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Effects of Climate Change on Thermal Comfort and Energy Demand in a Single-Family House in Poland

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Abstract: In regions with temperate climates, the thermal insulation of buildings is increased to reduce the need for heating. It might significantly reduce human thermal comfort in the summer period. The problem can increase with global warming. The aim of the paper is to analyze the heating and cooling demand, as well as thermal comfort in a single-family house located in Poland for three climate scenarios (typical, real, and future weather data) and for two types of thermal insulation of external walls. In the study, two ways of cooling the building were taken into account: using split air conditioners and using fresh airflow provided through the opening of windows. The open area and the temperatures for opening windows have been optimized using a two-criteria function. The energy simulation was carried out in EnergyPlus 9.4 software. The multi-zone model was validated on the basis of the temperature measurement. The results showed that there will be a problem with ensuring thermal comfort in the future, especially in well-insulated buildings. The energy demand for cooling will be greater than the demand for heating. The use of passive cooling is a good solution for residential buildings in these regions, and the number of discomfort hours is small (max 5%).

Keywords: building simulation; thermal comfort; heating and cooling demand; climate change; ventilative cooling

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1. Introduction

Increases in global air temperatures and solar radiation due to climate change have intensified the problem of ensuring human thermal comfort in buildings even in regions with currently temperate summers [1,2]. A significant amount of the energy produced in the world is used for the thermal comfort of the occupants [3]. It is commonly considered that in single-family houses located in temperate climates, the most energy is used for heating. For this reason, architects and engineers focus on reducing the heating demand, for example by increasing thermal insulation of external walls of the designed buildings. These operations, apart from the expected reduction in heat demand, also have negative effects, for example overheating building in the warm season. The heat and mass transfer between outdoor and indoor environment is limited. Therefore, finding the right balance between reducing a building's energy consumption and ensuring an adequate level of thermal comfort poses a major challenge.

Achieving a sufficient level of comfort in residential environments in the summer period most often requires the use of mechanical cooling devices, e.g., split air conditioners [4], which results in the additional consumption of electricity. In developed countries, air-conditioning can account for more than half of the electricity consumption in a single flat [5]. That is why the concept of passive cooling of a building has become so important, whereby buildings use the potential of the natural climate. One of the methods of passive cooling is the use of additional airflow by opened windows. The energy saving potential of using ventilative cooling is reflected in a large number of publications on the subject.

Mirakholi [6] carried out the simulation of the effectiveness of natural ventilation in a residential building in Texas San Antonio (one-story building with a total area of 94 m^2); simulations were made in the EnergyPlus program. It showed that electricity consumption in air-conditioned buildings with natural ventilation can be 20% lower than in buildings without natural ventilation. The best results were obtained in April and November, up to 50% energy savings. To achieve high cooling efficiency using only natural ventilation, which results in high energy savings, the windows should be opened properly. As a consequence, it is possible to use free-cooling for a maximum period of a year while ensuring the comfort of users. In the study by Stazi et al. [7], an analysis of the automatic window control system is presented based on indicators of thermal comfort (PMV and PPD) and indoor air quality in Mediterranean climate. Grygierek and Sarna [8] considered two options of passive cooling in a typical Polish single-family house: the former using outside air supplied to the building by means of fans, the latter by opening windows (automatically or by residents). Fuzzy controllers for the cooling time and supply airflow control were proposed and optimized in both cases. The research has shown that cooling with external air can significantly improve thermal comfort while insignificantly increasing heating demand. In turn, Brambilla et al. [9] analyzed the overheating hours associated with a different ventilation approach applied in an office building located in Fribourg. Among the different scenarios simulated, natural ventilation misuse showed a greater influence on the thermal human comfort, especially if coupled with low thermal mass of the building.

The effectiveness of passive techniques depends directly on the local climatic conditions, varying not only during the year but also during the day. Therefore, not every alternative method might be an adequate solution for a given location, but local climatic conditions must be always taken into consideration [10]. Artmann et al. [11] evaluated the effectiveness of passive cooling of buildings by ventilation in all climatic zones of Europe. They showed the high potential for night-time ventilative cooling in northern Europe and still a significant potential in the rest regions of Europe. However, owing to the inherent stochastic properties of weather patterns, a series of warmer nights can occur at some locations, where passive cooling by night-time ventilation alone might not be satisfactory to provide thermal comfort.

Another important issue in terms of the impact of climate change on buildings is the weather data files used in energy simulations. Researchers show that current weather data files used to simulate future energy and thermal behavior of buildings are not reliable [12]. The climatic conditions of the 20th century (commonly used in a typical meteorological year) may not reflect the full range of extreme conditions that will affect the indoor environment of the building [13]. Cui et al. [14] pointed out that the difference between a typical meteorological year (TMY) data and current weather data can lead to variations in the simulation of building performance, so climate change is an important factor in the energy simulation process. Many studies have revealed the impacts of climate change on heating and cooling demand. For example, Invidiata and Ghisi [12] investigated this problem in dwellings in three cities in Brazil. Using the EnergyPlus simulation program, they estimated the indoor temperature and the future annual heating and cooling energy demand. Passive cooling design strategies were implemented. The results showed an increase in annual energy demand ranging from 56% to 112% in the case of the three 2050 cities, but the use of passive strategies reduced the future annual cooling and heating demand by up to 50%. Kikumoto et al. [15] noted the variation in energy consumption over the lifetime of buildings in Japan. Simulations showed that the current heat load of the house increases by 15% in 2034. In turn, a study by Verichev et al. [16] analyzed the impact of climate change on energy consumption in three regions of southern Chile. Heating energy consumption in a single-family house was found to decrease by an average of 13% to 27% depending on the climate change scenario.

