evaluating overheating using large-scale survey data for typical residential buildings in the UK found that 19% of the bedrooms and 15% of the living rooms were overheated. Interestingly, it was found that households with family members aged 75 or older exhibited a significantly low overheating occurrence rate according to self-reports. However, in reality, the prevalence of monitored overheating of the elderly was higher than younger household members. They considered that these results appeared because the elderly did not perceive the heat well [20]. Morey et al. investigated overheating for social housing dwellings in which vulnerable people resided. They used the indoor temperature data collected from approximately 122 buildings in 2015. The mean bedroom and living room temperatures were 21.2 and 21.7 °C, respectively. Considering TM52 specifications, only 1% of all bedrooms and 2% of all living rooms were overheated. Considering TM59 specifications, 5% of all bedrooms and 1% of all living rooms were overheated [21]. In this way, if a vulnerable class such as the elderly exists in a building, there is a possibility that there is a risk of unrecognized overheating. Unlike the method using the experiment with empirical data, there are studies to evaluate the situation under extreme climate change. An analysis of overheating risk in three modern houses in 14 regions of the UK was conducted and focused on nighttime bedroom hours [22]. This study showed that the overheating of buildings occurred in 19 out of 42 cases for current climate. They simulated overheating cases for future climates (2030s, 2050s, 2080s) and argued it gets worse over time. In order to analyze indoor thermal comfort, Elsharkawy et al. built an EnergyPlus model and insisted that over-insulated and airtight buildings have high potential for overheating when exposed to direct solar radiation during warmer seasons [23]. There was research comparing and analyzing many simulation cases. Overall, 42,000 simulation models for typical dwellings were developed and analyzed to assess the possible overheating risk under current conditions and in a climate change scenario [24]. The results showed that 38% of the cases already involved overheating. Particularly, the median of both the percentage of hours of overheating during all occupied hours and that of the night hours increases by more than 40% due to global warming. In the days of extreme heatwave, there was also a study that analyzed the effects of climate change on the interior of buildings through experiments. The building performance in England was investigated to assess overheating risk issues during a long-term heatwave period [25]. The case study house was observed to exceed the acceptable limits of thermal comfort. Particularly, the bedroom exceeded the upper limit for overheating up to 11 h daily. They insisted that the main reasons for overheating were well-insulated and airtight fabrics without sufficient ventilation.

In the case of high-performance buildings constructed with higher energy efficiencies than typical residential buildings, in general, many studies have been conducted to evaluate the effect on the indoor environment in dwellings according to various performances of the building. The future overheating risk of four dwelling types of Passivhaus was evaluated through simulations [26]. The standard threshold for evaluation of overheating was 25 °C, and it was found that factors affecting solar transmission (i.e., shading devices, the window-to-wall ratio, etc.) had a significant influence on overheating of high-performance buildings, and that considerable overheating occurred in the bedroom. Gupta et al. conducted a simulation study using two cases to evaluate the energy consumption and overheating risk in net zero energy dwellings [27]. They reported that the overheating occurrence rate was high in the living room. In a similar study, Tian et al. evaluated the future overheating risk of a residential building retrofitted with high-level energy standards [28]. To achieve this, they created scenarios with different performances and compared overheating under the future weather conditions using EnergyPlus. The analysis results showed that too great of an airtightness performance increases the overheating risk, while the use of high-performance insulation slightly reduces the risk. Especially, they showed that the overheating risk becomes worse in the future. There was also a study to evaluate the performance of buildings using actual measured data. The empirical data were measured in Passivhaus in the UK to evaluate overheating risk. This study analyzed the data monitored in a target building in which vulnerable classes lived for 21 months using statistical methods [29]. They reported that Passivhaus is highly insulated, airtight, and that a fabric-first approach is used to secure passive solar heat gain. Based on these findings, they indicated the possibility of overheating in such dwellings. They also found that considerable overheating occurred during nighttime. Most previous studies related to overheating in high-performance buildings were conducted through simulation to compare the performance of buildings, and they have largely focused on analyzing the cause of overheating. There were also studies that analyzed the effects of climate change on high-performance housing. Rahif et al. developed a study to evaluate the climate change overheating resistivity of cooling strategies in six different climate conditions [30]. They analyzed indoor operative temperature and Exceedance Hours (EH). Even though Toronto is classified as having a cool-humid climate, frequent hot weather conditions are expected by the 2090s. Especially, the results showed that the higher insulation levels in Toronto based on ASHRAE 90.1 exacerbate the intensity and frequency of high indoor temperatures. In another study, Attia et al. assessed the climate change impact on thermal comfort, including the overheating risk in a Belgian reference case without active cooling systems [31]. Building performance analysis was carried out using EnergyPlus. This study argued that zero-energy buildings under the Passive House Standard comfort model will be vulnerable to overheating and overheating hours can reach 1195 h (13.6%) by the 2050s.

Although a lot of researchers recognize recent excessive heatwaves caused by climate changes and have analyzed indoor environments for overheating, most studies related to evaluation of the overheating risk focused on only a single building type such as typical or high-performance dwellings. Therefore, there are few studies to confirm the overheating risk between typical and high-performance dwellings.

1.3. Study Objectives

New standards that have emerged to mitigate climate change have focused on decreasing building energy consumption to reduce carbon emissions. As a result, high-performance buildings have been constructed; however, the improvement in the performances of these buildings may affect the thermal comfort of occupants. In particular, with the intensification of global warming, interest in the likelihood of indoor overheating is increasing, and numerous studies have recently been conducted to analyze the status of overheating. Considering typical residential buildings, the overheating risk has been typically evaluated by analyzing collected data and simulation results. Conversely, studies on high-performance residential buildings, such as Passivhaus, have been conducted based on simulations. In the case of the overheating risk evaluated via simulation, the results have differed depending on each study. This appears to have occurred because the influence of overheating on various rooms differs depending on the parameters and modeling conditions used in the building simulations. As a building is a combination of various elements, it is difficult to perfectly construct an actual building through simulation. Overheating cases that have used simulations under individual conditions can be found, but it is difficult to determine general results considering the cause of overheating because the evaluation results differ depending on the conditions that were used [32]. For these reasons, it is important to utilize data measured in actual buildings to accurately identify the overheating risk in actual buildings. Especially, for Passivhaus cases, because it is difficult to obtain empirical measured data samples due to the small number (1300) of Passivhaus buildings found in the UK [33], most studies to evaluate overheating in high-performance buildings in the UK have been conducted through simulation. In addition, most previous studies have focused on analysis for a single building type, such as typical residential buildings or high-performance buildings, rather than on a comprehensive analysis.

While there has been significant recent research activity on overheating risk in highly insulated dwellings, there is not yet sufficient evidence from real buildings at scale. Hence, our research question is “Do highly insulated buildings such as those built to the Passivhaus standard overheat at the same rate as less insulated or poorly insulated typical buildings, under real conditions?” Therefore, it is necessary to know how much the type of building affects the indoor environment in a situation where Passivhaus is starting to be applied in places with climates such as that in the UK (temperate). In addition, it is important to inform the larger international debate around overheating in temperate climates.

Thus, this study compared indoor environments of typical dwellings and Passivhaus using actual measured data to confirm overheating risk in the UK climate. In order to conduct the analysis, this study utilizes indoor environment data that were collected for typical residential buildings and high-performance Passivhaus in the UK, and the overheating risks between buildings with different performances is compared. Indoor temperature data collected from 195 residential buildings (113 typical residential buildings and 82 Passivhaus) between 2011 and 2018 are used. Based on this large number of cases, this study aims to identify the building and room types that are vulnerable to thermal comfort through the analysis of the overheating risk. Thus, this study is expected to clarify the situation of overheating in residential buildings and serve as a guide to understanding the status of overheating in countries with a climate similar to the UK where Passivhaus is starting to be introduced.

2. Materials and Methods

In this section, the analysis method used in this study is described. The overheating risk according to the room type and building type was evaluated using indoor temperature data from many cases in the UK. This study conducted a meta-analysis of existing data. For the analysis of overheating in buildings, the overheating risk was compared between typical residential buildings and Passivhaus in three steps, as shown in Figure 1.

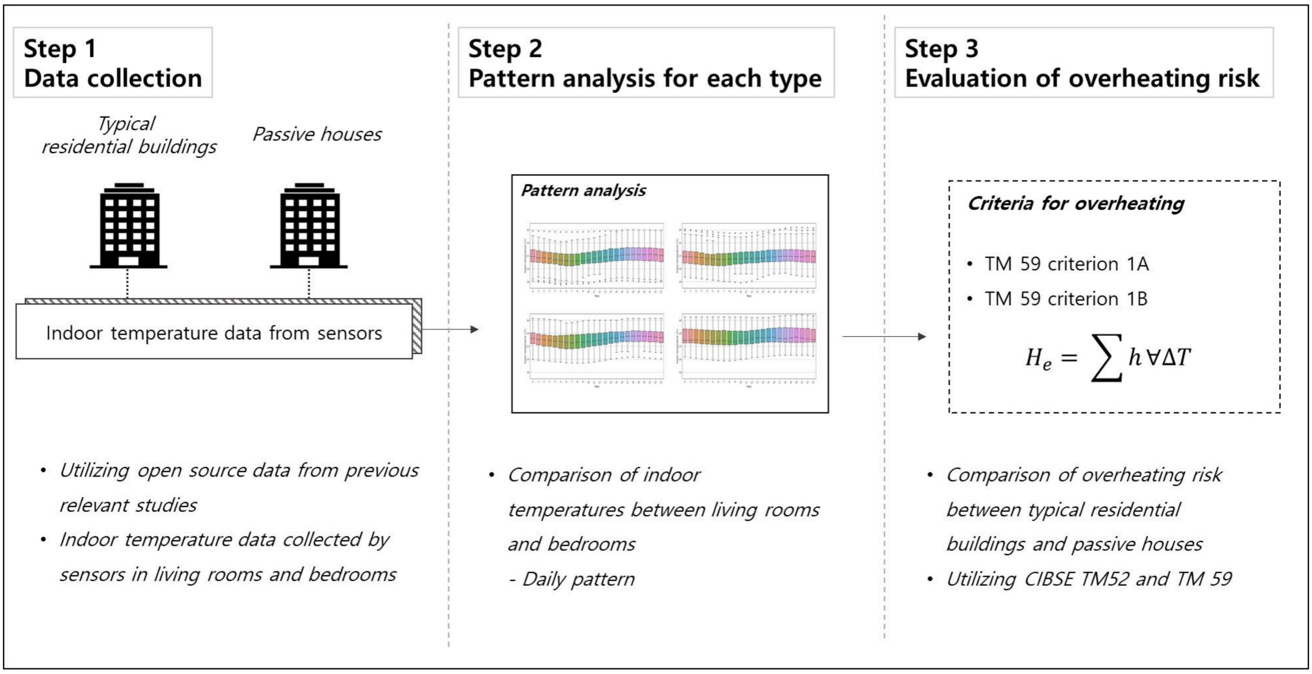

Figure 1. Flowchart of the research method.

In step 1, data were collected and arranged for the analysis of the overheating risk in typical residential buildings and Passivhaus. Open-source data from previous relevant studies were utilized, and indoor temperature data from 113 typical residential buildings and 82 Passivhaus in the UK were used. The data collected from the buildings included the indoor temperature data for each bedroom and living room.

In step 2, the indoor temperature pattern by room type in each case was analyzed. The focus was on the analysis of the daily patterns of indoor temperatures collected from bedrooms and living rooms.

In step 3, the overheating risks of typical residential buildings and Passivhaus were calculated and evaluated through the criteria provided by the Chartered Institution of Building Services Engineers (CIBSE). After analyzing the overheating risk, the degree of overheating was evaluated for each residential building type via comparison.

2.1. Data Collection

In this subsection, the basic characteristics of the data used in this study are described. To conduct meta-analysis for evaluation of the overheating risks of the typical and high-performance buildings, open-source data from previous studies were utilized [10,34,35], and the basic characteristics of these data are shown in Table 1. (Links for raw data are included in the references [10,34,35].) Indoor temperature data were collected from 195 residential buildings (113 typical residential buildings and 82 Passivhaus) over several years. These data included data collected from several room types (bedroom, living room, kitchen, bathroom, etc.), but with a focus on only two types (bedroom and living room) for overheating evaluation. This study set 113 typical residential buildings as baseline and compared them with the status of the overheating risks of Passivhaus. Most sensors for living rooms and bedrooms were located away from windows and local heat sources and installed at a height of 1–1.5 m above the ground.

Table 1. Summary of the used data from the previous studies.

No.	Types of Buildings	Year	Types of Data	Sensor Type	Accuracy	Resolution of Data	Data Source
1	Typical dwellings including social housing	2014, 2015	Indoor temperature	Wireless sensor	±0.5%	5 min	[34]
2	Typical dwellings	2017, 2018		iButton	±0.5%	90 min	[35]
3	Passivhaus	2011–2017		Wireless sensor	±0.5%	5 min 10 min 30 min Hourly	[10]

For the typical residential buildings, data from 60 bedrooms and 89 living rooms were collected. For the Passivhaus, data from 31 bedrooms and 82 living rooms were obtained. The data collected from buildings in the southern region of the UK were utilized to represent the typical residential buildings, whereas the data collected from buildings located throughout the UK were used to represent the Passivhaus. Data collected during summertime from June to September were used. Table 2 shows the percentage of dwelling types for each data source. Since the open-source data exhibited different data collection intervals, as they were collected for different purposes depending on each study, all of the data used in this study were converted into hourly average values. Additionally, data collected over a period of 90 min were converted into hourly data through linear interpolation.

Table 2. Summary of the configuration of the buildings.

No.	Types of Buildings	Percentage of Dwelling Types (%)					Data Source
		Flat	Detached	Semi-Detached	Terrace	House	
1	Typical dwellings including social housing	40	5	31	24	-	[34]
2	Typical dwellings	16	23	33	28	-	[35]
3	Passivhaus	24	-	-	-	76	[10]

2.2. Evaluation of Overheating Risk

The CIBSE provides criteria to prevent overheating risks in buildings and ensure indoor thermal comfort [36]. The CIBSE recommends using an adaptive comfort model rather than fixed temperature described in CIBSE TM 52 to evaluate overeating risk. In particular, CIBSE TM 52 is based on the adaptive comfort model in which the internal comfort temperature of a building is changed by the outdoor environment. The CIBSE TM 59 criterion is based on CIBSE TM 52 and CIBSE Guide A, which provides a bedroom temperature criterion for residential buildings [37]. CIBSE TM 59, which is a design methodology for the assessment of overheating risk in homes, presents criteria and calculation methods for evaluating the overheating of naturally and mechanically ventilated residential buildings during summertime [9]. The criteria for calculating overheating risk are divided into two categories (mechanical and natural ventilation): (i) The criterion for naturally ventilated buildings is based on an adaptive comfort model; (ii) The criterion for mechanically ventilated buildings is based on a fixed threshold (26 °C) and applied where windows can hardly be used for cooling. Therefore, this study used a criterion with an adaptive comfort model because the target buildings are general domestic dwellings without constraints for where occupants can control their internal environment. In addition, Category II was used for a normal level of expectation. The related formula is as follows:

$$\Delta T = T_{op} - T_{max}. \quad (1)$$

To calculate the value of ΔT required to evaluate overheating risk, the hourly indoor operative temperature (°C), T_{op}, and the upper limit temperature for Category II from EN16798-1 (°C), T_{max}, are used [38]. The upper limit temperature represents the absolute maximum daily temperature for a room. In general, the simplified operative temperature (T_{op}) is derived using the indoor air temperature (T_a), and the mean radiant temperature (MRT), whereas data in this study only include the indoor air temperature (T_a). At the low air velocities that prevail in homes, the operative temperature is the average of the air and mean radiant temperature [20]. In this study, it was not easy to install complex experimental devices, such as black bulb thermometers, for an extended period of time, because the data were collected from real occupied households. In the case of experiments or simulations, operative temperature can be easily obtained, but it is difficult to collect it in actual occupied dwellings. If buildings have high radiant temperature and air movement, errors could be caused. However, previous research which collected the data for this study assessed the indoor environment of 30 houses through a transverse survey, using the ISO 7730-compliant Swema equipment, and showed a regression of T_a and MRT showed a strong correlation (R^2 = 0.96). In addition, most measurements of air velocity in houses indicated less than 0.15 m/s [35]. Other previous studies also showed the difference between T_a and MRT tends to be small even in commercial building for summer period [39,40].

There are many studies utilizing indoor air temperature as a substitute of operative temperature when using measured data in real conditions [10,20,21,29,34,35,41–43]. Especially, the indoor air velocity and radiant temperature is likely lower rather than other types of buildings because this study focused on only bedrooms and living rooms. Therefore, in this study, T_a was used as a substitute for T_{op} under the assumption that the difference between T_a and MRT is small. Overheating in the buildings should be read under the premise that T_a is an approximation of T_{op} in this study. In fact, although this study did not undertake a complete thermal comfort assessment for these reasons, interest of this research is to compare the relative performance of buildings over a comparable time frame and take steps to treat the data to ensure comparability.