Northern and Central Europe are one of the regions doomed to dramatic changes as a result of global warming. While warming of the climate reduces the number of days where heating is necessary, increased cooling demand might lead to higher total energy consumption. This is of paramount importance during heat waves and peak cooling demand days [17]. In Sweden, Dodoo et al. [2] studied the effect of global warming on the energy performance of conventional and passive multi-family buildings. The energy consumption for heating in a conventional building decreased by 13% in 2050 and 16% in 2100, while the energy consumption for cooling increased by 33% and 42% respectively. On the other hand, energy consumption for heating a passive house dropped from 17% to 22% in 2050 and 2100, and for cooling increased from 39% to 49% respectively. The results showed that passive buildings are designed mainly to reduce heat consumption. The conclusions were confirmed in subsequent studies by this research team [18].

The study presented in this article combines all the three issues discussed above: global warming, conventional building standard versus passive building standard, and using passive systems for cooling. Most of the previous research addresses one of these problems, or at most a combination of the two. In addition, research on the problem of building overheating has been carried out mainly in countries with a warm climate. However, there are very few studies on the effects of different climate scenarios on residential buildings in the Baltic Sea region. The aim of this work is to analyze the demand for heating and cooling, as well as human thermal comfort, in a single-family house located in Poland for three cases of climate data (TMY, real for 2018, and future for 2050) and for two cases of thermal insulation of the building envelope. For each of these cases, the possibilities of reducing energy consumption and improving thermal comfort with the use of passive ventilative cooling were investigated.

2. Method

2.1. The Building

A single-family semi-detached house, built in 2017–2018, has been selected for analysis. The building is located in the southern Poland in the city of Skoczów (Figure 1). The topology of the building represents the Polish building stock. The construction details are presented in Figure 2. Only the right part of the semi-detached house that was one dwelling has been taken into account. The building consists of two usable storeys: ground floor with separate living area (entrance, living room with kitchen, hall, bathroom) and attic floor (two children's rooms, bedroom, bathroom, hall). The building is naturally ventilated and gas boiler is a heat source.

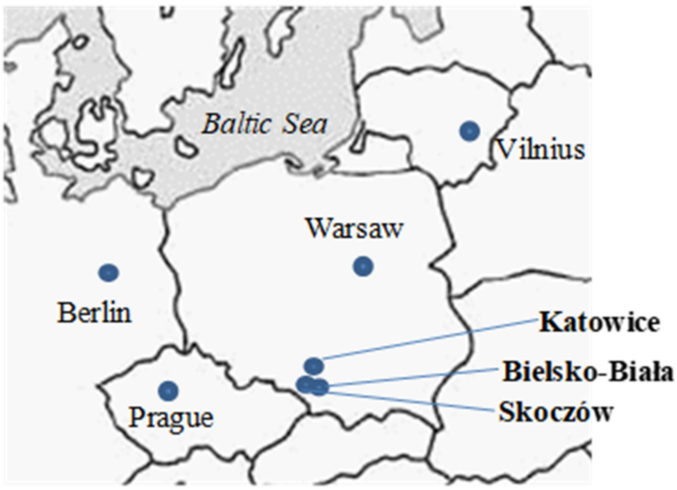
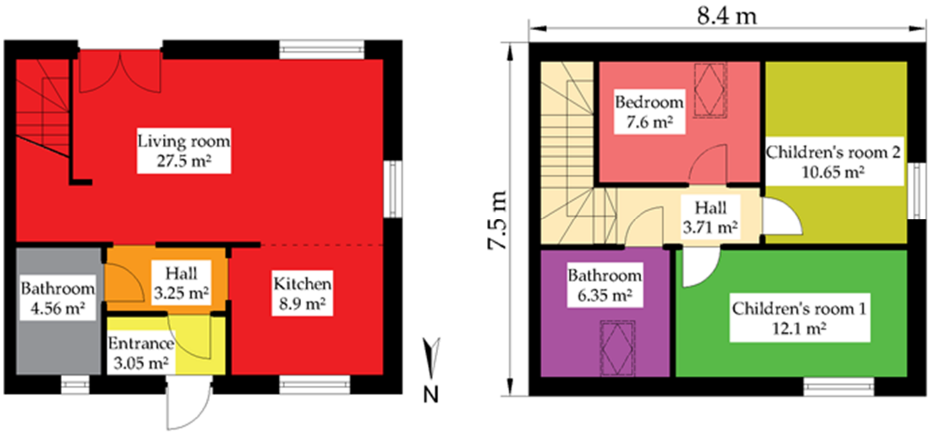


Figure 1. Overview map.



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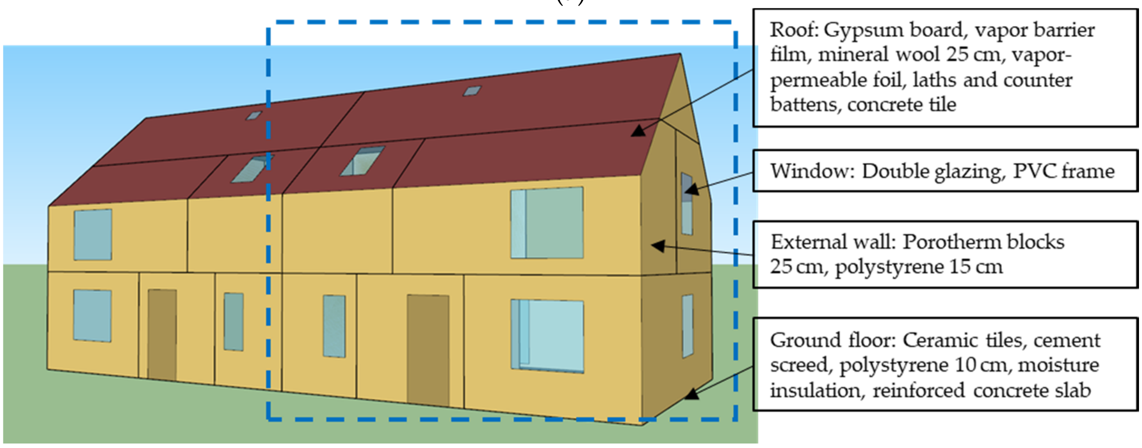


(**b**)

Figure 2. (**a**) Plan of the ground floor (on the **left**) and the first floor (on the **right**) with thermal zones marked in colors; (**b**) model view (blue line indicated part under consideration).