T_{max} is calculated using the exponentially weighted running mean of the daily mean outdoor temperature (°C), T_{rm}, via the following formula:

$$T_{max} = 0.33T_{rm} + 21.8, \tag{2}$$

$$T_{rm} = (T_{od-1} + 0.8T_{od-2} + 0.6T_{od-3} + 0.5T_{od-4} + 0.4T_{od-5} + 0.3T_{od-6} + 0.2T_{od-7})/3.8, \tag{3}$$

where $T_{od\text{-}nth\ days}$ (°C) is the daily mean outdoor temperature of the n-th day before. These formulas are used to evaluate the overheating risk, and the target months for evaluation are May to September, which aligns with summertime.

In CIBSE TM 59, the overheating risk is evaluated by calculating the total amount of time that exhibited overheating in a building based on the formula derived from CIBSE TM 52 as follows:

$$H_e = \sum h \forall \Delta T \ \geq 1\ °C, \tag{4}$$

Here, H_e is the hours of exceedance, which indicates the total amount of time that exhibited overheating during the entire observation period. This value must not exceed 3% of the entire target period. Therefore, when the difference between the indoor temperature of a residential building and the daily maximum temperature is 1 °C or larger, the corresponding hours are regarded as overheating hours. In particular, CIBSE TM 59 separately evaluates the overheating risk that occurs during the activity time and that which occurs during sleeping hours. The respective criteria for these cases are outlined in Table 3. In the case of a bedroom in a residential building, a stricter criterion applies compared to that of the living room based on CIBSE Guide A. During sleeping hours, if the indoor temperature exceeds 26 °C, the corresponding hours are regarded as overheating hours. The total overheating hours must not exceed 1% per year.

Table 3. CIBSE TM 59 criteria for evaluation overheating risk.

Criterion 1A	Criterion 1B
- For living rooms and bedrooms - Occupied hours are set from 9 a.m. to 10 p.m. for living rooms and kitchens - Occupied hours are set 24 h per day for bedrooms	- For bedrooms only - During sleeping hours from 10 p.m. to 7 a.m., 26 °C must not be exceeded

Passivhaus, which is a building standard supervised by the Passivhaus institute (PHI), aims to create low-energy buildings while satisfying indoor comfort [44]. They are built to implement low-energy buildings with high performance through strict standards. The requirements for such houses are as follows: super-insulated envelopes, airtight construction, high-performance glazing, being thermal-bridge-free, and heat recovery ventilation (HRV). In particular, Passivhaus has their own standards for evaluating overheating risk to ensure indoor thermal comfort in the summer, and this process is evaluated through the Passivhaus Planning Package (PHPP). When the indoor temperature exceeds 25 °C, the corresponding hours are regarded as overheating hours. The overheating risk is evaluated to be excellent if this time ranges from 0% to 2%, good if it ranges from 2% to 5%, acceptable if it ranges from 5% to 10%, poor if it ranges from 10% to 15%, and catastrophic if it exceeds 15% [45]. As the overheating risk for the indoor temperature of Passivhaus is evaluated for the entire building rather than individual rooms [46], it is highly likely that the indoor environmental characteristics of the individual rooms of the building will be neglected. In the case of residential buildings, the indoor temperature characteristics of rooms with relatively longer occupied hours, such as the bedroom and living room, need to be specifically evaluated. However, this is difficult to achieve based on existing Passivhaus standards. Therefore, entire buildings that are certified as Passivhaus should not experience overheating, but overheating may occur when the indoor temperature is measured in individual rooms after the construction of the actual building.

3. Results

In this section, the patterns of each room type (bedroom and living room) were analyzed using the indoor temperature data collected from typical residential buildings and Passivhaus, and the overheating risk was evaluated for each building type (typical residential buildings and Passivhaus). For each building type, the daily indoor temperature patterns of the bedroom and living room were analyzed. In the daily analysis, the hourly average temperature in each room was obtained and the hourly pattern was determined. The overheating risk was evaluated for bedrooms and living rooms during the activity time using Criteria 1A and 1B from the CIBSE.

Figure 2 shows the outdoor temperatures in the UK during summer (June to September) from 2011 to 2018, during which period data for each building were collected in this study. The data were collected through the Environmental Data Service of the Natural Environment Research Council (NERC) and arranged using land surface station data from the UK [47]. The average outdoor temperature over the eight-year period was approximately 15.6 °C (dotted line) and the standard deviation was approximately 3 °C (solid line). The observed outdoor temperature indicates a mild climate even though it was summer. The red X marks show the average summer temperatures of each year. Most of these temperatures were close to the average temperature, and slightly higher temperatures were observed in 2018 compared to the other years.

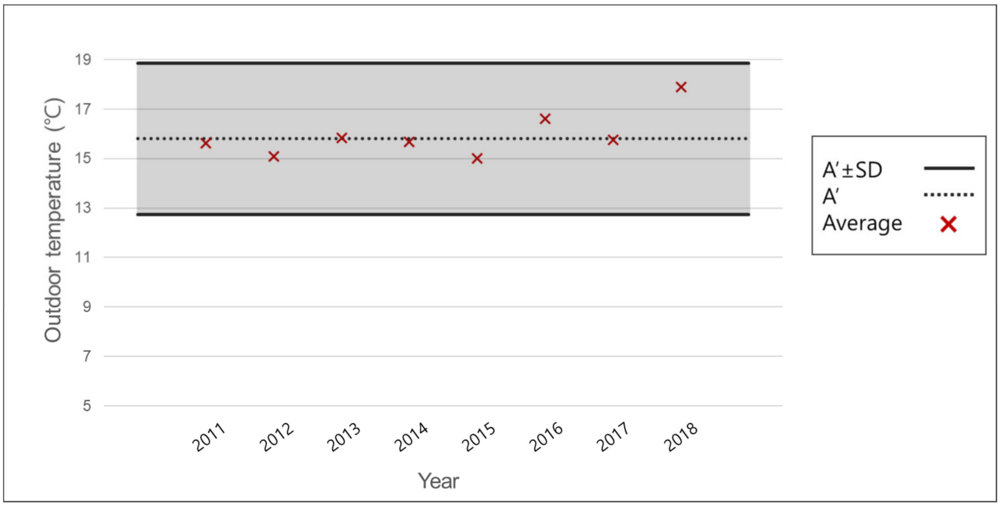

Figure 2. Outdoor air temperatures during the summers from 2011 to 2018 in the UK. Summers are evaluated between May and August. A′ and A′ ± SD are the average outdoor summer temperature and standard deviation over the summer period and each cross indicates the summer mean temperature from May to August for a given year.

3.1. Analysis of Indoor Temperatures in Typical Residential Buildings

In this subsection, the indoor temperature patterns of bedrooms and living rooms in typical residential buildings are analyzed. Figure 3 shows the indoor temperature distributions of bedrooms and living rooms for both types of buildings from June to September in ascending order. Considering the typical residential buildings, 60 bedrooms and 89 living rooms were analyzed. In Figure 3a, the bedroom of a typical residential building with the lowest average indoor temperature was found to be 18.4 °C during sleeping hours, while the bedroom with the highest average indoor temperature was 25.8 °C. The overall average indoor temperature for all bedroom cases was found to be 21.8 °C. In Figure 3c, the living room of a typical residential building with the lowest indoor temperature was 18 °C during activity hours, while the living room with the highest indoor temperature was 25.8 °C. The overall average indoor temperature for all living rooms was found to be 21.8 °C. In general, values that exceed 1.5 times the interquartile range (IQR) in a box plot graph are treated as outliers. The outliers observed in this study appear to have occurred when the temperature varied in contrast to the general temperature trend. These outliers may have occurred because the obtained temperature values were biased when the indoor temperature rapidly decreased or increased due to changes in the outdoor and indoor environment. Therefore, for cases with many outliers, the indoor temperature was determined to be sensitive towards the outdoor environment and the behaviors of the indoor occupants. The frequency of observed outliers was significantly low for the bedrooms compared to the living rooms. This appears to have occurred because the change in indoor temperatures was relatively less salient in the bedrooms than in the living rooms.

Figure 4 shows the indoor temperature distributions by each measurement year in ascending order. Most average temperatures for bedrooms were marginally higher than those for living rooms. The highest average temperature during the observation period occurred in 2014 in typical dwellings. The indoor average temperatures for bedroom and living room in 2014 were 23.2 °C and 22.8 °C, respectively.

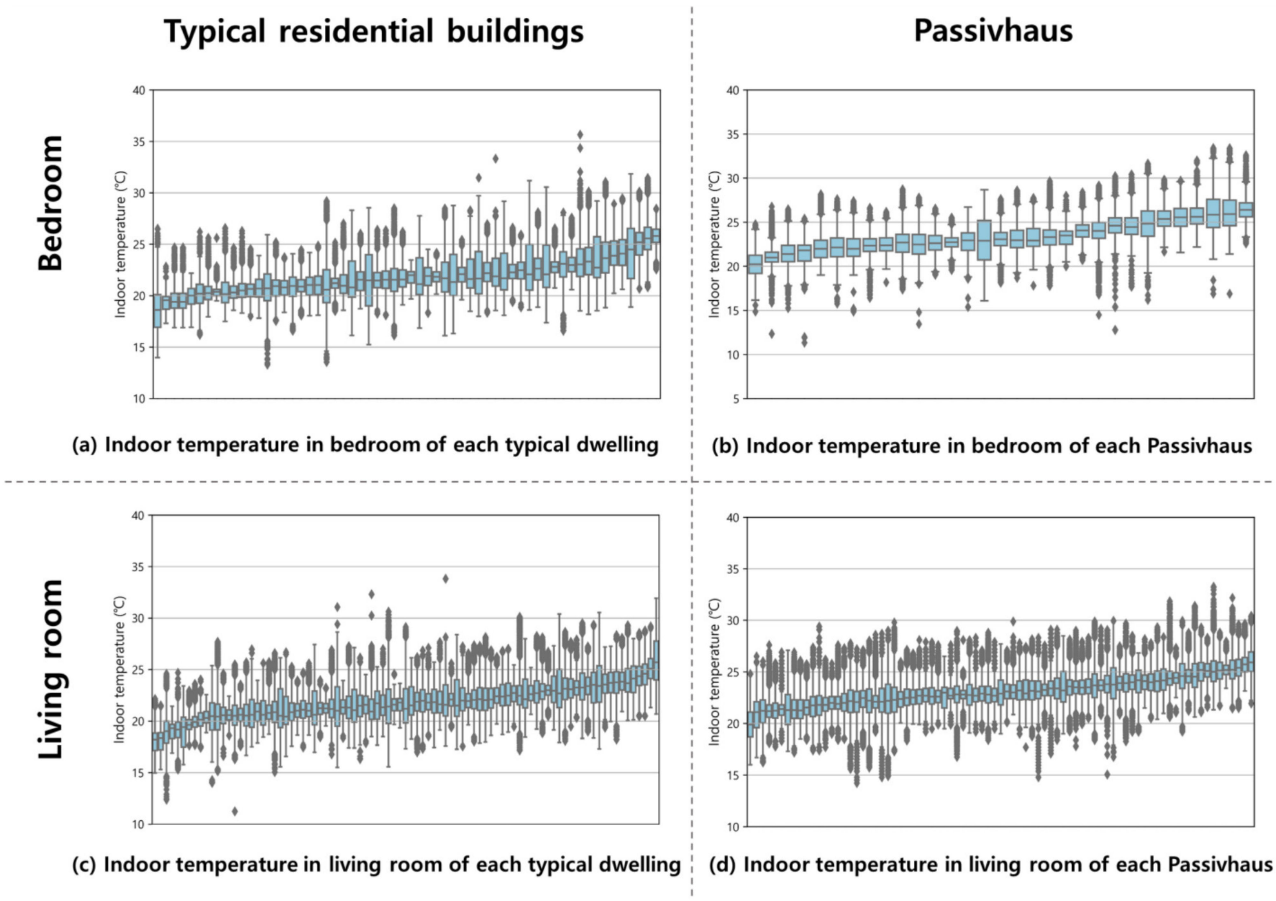

Figure 3. Rank-ordered indoor air temperatures by typical and Passivhaus residential buildings for each bedroom and living room. House IDs have been removed from the x-axes in each panel to improve readability.

Figure 5 shows the average indoor temperature by hour for both types of rooms in the typical residential buildings from June to September. This graph is organized by utilizing all room cases of typical residential buildings to calculate the mean temperature by hour. The orange bars show the 24-h pattern of the indoor temperature in the bedrooms, while the blue bars show the hourly pattern of the indoor temperature in the living rooms. Considering the bedrooms, the lowest indoor temperature occurred at 7 a.m. The highest indoor temperature was observed at 6 p.m. when people began their indoor activities after work. The difference between the maximum and minimum average temperatures was not significant for the bedrooms as it was approximately 0.7 °C. In the living rooms, the indoor temperature reached its minimum and maximum values at 7 a.m. and 6 p.m., respectively, as observed in the bedrooms.

The average temperatures of the bedrooms and living rooms showed similar patterns. For the living rooms, however, the hourly temperature distribution was wider than that of the bedrooms. In particular, the maximum indoor temperature of the living rooms (22.3 °C) was higher than that of the bedrooms (22.1 °C), while its minimum temperature (21.2 °C) was lower than that of the bedrooms (21.4 °C). These findings indicate that the indoor temperature change over time is larger for the living rooms compared to the bedrooms, and this appears to have occurred because the temperature of the living room was sensitive to changes in environmental conditions.

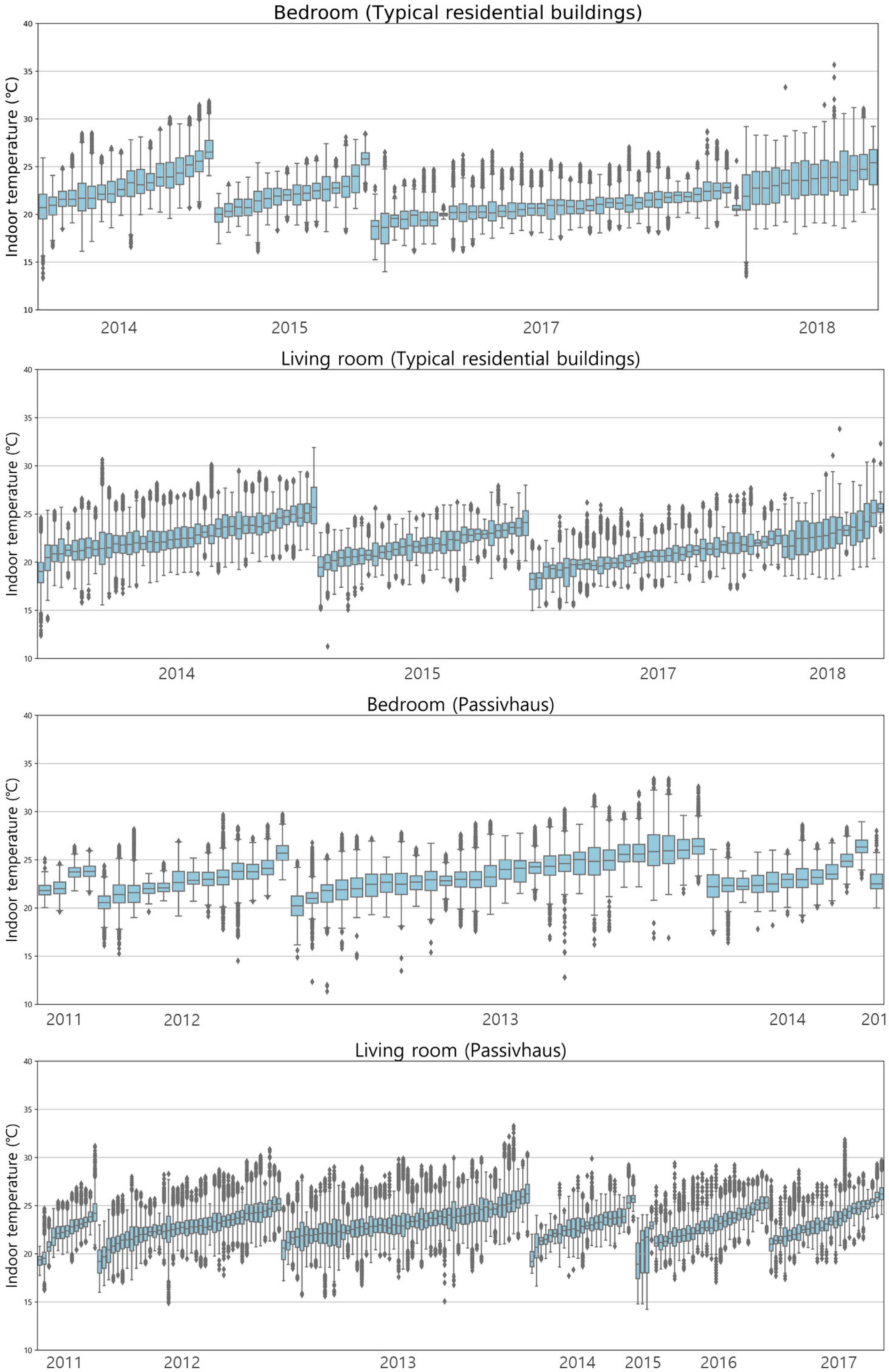

Figure 4. Rank-ordered indoor air temperatures by each measurement year for typical and Passivhaus residential buildings for each bedroom and living room. House IDs have been removed from the x-axes in each panel to improve readability.