2.2. Thermal Model

The numerical model of the building was created using the graphical application of the OpenStudio SketchUp Plug-in [19]. The model contained ten thermal zones, as shown in Figure 2. The numerical simulations were carried out in EnergyPlus software (EP) [20] because not all options required for this study were included in the OpenStudio program [21].

Internal heat gains were included in the model (Table 1). Human gains were assumed as following ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) standards [22]. The heat gains schedules for four occupants (with a 15 min time step) were prepared on the basis of attendance registration conducted by occupants. Control of internal blinds was introduced depending on the intensity of solar radiation. For this purpose, a type of control "On If High Solar On Window" was used.

The Sherman and Grimsrud (1980) model was used for modelling air infiltration [20]. This is one of the recommended models for building simulation in the EnergyPlus program and is based on the method "Infiltration by Effective Leakage Area" (ELA). The ELA value is defined as the equivalent amount of open area through which the same amount of air would flow jointly through the building envelope at a pressure differential of 4 Pa [20,23]. The value of the airtightness coefficient for windows was assumed at 0.3 $m^3/(m \cdot h \cdot Pa^{0.67})$ based on available research on the airtightness of the windows in Polish dwelling buildings [24,25]. The effective area of the chimney and the leaks in the roof were established according to the ASHRAE guidelines [26]. The method allowed one to take into account the instantaneous difference in internal and external temperatures, and the effect of wind on the airflow infiltrating the building.

Table 1. Internal heat gains.

Heat Gain	Value	Occurrence
Occupants	126 W (sensible + latent)	All zones schedule
Electric cooker	300 W	Living room schedule
Fridge	150 W	Kitchen clockwise
TV set	50 W	Living room schedule
Computer	100 W	Children's rooms schedule
Steaming hot water	913 W (latent fraction of 0.89)	Bathrooms schedule
Lighting	2 W/m^2	Switching on and off controlled using the function "DaylightingControl", the light source switched on depending on the lighting intensity of the room

2.3. Climate Data

A wide variety of weather data can be used for building performance simulation programs—from locally recorded weather data to preselected "typical" years. The latter is available as: TMY (Typical Meteorological Year), TRY (Test Reference Year), and IWEC (International Weather for Energy Calculation). Herrera et al. [27] described each of these files in detail. In order to carry out the simulation for future years, it is necessary to prepare a file for the future climate by specialist software. The most used are the CCWorldWeatherGen, the WeatherShift, the Advanced Weather GENerator, and the Meteonorm. The comparison of these programs was described in the study Yassaghi et al. [28] and Moazami et al. [29]. The programs use special methods to predict the future climate, the most popular is the so-called morphing method which is based on the morphing of historical observation. Future climates are prepared in accordance with the document SRES (the Special Report on Emissions Scenarios) [30], published by IPCC (the Intergovernmental Panel on Climate Change) [31]. In this document, a series of greenhouse gas emission scenarios A1FI, A1B, A1T, A2, B1, and B2, with different social and economic variables, are presented. The most unfavorable scenario is A2, which divides (regionalization) the world, focuses on regionally oriented and differential economic development. Moreover, the predicted concentration of CO_2 for the 2100 year is the highest compared to other scenarios [16,32]. The IPCC regularly updated the global warming forecasts, the last reports are AR4 (the 4th Assessment Report of IPCC) [33] and AR5 (the 5th Assessment Report of IPCC) [34].

Poland has a temperate climate with cold winters and warm summers. The heating season typically lasts from September to May; the number of heating degree days is about 3743 (°C·day). Three different climate models were used for the analyses. In the first case, it was a TMY weather file, developed by the Polish Ministry of Infrastructure for use in energy calculations for buildings [35] based on the 30-year data (1971 to 2000) from the Institute of Meteorology and Water Management (IMGW), for the city of Katowice, located 60 km from Skoczów (TMY) [36]. This is the nearest location to the building with TMY data available. The annual outdoor temperature ranges from −18.3 °C to 30.8 °C, with an average of 8.0 °C. The second weather file was built on the real climate data from 2018 for the city of Bielsko-Biała, located 20 km from Skoczów (real 2018). This is the nearest location to the building with the available current weather data of the IMGW. The annual outdoor temperature ranges from −16.7 °C to 32 °C, with an average of 10.1 °C. The comparison of these two types of climates was to check whether the use of publicly available standard climate data did not significantly affect the simulation results when compared with the data from the analyzed period of time. The future climate was selected as the third climate, due to the noticeable warming-up in recent years and further projected warming. Based on the first climate and the A2 scenario, the warmer climate for 2050 was generated. It was prepared in the generally available CCWorldWeatherGen program [37], which is based on the morphing of historical observation. Annual, outdoor temperature ranges from −13.8 °C to 37.6 °C, with an average of 11.0 °C (future). Climate data of these three cases were prepared in weather file format—The EPW file [38]. EPW (Energy Plus Weather) is a typical file format commonly used in the EnergyPlus program. It is a text-based CSV file that contains a year-worth of hourly weather variables for a given location. Weather variables include temperature, dew point, global horizontal radiation, diffuse solar radiation, wind speed, and wind direction. The EPW file can be used in different simulation programs such as ESP-r [39], IES [40], and TAS [27,41]. Figure 3 presents the comparison of minimum, average, maximum monthly exterior temperature.