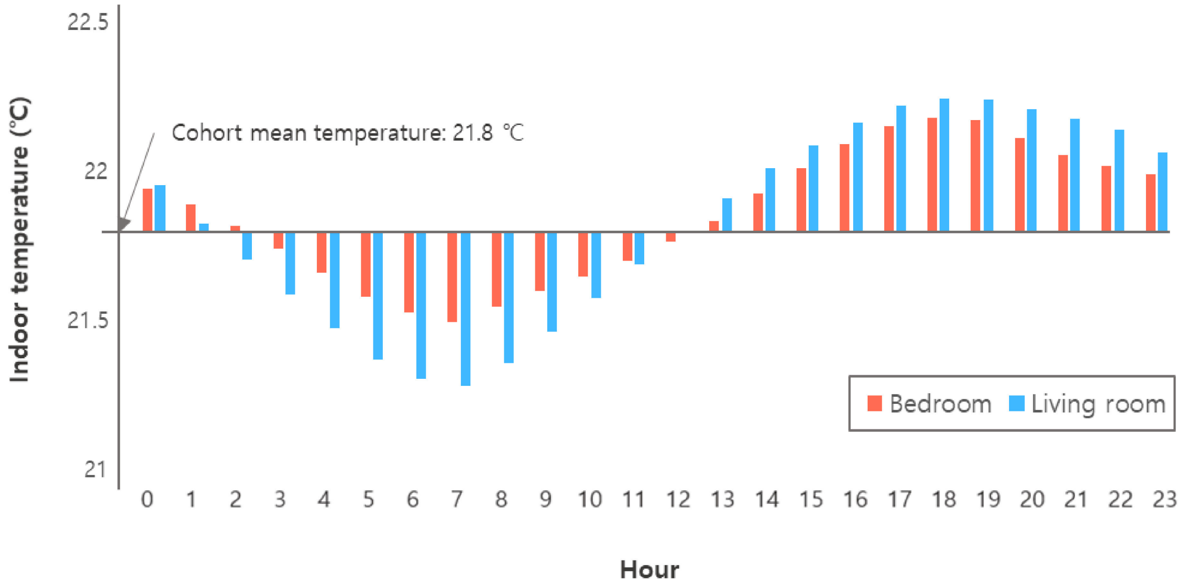

Figure 5. Hourly mean air temperature deviation from the cohort summer mean for living rooms and bedrooms for typical residential buildings.

3.2. Analysis of Indoor Temperatures in Passivhaus

Here, the indoor temperature patterns observed in the Passivhaus are analyzed for 31 bedrooms and 82 living rooms. Figure 3b shows the indoor temperature distribution for the bedrooms of Passivhaus. The overall average indoor temperature was 23.4 °C. The case with the lowest average temperature was 20.1 °C during sleeping hours, while that with the highest temperature was 26.5 °C. Figure 3d shows the indoor temperature distribution of the living rooms of Passivhaus. The overall average indoor temperature was 23.1 °C. The case with the lowest average temperature was 19.9 °C during activity hours, while that with the highest temperature was 25.9 °C. Considering the Passivhaus, a number of values exceeded the range of 1.5 IQR. For the living rooms in particular, the frequency of outliers was significantly high, and the temperature range of each case was found to be wider compared to that of the bedrooms. This indicates that the living room temperature is more easily changed by external factors than the bedrooms. Figure 4 shows the highest average temperature during observation period was occurred in 2013 in Passivhaus. The indoor average temperatures for bedroom and living room in 2013 were 23.7 °C and 23.4 °C, respectively.

Figure 6 shows a bar chart of the average indoor temperature by hour for each room type in the Passivhaus. This graph is organized by utilizing all room cases of Passivhaus to calculate mean temperature by hour. The orange bars in Figure 6 show that the lowest average temperature (23.1 °C) in the bedrooms occurred at 8 a.m., while the highest average temperature (23.6 °C) occurred at 6 p.m. The difference between the maximum and minimum temperatures was found to be approximately 0.5 °C. The blue bars in Figure 6 show that the lowest indoor temperature (22.6 °C) in the living room was recorded at 6 a.m., while the highest indoor temperature (23.5 °C) occurred at 7 p.m. The difference between the maximum and minimum temperatures was approximately 0.9 °C. In the Passivhaus, the average indoor temperature was higher compared to that of the typical residential buildings. For the bedrooms in particular, the temperature change was extremely insignificant and the difference between the maximum and minimum temperatures was approximately 0.5 °C, indicating that the indoor temperature remained nearly constant. In contrast, the indoor temperature of the living rooms significantly changed compared to that of the bedrooms. The maximum indoor temperature in the living rooms was observed at 7 p.m., which was slightly later compared to that of the bedrooms.

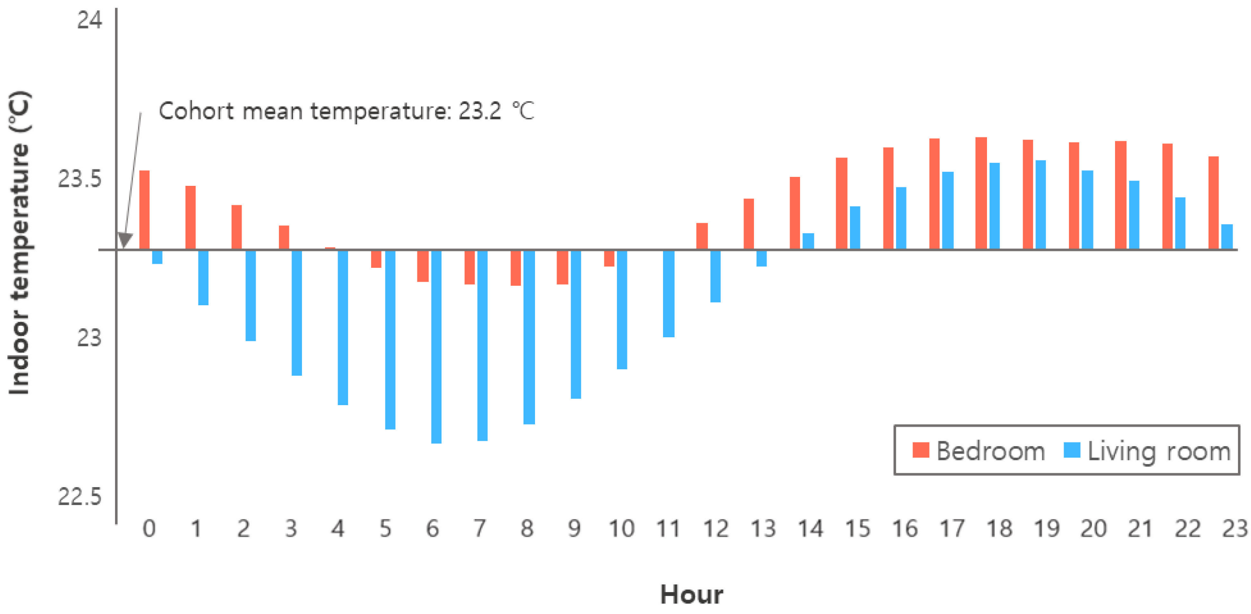

Figure 6. Hourly mean air temperature deviation from the cohort summer mean for living rooms and bedrooms for Passivhaus residential buildings.

3.3. Evaluation of Overheating Risk

In this section, the indoor temperatures of the typical residential buildings and Passivhaus were evaluated using TM 59, which is the criterion used to evaluate the overheating risk provided by the CIBSE. Figure 7 shows the results of evaluating the bedrooms using Criterion 1A of CIBSE TM 59. For each room type, the percentage of overheating during the observation period is shown in an ascending order. For Criterion 1A, the bedrooms are evaluated based on the results observed over the course of an entire day (00:00 to 23:00) based on CIBSE TM 59. The red lines in Figure 7 are the reference points for the total overheating hours, which correspond to values of 3%. In the overheating calculation results for the typical buildings, 2 cases out of 60 exceeded the criterion, and the average percentage of overheating for all cases was found to be approximately 5.3%. In the overheating results of the Passivhaus, five bedroom cases exceeded the criterion. Overheating occurred in approximately 16% of a total of 31 cases. In particular, considering the overheated buildings that exceeded the abovementioned criterion, the average percentage of overheating hours during summertime was found to be 9.8%.

Figure 8 shows the results of evaluating the overheating risk of living rooms using Criterion 1A of CIBSE TM 59. For Criterion 1A, rooms other than the bedroom are evaluated based on the activity time of occupants. Therefore, in this study, the overheating risk from 9 a.m. to 10 p.m. was evaluated for the living rooms. As with the criterion for the bedroom, the overheating criterion for the living room is also 3%, and therefore, the percentage of overheating during the entire summertime observation period must not exceed 3%. The number of the overheated living room cases was found to be 1 out of 89 for the typical residential buildings and 4 out of 82 for the Passivhaus. Therefore, the majority of the observed living rooms satisfied the criterion.

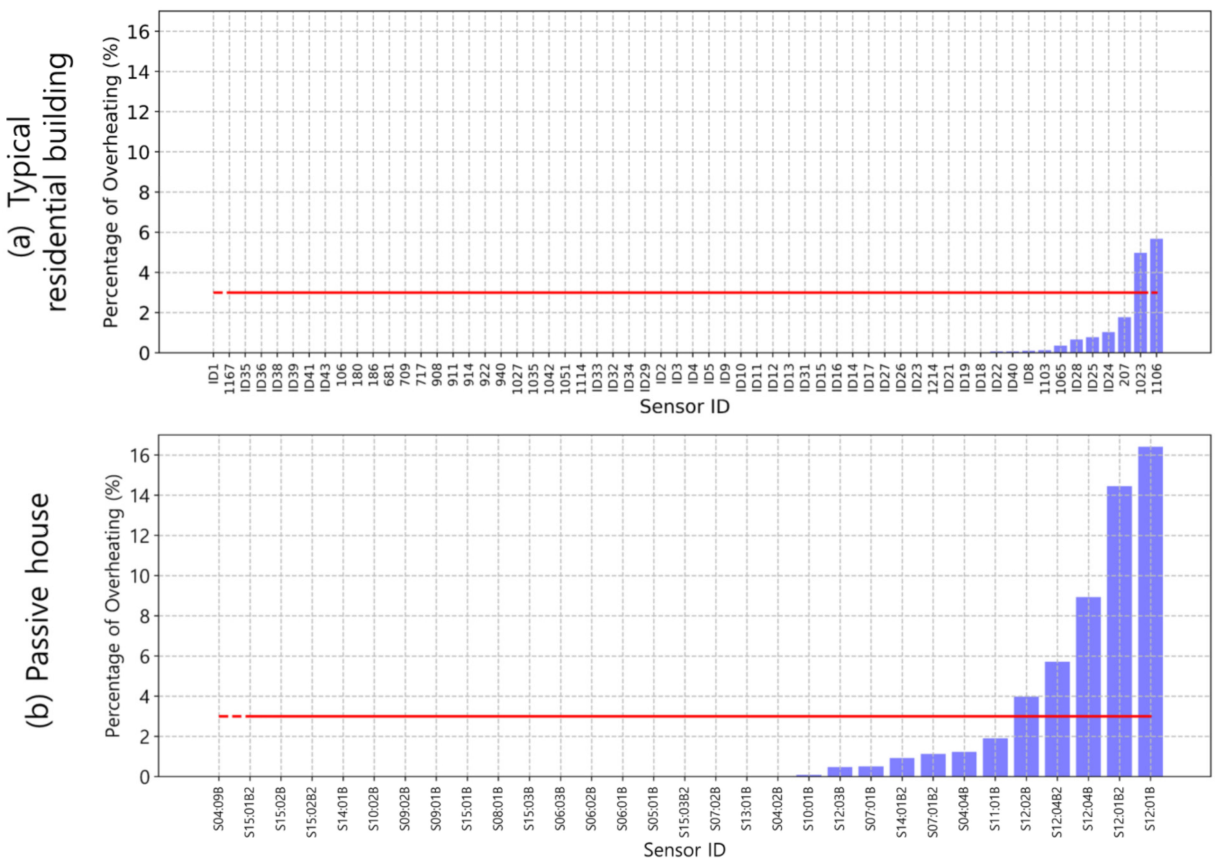

Figure 7. Evaluation of the overheating risk for bedrooms for all 24 h using Criterion 1A. The red line represents overheating standard of 3%.

Figure 9 shows the results of evaluating the bedrooms based on Criterion 1B of CIBSE TM 59. For Criterion 1B, overheating is evaluated using a criterion that is applied more strictly than Criterion 1A based on the indoor temperature observed in the bedrooms during sleeping hours. The sleeping hours extend from 10 p.m. to 7 a.m. If the time during which the indoor temperature of the bedroom exceeds 26 °C is more than 1% of the observed period, overheating has occurred. A stricter criterion is applied to the bedrooms compared to the other rooms because sleeping has a significant influence on health and it is particularly difficult for building occupants to control thermal conditions during sleeping hours. Figure 9a shows the overheating results of the typical residential buildings during sleeping hours. Overall, 26 bedroom cases out of 60 exhibited overheating, indicating that approximately 43% of all cases were overheated. For the cases that exceeded the overheating criterion, overheating occurred for approximately 12% of the total sleeping hours on average. Figure 9b shows the overheating results for the bedrooms of the Passivhaus. In total, 20 bedroom cases out of 31 exhibited overheating. This indicates that more than half (65%) of all bedroom cases were overheated. For the bedroom cases that exhibited overheating, overheating occurred for approximately 19% of the total sleeping hours on average. The bedrooms in the Passivhaus exhibited a significantly higher percentage of overheating than those in the typical buildings. For the Passivhaus, there were also many cases in which the percentage of overheating exceeded 30%. In the most overheated case (Sensor ID: S12:04B), the percentage of overheating hours was found to be approximately 63%.

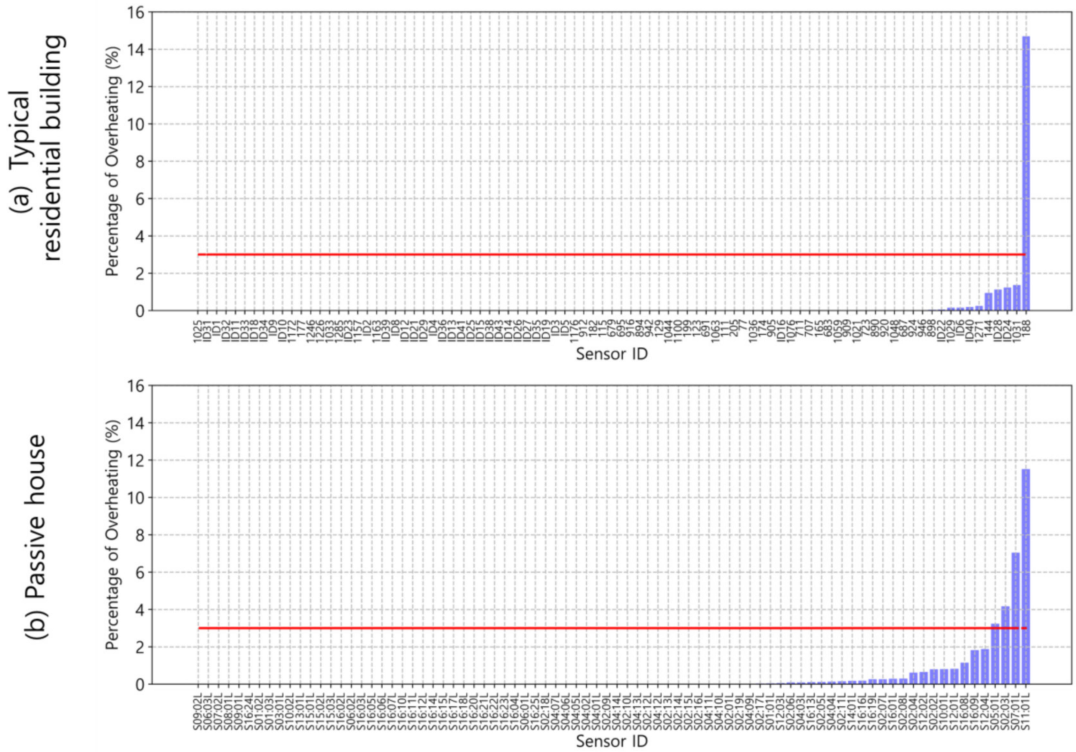

Figure 8. Evaluation of the overheating risk for living rooms using Criterion 1A. The red line represents overheating standard of 3%.