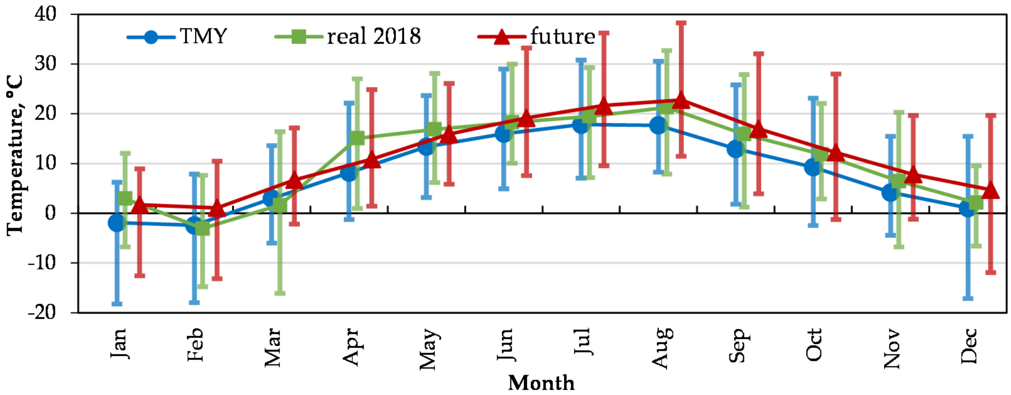


Figure 3. The comparison of average, minimum, and maximum monthly exterior temperature for analyzed climates.

2.4. Model Validation

In order to verify the thermal model, the indoor temperature measurement campaign was carried out in September 2018. The measurements were conducted with 15 min time step using Apar235 recorders (measuring range: −30–80 °C, measuring accuracy: ±0.5 °C in the range 20–30 °C and ±0.5–1.8 °C in the remaining range) in four selected rooms (living room, children's room 2, bathroom on 1st floor, and unheated attic). During the measurement, there were three occupants (two adults and child) in the building. For that reason, a separate schedule (based on the actual recording of staying occupants) of the heat gains was prepared to validate the model. The comparison of measured and simulated indoor temperature is shown in Figure 4. The article by Sarna et al. [42] describes in detail the process of model validation and calibration.

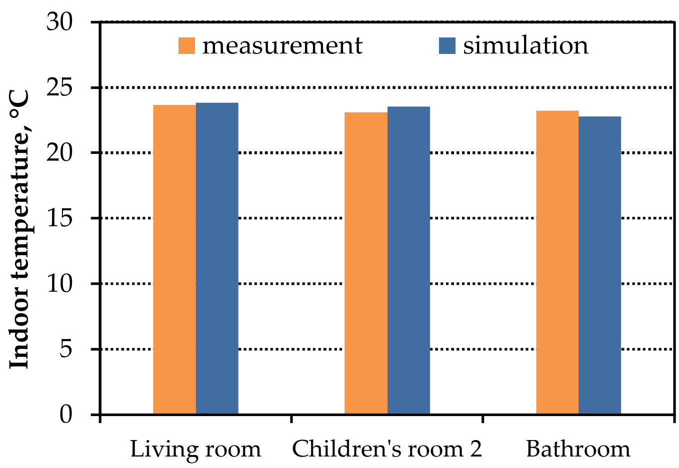


Figure 4. The monthly temperature in September.

To assess the compliance of the simulation model, the indicators given in the ASHRAE guide were used [43]. There normalized mean bias error (NMBE) and coefficient of variation of root mean squared error (CVRMSE) were evaluated. The indicators are used for average hourly and average monthly values and ought to be calculated based on Equations (1) and (2). For the hourly step, the NMBE and CVRMSE rates should not be more than 10% and 30%, while for the average monthly data the NMBE and CVRMSE rates should not exceed 5% and 15% respectively. It was found that the model could be used for simulation results which were within the acceptable range (Table 2). Monthly values of indoor temperature did not differ by more than 0.5 °C (Figure 4).

$$\mathrm{NMBE} = \frac{\sum_{i=1}^{n}(M_i - S_i)}{n \cdot \overline{M_i}} \times 100 \tag{1}$$

$$\mathrm{CVRMSE} = \frac{1}{\overline{M_i}} \sqrt{\frac{\sum_{i=1}^{n}(M_i - S_i)^2}{n}} \times 100 \tag{2}$$

Table 2. The values of NMBE and CVRMSE indicators for average hourly values of indoor temperature after the model calibration.

Building Zone	Error
Living room with open kitchen	NMBE = 1%; CVRMSE = 3%
Children's room 2	NMBE = 2%; CVRMSE = 3%
Bathroom on 1st floor	NMBE = 2%; CVRMSE = 3%

M_i—measured value, S_i—simulated value, n—number of compared values, $\overline{M_i}$—mean of the measurement values.

2.5. Thermal Comfort Model

The adaptive thermal comfort model based on EN 16798-1:2019 [44] standards was adopted for the calculations. The adaptive model is "a model that relates indoor design temperature or acceptable temperature ranges to the outdoor meteorological or climatological parameters" [22]. The model assumes that people can adapt to changing environmental conditions at different times of the year using adaptive possibilities [45]. The model was used to simulate thermal comfort in naturally ventilated buildings [46]. There are three comfort categories: I (90% acceptability), II (80% acceptability), and III (65% acceptability). To obtain the optimal temperature of the internal environment, an algorithm of a linear function of the average outdoor temperature has been defined. The model indicates the range of comfortable operative indoor temperature. The operative temperature is "the uniform temperature of an imaginary black enclosure, and the air within it, in which an occupant would change the same amount of heat by radiation and convection as in the actual non-uniform environment" [22]. The value of the operative temperature differs from the indoor air temperature because it takes into account the thermal radiation of the surrounding building partitions. Research on this topic can be found in the work of Kaczmarczyk et al. [47].

It was also assumed that the rooms can be heated from September to May depending on the instantaneous heating demand. The heating set-point for all rooms, except bathrooms, was 21 °C, for bathrooms it was 24 °C according to Polish requirements. It was decided to use a higher heating set-point for bathrooms for the comfort of people during bathing. At night, the heating temperature was reduced to 18 °C to ensure the best possible conditions for sleep. Rooms, except bathrooms, could be cooled (all year) according to the assumption described in the next section.

2.6. Case Studies

The simulations (with a 15 min time step for the whole year) were carried out for two external partitions insulation scenario according to Polish technical requirements [48] and passive building standard [49] (Figure 5), three weather data scenario (see Section 2.3), and two types of cooling system (Table 3).

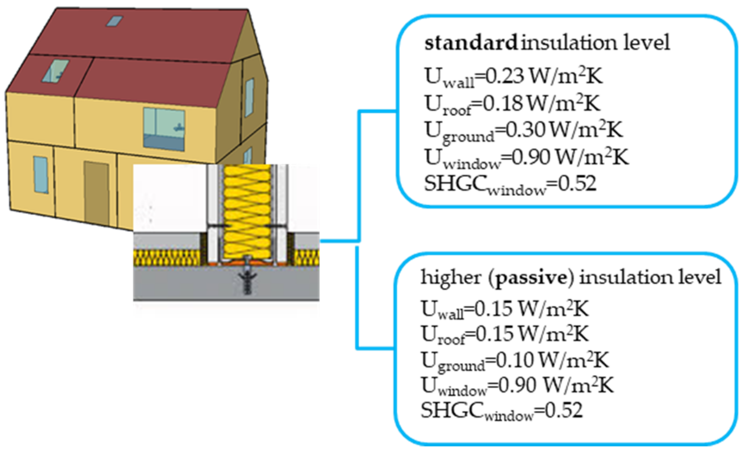


Figure 5. Heat transfer (U) and solar heat gain (SHGC) coefficients for the building's external partitions.

Table 3. Cases under consideration.

Parameter		**Case**											
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Cooling System	mechanical	+	+	+	+	+	+						
	passive							+	+	+	+	+	+
Climate	TMY	+	+					+	+				
	real 2018			+	+					+	+		
	future					+	+					+	+
Building Insulation	standard	+		+		+		+		+		+	
	passive		+		+		+		+		+		+

The aim of both cooling systems was maintenance of comfort temperature in range of the 2nd category of the adaptive model (as the most recommended category for energy calculations [44]).

The first type of cooling was mechanical cooling using electric air conditioners (splits). Air conditioning was automatically turned on if the temperature exceeded the comfort temperature. As mentioned earlier in the adaptive model, the operative temperature occurred, while the cooling devices are controlled by the air temperature. In this study, according to the literature [47], it was assumed that the air temperature was 1.5 °C lower than the operative temperature. Instantaneous values of the air temperature set-point (theoretical comfort air temperature line) were calculated for the entire year as instantaneous operative temperature determined according to EN 16798-1:2019 [44] with the assumed offset. For this assumption, the number of thermal discomfort hours during the year was zero; however, additional cooling energy demand was required.

The second type of cooling was passive ventilative cooling which relied on the use of the cooling capacity of the external airflow through the opened windows. It is common for occupants of the buildings without mechanical ventilation or cooling to open windows to improve the indoor environment. To model ventilative cooling (by opening windows), a built-in EP model was used, described as "Wind and Stack Open Area". The main parameter used in this model was the window opening area. For the assumed opening area, airflow changes with outdoor conditions. The degree of window opening was decided by the sensor simulating the behavior of residents, depending on instantaneous thermal conditions in the room and depending on the outside temperature. In EP, a model based on the “if . . . then” principle was built to predict the window opening process. The duration and degree of window opening depended on indoor and outdoor temperatures. For the simulation model, the temperatures at which the windows were opened and the degree of window opening were optimized (three possible settings for opening windows were assumed). The aim was to keep the number of discomfort hours (for 2nd category) as low as possible with the smallest increase in heat demand. The introduction of the second objective function was to limit the rapid cooling of the rooms (especially in transitional periods, in spring and autumn). Two-criteria optimization was performed in MATLAB with the use of the NSGA-II algorithm. A set of non-dominated solutions (Pareto front) was a result of the multi-criteria optimization. The utopia point solution was selected for the analysis presented. The control model has been implemented in the EMS (Energy Management System) part of the EP program. The window opening model was described in detail in the work of Grygierek et al. [50].

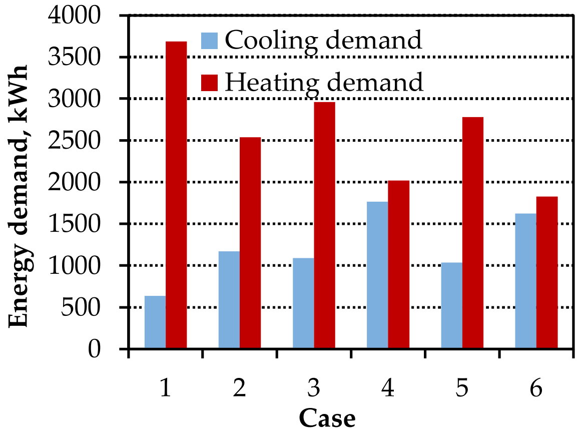
For each calculation case of ventilative cooling, the number of discomfort hours (H_{dis}) was determined as the sum of the discomfort hours from the living room, children’s rooms and the bedroom. Thermal comfort was calculated only for the hours occupied in each zone (the sum of hours occupied for these rooms was 14,511 h per year). The night hours when the temperature was intentionally reduced to 18 °C during the heating period were excluded from the calculations. The adaptive thermal comfort model determines the degree of comfort in buildings with natural ventilation, as long as the weighted average outdoor temperature exceeds 10 °C. Therefore, in winter, when there are lower temperatures in Poland, the heating system was assumed to ensure adequate thermal comfort.

3. Results and Discussion

The comparison of annual energy demand and the thermal comfort for the cases considered was the main aim of the analysis (Table 4). The values of heating and cooling demand were presented for the entire building and the living room (as the most representative zone of the building). In the first step, simulations were carried out for cases with mechanical cooling to compare the annual cooling and heating demand (Figure 6). In case 1 (standard climate and insulation), the annual heating demand was 3689 kWh (including 648 kWh in the living room) and the cooling demand was 636 kWh (including 182 kWh in the living room). The value of the heating demand for the entire building was much higher than the cooling demand (about six times). In case 2, as expected, there was a reduction in the heating demand (about 31%) due to the use of better thermal insulation of the building envelope. However, on the other hand, the value of cooling demand increased (about 84%), especially in the living room (about 212%). In case 1, the cooling demand was only 17% of the heating demand, while in the second one it was as much as 46%. Furthermore, in the living room, the cooling demand was 28% of the heating demand for case 1, while for case 2, the cooling demand exceeded the heat demand and amounted to 188% of its value. The living room was the most often used room and involved the largest internal heat gains from occupants and devices. Moreover, there was a large, south window area in this room that generated large solar gains. In the case of very good building insulation, the heat losses during the colder periods of the day (e.g., at night) were smaller and the room was overheated.