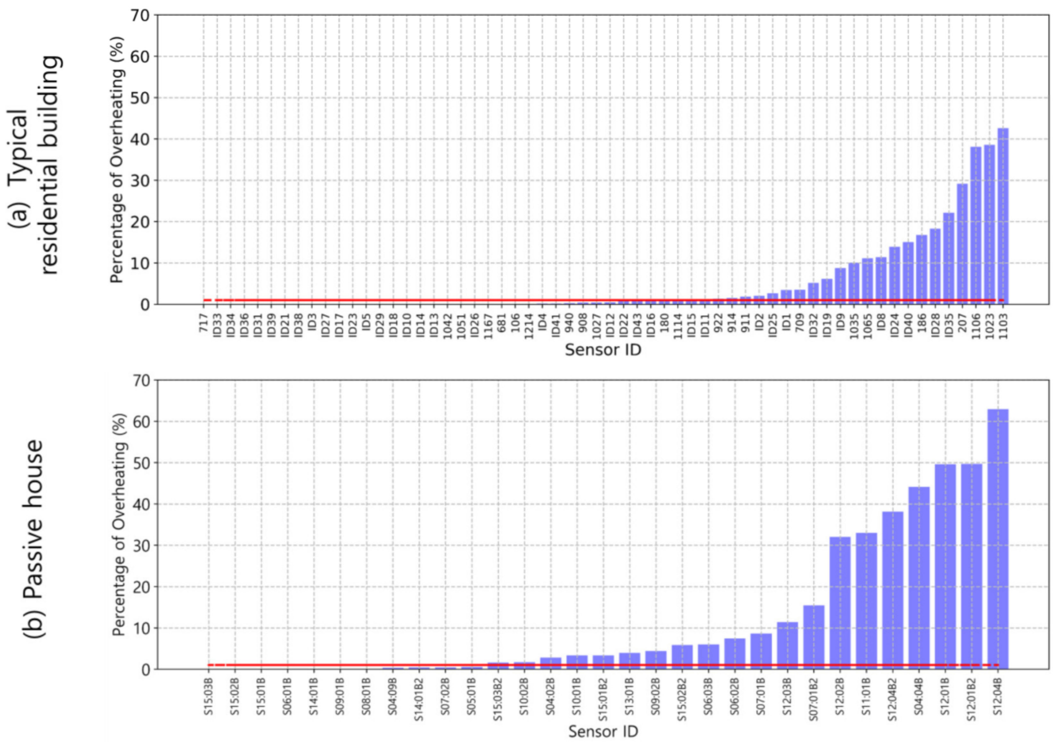

Figure 9. Evaluation of the overheating risk for bedrooms using Criterion 1B. The red line represents overheating standard of 1%.

Figure 10 shows the overall results of the percentage of exceedance hours for overheating by each measurement year. For living rooms, although more hours in excess of the standard are observed in Passivhaus than typical dwellings, few overheating cases were observed in living room cases. For bedroom cases during sleeping hours (Criterion 1B), many bedrooms were overheated over the years in both cases. In particular, the number of overheated typical dwellings was the highest in 2018 when the heatwave with highest outdoor temperature was observed according to Figure 2. In this year, more than 93% of the typical dwellings were overheated and the average of percentage of overheating hours was about 13%. Unfortunately, however, the indoor temperatures in Passivhaus were not measured in 2018, so it is not possible to compare the results for overheating in 2018 in this study. The year when Passivhauses were seriously overheated was 2013. The percentage of overheated Passivhauses was 71% and the average of percentage of overheating hours was 16% in 2013.

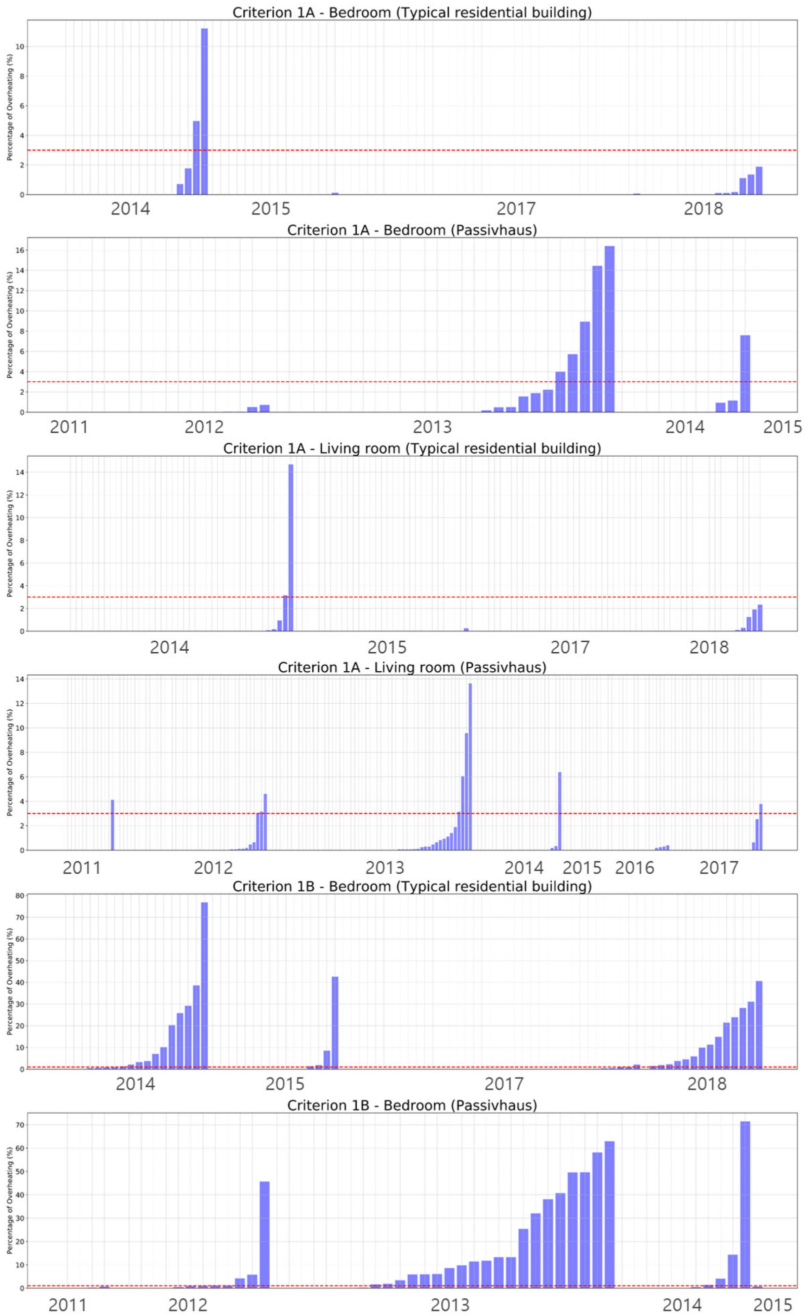

Figure 10. Overall evaluation of the overheating risk by each measurement year. The red line represents overheating standard.

4. Discussion

In this section, based on the analysis results presented in the preceding section, the characteristics of the overheating risk in typical residential buildings and Passivhaus are discussed.

As shown in the results of the hourly pattern analyzed in Section 3.2, the maximum indoor temperature in the buildings occurred around 6 to 7 p.m. when occupant activities generally began after work in the residential buildings. During this time period, the heat accumulated by the thermal mass of each building is slowly transferred to indoor spaces with a time-lag, and elements that cause internal heat gain (lighting, body heat, and devices) increase with the start of occupant activities. Therefore, the decrease in temperature over time becomes smaller compared to the time period with the small number of occupants, and the high indoor temperature observed around 6 to 7 p.m. slowly decreases during this activity time. In this instance, if the temperature remains in the temperature range that causes overheating for an extended period of time, it is highly likely to adversely affect the thermal comfort of the occupants. As the indoor temperature increases with the start of activities for most of the buildings considered in this study, special attention must be paid to ventilation to prevent the overheating risk during the observed time period. In the UK, the indoor temperature must be reduced by cooling through natural or mechanical ventilation systems because the penetration rate of air conditioners in residential buildings is low.

Table 4 summarizes the overheating risk results presented in the previous section. Although average indoor temperature for Passivhaus satisfied recommended indoor temperature well, as defined in EN16798-1 for the summer period (23–26 °C), the number of total overheated cases is more than for typical dwellings because the overall room temperature is higher during the daytime rather than typical dwellings and it tends not to change significantly. For living rooms, few overheating cases were observed according to results. This indicates that the indoor temperature is well managed for many living room cases rather than bedrooms.

Table 4. Summary of the evaluation of overheating risks in typical dwellings and Passivhaus.

Category	Type	Average Indoor Temperature	Number of Cases	Evaluation Criterion (CIBSE)	Number of Overheating Cases	Average Percentage of Overheating Hours (Only for Buildings Exceeding the Overheating Standard)
Typical dwellings	Bedroom	21.85 °C 21.77 °C	60	Criterion 1A Criterion 1B	2 26	5.3% 12%
	Living room	21.83 °C	89	Criterion 1A	1	1.1%
Passivhaus	Bedroom	23.43 °C 23.38 °C	31	Criterion 1A Criterion 1B	5 20	9.8% 19%
	Living room	23.15 °C	82	Criterion 1A	4	6.4%

In contrast to the living room results, the analysis results of the bedrooms exhibited a different trend. The outdoor air temperatures in most years were near the overall average temperature and there were no cases beyond the range of standard deviation in Figure 2. Therefore, the temperature difference by year did not appear large. Even though the summertime outdoor temperature in the UK from 2011 to 2018 was approximately 15.6 °C (indicating a mild climate), the frequency of overheating cases in bedrooms was significantly high in both cases. When the frequency of overheating in the bedroom during sleeping hours was evaluated for both the typical residential buildings and Passivhaus, it was found to be more serious compared to the living rooms. When the indoor temperature was analyzed for the target buildings, it was found that approximately 43% and 65% of the bedroom cases in the typical residential buildings and Passivhaus were exposed to overheating risk, respectively. This suggests that overheating in bedrooms, as measured by the

TM59 standard, is widespread regardless of the type of construction. However, there was a significant effect for the type of construction according to results of the two-sample *t*-test (*p*-value = 0.048). Passivhaus bedrooms (mean = 12.5, standard deviation = 18.4) attained higher overheating scores than for typical dwellings (mean = 5.2, standard deviation = 10.1). In addition, Cohen's d for both groups is about 0.49 as a medium effect.