Table 4. Results set.

Result	Mechanical Cooling Cases 1–6	Passive Cooling Cases 7–12
Heating demand	YES	YES
Cooling demand	YES	NO
Number of discomfort hours	NO	YES



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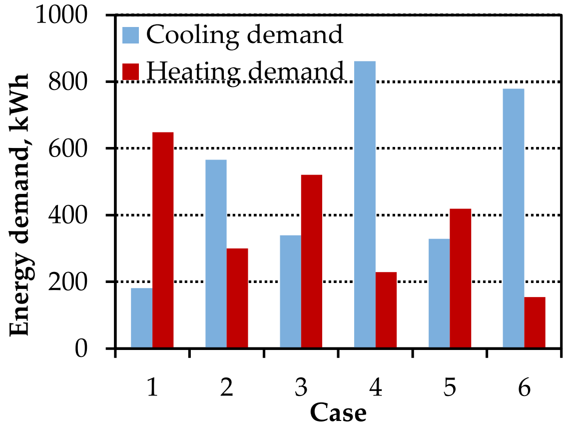


(**b**)

Figure 6. The annual cooling and heating demand: (**a**) the whole building; (**b**) living room.

In cases 3 and 4, warmer climate parameters were used, therefore the values of heating demand decreased, compared to cases 1 and 2 (about 20% and 20% respectively). In both cases, the value of heating demand was still higher than the cooling demand but in the case of 4, the difference was only 12%. For case 4 with the insulation of passive building standard, as in case of 2, the value of cooling demand was higher than heating demand in the living room. As expected, for cases with future climate (case 5 and 6) the cooling demand slightly decreased compared to cases 3 and 4 (about 5% and 8% respectively). In case 6 the values of heating and cooling demand were similar, the cooling demand was 89% of heating demand, while in the living room the value of cooling demand was almost five times higher.

Currently, Polish guidelines on the insulation of external partitions are aimed at reducing the heating demand. However, as the simulations showed, in the era of a warming climate, cooling can have a significant share in the energy demand of the building. In this case, increasing the insulation of external partitions has an adverse effect. The building becomes like a thermos and on hot days it cools down much more slowly. This problem intensifies in the case of large internal heat gains as in the presented study—a building with an area not exceeding 100 m^2 is inhabited by a four-person family. However, it should be noted that the windows were not opened in this case, which could help cool the building.

In the second step, calculations were carried out for cases with passive ventilative cooling using natural airflow through open windows. The results of optimization are presented in Figure 7. The main criterion for choosing the best solution for each case was to obtain the minimum number of discomfort hours. However, to achieve this criterion, windows had to be often opened, thus it caused a rise in heating demand. Therefore, two objective functions were adopted (H_{dis} and heating demand) in the research. The optimal solutions in this case provide the lowest discomfort (min H_{dis}) with a small rise in heating demand.

The extreme case with the lowest heating demand was when the windows were not opened in the building or the windows were opened very rarely. It is rather a theoretical case because in a building with natural ventilation people often open windows from spring to autumn. The lower the heating demand the higher the number of thermal discomfort hours, and the more insulated the building the higher discomfort. Each subsequent point in Figure 7 indicates a possible solution to improve comfort conditions. Using a large regime for window opening in appropriate periods caused a significant improvement of thermal comfort conditions. The H_{dis} for the best solutions due to the heating demand varied from 2699 to 5471 h of discomfort depending on the considered case (it was from 19% to 38% of the cumulative time spent in the rooms). This comparison best shows how building insulation and climate change affect the H_{dis}. While the differences between heating demand in optimal solutions were from 118 to 263 kWh, the highest value was only from 3% to 12% less than the lowest. Better conditions for the use of this cooling system occur in a less insulated building (this can be seen especially in warmer climates). For case 9 in the most favorable solution from the comfort point of view (minimum value of H_{dis}) 31 discomfort hours were calculated; for a passive standard building, it was 52 h (case 10). For cases 11 and 12, minimum value of H_{dis} increased, it was 203 and 433 h of discomfort, respectively. Compared to real climate 2018 it was six and half times greater (case 11) and more than eight times greater (case 12). Along with the warming of the climate, passive cooling of the building will be able to provide comfort for a smaller period per year.

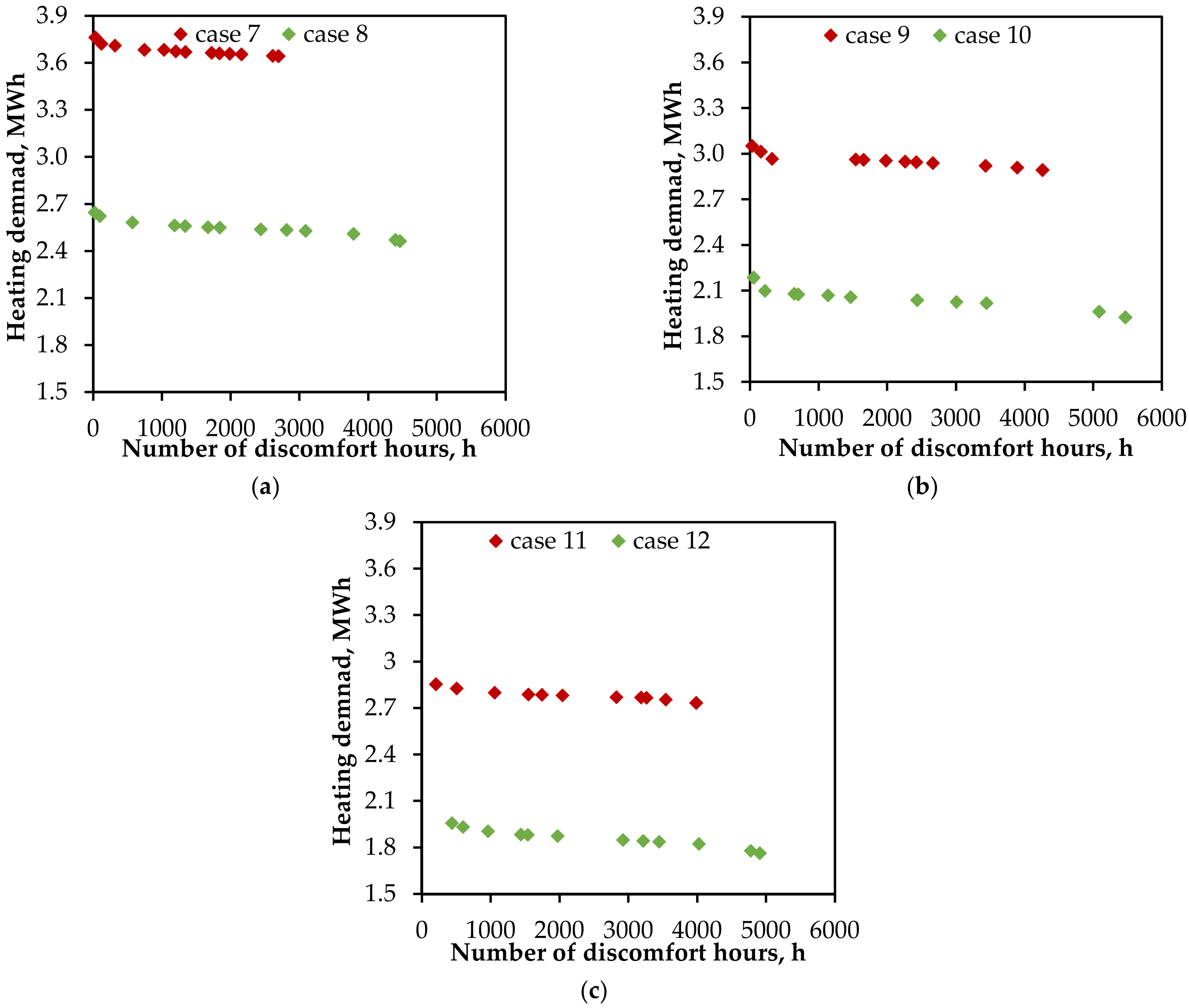


Figure 7. Pareto front: (**a**) TMY; (**b**) real 2018; (**c**) future 2050.

Table 5 presents the total number of discomfort hours for all rooms that were calculated for the optimal solution with the lowest H_{dis}. In this solution, only a few to several dozen hours of discomfort in the rooms was calculated. For all cases, the largest ratio of discomfort hours to all occupied hours was obtained for the bedroom, but it was still only 0.3% to 4.6% of the time. This room is located on the south side of the building and is a relatively small room occupied all nights by two persons. The best comfort conditions were obtained in children's room 2 (actually, there were comfortable environmental conditions all the time, for cases 7–10). The highest values of the H_{dis} were obtained for case 12, it was even 4.6% for bedroom. It could be the effect of the increase in exterior temperature and the high insulation of the external partitions. Most of the discomfort hours were calculated in the summer (Table 6), but the share of its time did not exceed 4.7% of all occupied hours in this period for cases with standard and real climates. This was possible owing to the appropriate window opening control and thus obtaining various values of air change rate in the rooms (Table 7). In this study, the high airtightness of the building was assumed. Due to this fact, the air change rate values for cases 1 to 6 were low (Table 7); the mean value was approximately 0.1 h^{-1}. In cases 7 to 12, the opening of the window had a huge impact on the calculated mean and maximum infiltration airflows. The window opening period varies depending on the optimal solution. To obtain the best thermal comfort conditions, the window opening area had to be larger and the opening time had to be longer, causing increased air exchange. It should also be emphasized that in the research it was a tilted window, not fully open, which is a common practice used in single-family houses in Poland—windows are often tilted throughout the summer season. Single-family houses are usually not on busy roads, so noise should not be a problem. The maximum instantaneous air change rates were not very high and amounted to 4–7 h^{-1}. Windows were opened mainly in summer; average air change rates did not exceed 1 h^{-1}. So, the risk of a draft was low. Nevertheless, this problem requires further investigation.

Table 5. The number of discomfort hours for the whole year and a percentage of discomfort hours in relation to the occupied hours in the rooms (in brackets).

Case	Living Room	Bedroom	Children's Room 1	Children's Room 2
7	2.5 (0.1%)	8.5 (0.3%)	19.8 (0.5%)	2.3 (0.1%)
8	0.0 (0.0%)	12.3 (0.4%)	8.8 (0.2%)	2.3 (0.1%)
9	2.0 (0.1%)	21.0 (0.7%)	5.5 (0.1%)	3.0 (0.1%)
10	6.5 (0.2%)	38.7 (1.2%)	4.0 (0.1%)	3.0 (0.1%)
11	2.8 (0.1%)	88.8 (2.8%)	53.3 (1.2%)	58.5 (1.4%)
12	102.8 (3.7%)	146.5 (4.6%)	91.5 (2.1%)	92.0 (2.2%)

Table 6. The number of discomfort hours for the summer period and a percentage of discomfort hours in relation to the occupied hours in the rooms (in brackets).