In addition, the overall average temperature of the rooms tended to be more than 1 °C higher in the Passivhaus than in the typical residential buildings. For the bedrooms during sleeping hours (22:00–07:00), the indoor average nighttime temperature of the Passivhaus was approximately 1.6 °C higher than that of the typical buildings. In particular, the average percentage of the overheating hours was found to be approximately 19% for the bedrooms in the Passivhaus. This indicates that an indoor temperature of 26 °C or higher is maintained for 19% of the overall sleeping hours when overheating occurs in the bedroom. As high indoor temperatures were maintained in the bedrooms of the Passivhaus, the Passivhaus is deemed to be more vulnerable to overheating risk than the typical residential buildings.

For Passivhaus, a high performance is required to achieve low-energy buildings. In general, the Passivhaus standards require an air tightness of 0.6 air change per hour (ACH) at a pressure of 50 Pa, a U-value of less than 0.15 W/m^2 K for the walls, and a U-value of less than 0.8 W/m^2 K for the windows, which are higher than typical UK building regulations [48,49]. As Passivhaus has such high standards to achieve good thermal performances and produce extremely airtight structures, the installation of heat recovery ventilators is recommended. As Passivhaus is significantly airtight, mechanical ventilation is essentially required for air circulation though all rooms must also contain an operable window. Previous studies in the UK related to post occupancy evaluation for Passivhaus have recommended occupant activities to avoid overheating, such as opening windows, ensuring cross ventilation, using nighttime cooling, and HRV [10]. As bedrooms are primarily used during sleeping hours, natural ventilation is not easy to achieve because the occupants cannot ensure adequate ventilation while sleeping. In addition, even in buildings with air-conditioning or ventilation systems that can control thermal conditions, the optimal operation of such systems is not easy to achieve during sleeping hours unless they are operated at all times.

Since daily living spaces such as living rooms are mostly used during the active time of the occupants, comfortable and energy-efficient living spaces may be achieved if the occupants efficiently use natural and mechanical ventilation. Conversely, considering the spaces used during periods when it is difficult for occupants to pay adequate attention (i.e., bedrooms), the indoor temperature can be vulnerable to overheating. The finding that Passivhaus with higher building performances can be more vulnerable than typical residential buildings was confirmed through the frequency of overheating measured in actual buildings in operation. In general, in the certification standards of Passivhaus (with the exception of large-scale buildings), the characteristics of each individual room tend to be neglected because standards focus on the entire building, not individual rooms, to prevent overheating at the design stage. Due to this process, problems may not be found in the design stage for Passivhaus certification. However, overheating issues for individual rooms can be encountered during the operation of the actual occupied building (as indicated by the results of this study). It is noteworthy that 83% of the Passivhaus buildings in this sample meet Passivhaus's own overheating standard of no more than 10% of occupied hours over 25 °C, evaluated at a whole-house level [10]. The number of Passivhaus bedrooms in our sample (38% of studied Passivhaus dwellings) is also smaller than those for typical dwellings (67% of studied typical dwellings), and the indoor temperature data for both types of buildings were not measured in the same year, so the observed rate of overheating in bedrooms cannot be directly compared. Nonetheless, more careful design requirements for individual rooms of residential buildings (especially in the bedroom during sleeping hours) being included in the PHPP guidelines for Passivhaus certification is likely to ensure better control over indoor overheating risk during summertime.

5. Conclusions

In this study, a comparative analysis was conducted on the overheating risk for typical residential buildings and Passivhaus using data collected in the UK. The data used for analysis were indoor temperature data collected from 195 residential buildings (113 typical residential buildings and 82 Passivhaus) between 2011 and 2018. In particular, the overheating risk for each room type was evaluated based on criteria 1A and 1B of the CIBSE TM 59 using the indoor temperature data measured in the bedrooms and living rooms of each residential building. The findings of this study according to each room and building type are as follows:

- When the indoor temperature pattern by hour in the target buildings was analyzed, it was found that the maximum indoor temperature generally occurred from 6 to 7 p.m., as occupants generally started their indoor activities after work. During this time period, the overheating risk is expected to be high because the decrement in indoor temperature is small due to an increase in internal heat gain (due to lighting, body heat, and devices);
- The average indoor temperature of the typical residential buildings was found to be 21.8 °C for both the bedrooms and living rooms, whereas the average indoor temperatures of the Passivhaus were 23.4 °C for the bedrooms and 23.1 °C for the living rooms. Compared to the typical buildings, the indoor temperature observed in the Passivhaus tended to be more than 1 °C higher on average;
- When the overheating risk during the activity time (9 a.m. to 10 p.m.) was evaluated through Criterion 1A of CIBSE TM 59, few overheating cases were observed for the living rooms in both the typical buildings and Passivhaus;
- When the overheating risk in the bedrooms during sleeping hours (10 p.m. to 7 a.m.) was evaluated through Criterion 1B of CIBSE TM 59, 26 cases out of 60 exceeded the overheating criterion for the typical residential buildings. Considering the Passivhaus, 20 bedroom cases out of 31 exceeded the overheating criterion, indicating that more than half of all bedroom cases were exposed to overheating and that relatively more cases exhibited overheating than in the typical residential buildings.

The results of this study confirmed that it is difficult to ensure thermal comfort during sleeping hours because the frequency of overheating in bedrooms is significantly high regardless of the type of construction. In this study, the practical overheating risk in UK buildings was evaluated using empirical data collected from a large number of cases compared to previous studies. However, this study had several limitations and possible future improvements to consider. The data for typical residential buildings were focused on the southern region of the country. Whilst data for Passivhaus buildings had better geographical coverage, bedroom data availability was proportionately lower (38%) than for typical dwellings (67%). In addition, comparison by each year would produce more useful results, unfortunately however, this study focused on analysis for each case because there were not enough samples to compare by year and the observation year was different for each case. Therefore, collecting data on typical buildings and Passivhauses throughout the UK and improving coverage of bedrooms in both types could allow for more generalized evaluation results.

As another limitation, this study conducted meta-analysis of existing data from previous research, hence, the analysis is subject to several data constraints, and these are listed in the following bullet points:

- As data from different studies were used, it was impossible to unify the occupancy conditions;
- The risk of overheating is likely to vary due to behavioral habits as the data were measured by occupants of different buildings;
- In actual buildings, because of the convenience of measurement, few studies have measured the radiant temperature for calculation of operative temperature. Hence,

for these reasons, this study utilized air temperature of room and did not undertake a complete thermal comfort assessment.

Another limitation was that it was difficult to identify the exact causes of the results. For example, this study could not restrict occupancy behaviors, operation patterns, and ventilation habits in target dwellings because most of dwellings were actually occupied by different people. In addition, every building has different physical elements of the buildings (such as building location, orientation, fabric, window). Therefore, although there is no doubt that the exceedance hours of Passivhaus dwellings were certainly more than of typical dwellings, there is the uncertainty in determining the exact causes. Thus, this research focused on statistical comparative analysis based on values of indoor temperature because it was not possible to know the specific causes of the overheating risk in this study. However, the findings of this research work will provide information to judge the situation of overheated cases between typical and Passivhaus dwellings. If future research is conducted to collect detailed boundary conditions using surveys or simulations and analyze it, it will be possible to establish more reliable overheating prevention guidelines. If the results of this study are used to improve and evaluate building performances, it will be possible to prevent the risk of overheating that may occur in residential buildings in advance.

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Data Availability Statement: The links of datasets used in this study are as follows: (i) Dataset for "Overheating Risk in Passivhaus Dwellings". Bath: University of Bath Research Data Archive. Available from: https://doi.org/10.15125/BATH-00774; (ii) Dataset for "Overheating in vulnerable and non-vulnerable households". Bath: University of Bath Research Data Archive. Available from: https://doi.org/10.15125/BATH-00203; (iii) Dataset for "Summer thermal comfort and overheating in the elderly". Bath: University of Bath Research Data Archive. Available from: https://doi.org/10.15125/BATH-00562.

Conflicts of Interest: The authors declare no conflict of interest.

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