Case	Living Room	Bedroom	Children's Room 1	Children's Room 2
7	0.8 (0.1%)	7.8 (1.0%)	19.0 (1.8%)	1.5 (0.1%)
8	0.0 (0.0%)	11.3 (1.4%)	7.5 (0.7%)	2.3 (0.2%)
9	1.5 (0.2%)	20.0 (2.5%)	5.0 (0.5%)	2.0 (0.2%)
10	6.0 (0.9%)	37.5 (4.7%)	3.0 (0.3%)	2.5 (0.2%)
11	0.3 (0.0%)	88.8 (11.1%)	50.8 (4.7%)	57.8 (5.4%)
12	102 (14.6%)	145 (18.1%)	90.8 (8.4%)	92.8 (8.6%)

In the case of the future climate the value of H_{dis} for all occupied hours in the summer period increased significantly from 8.4% to even 18.1%. Such an increase in H_{dis} may be noticeable by the residents and significantly affect their dissatisfaction with the use of this passive cooling system.

The least favorable conditions occurred in the passive insulated building (case 12). In unheated months, the value of discomfort hours was higher than in other months. In this period, the external temperature was significantly higher. Due to this fact, thermal comfort could not be obtained all the time using only ventilative cooling. Figure 8 presents the variation of indoor air temperature. For the cases with the mechanical cooling system, the temperature values were consistent with the assumption, and the largest differences were 1 °C (case 3). However, in variants with ventilative cooling, the indoor temperature was often different by 1–2 °C from the assumed value. Indoor temperature values for cases with 2018 weather data were higher than for cases with standard weather data. In cases with future climate values of indoor temperature exceeded even 30 °C if ventilative cooling was used.

Table 7. Infiltration air change rate in the living room.

Case	Mean (Annual), h^{-1}	Max (Annual), h^{-1}	Mean (June–August), h^{-1}	Max (June–August), h^{-1}
1	0.1	0.2	0.1	0.1
2	0.1	0.2	0.1	0.1
3	0.1	0.2	0.1	0.1
4	0.1	0.2	0.1	0.1
5	0.1	0.2	0.1	0.1
6	0.1	0.2	0.1	0.1
7	0.2	5.0	0.4	4.1
8	0.3	5.2	0.6	4.2
9	0.3	4.0	0.5	3.0
10	0.5	7.3	0.9	5.7
11	0.3	4.9	0.5	3.6
12	0.4	3.8	0.7	3.1

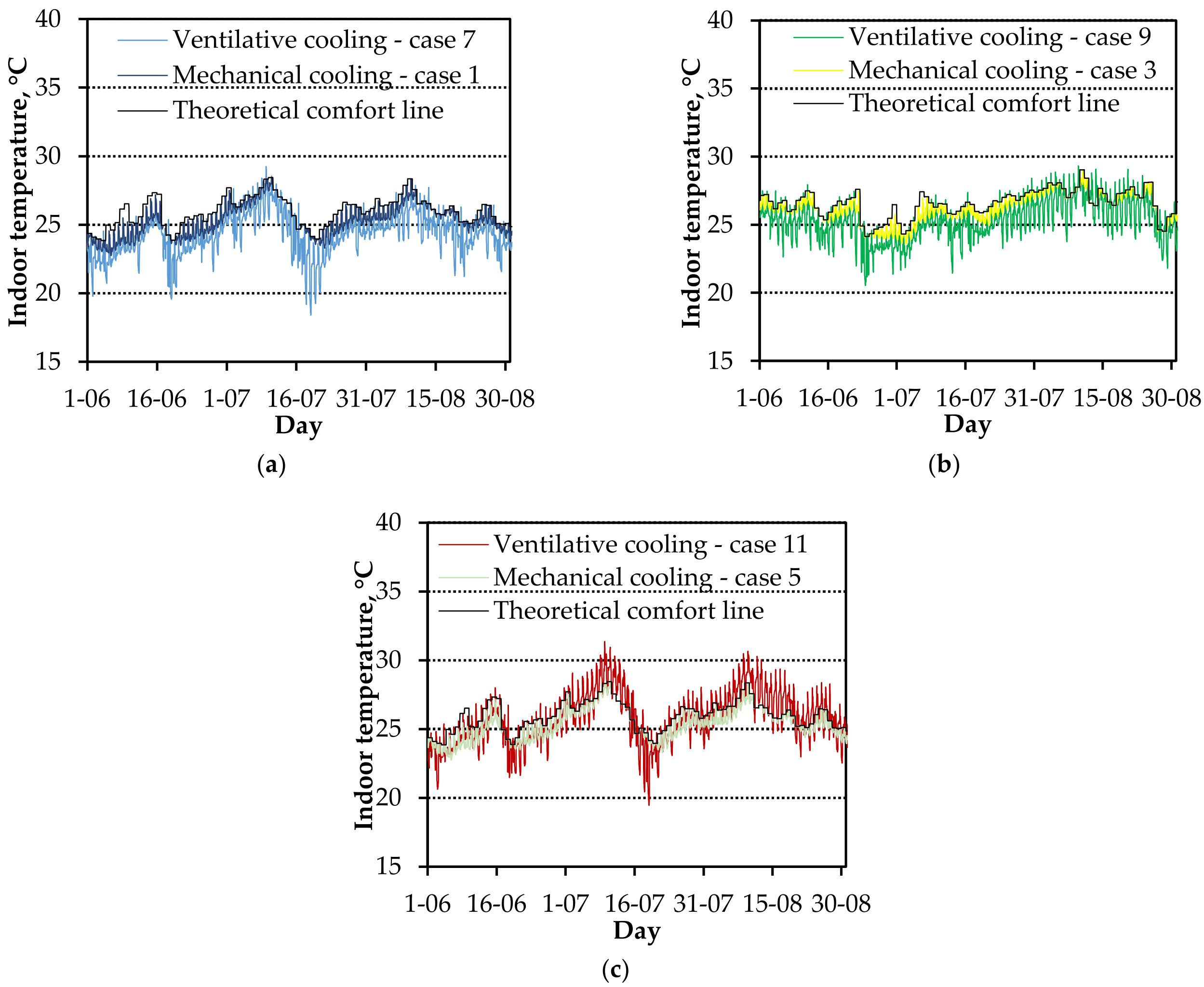
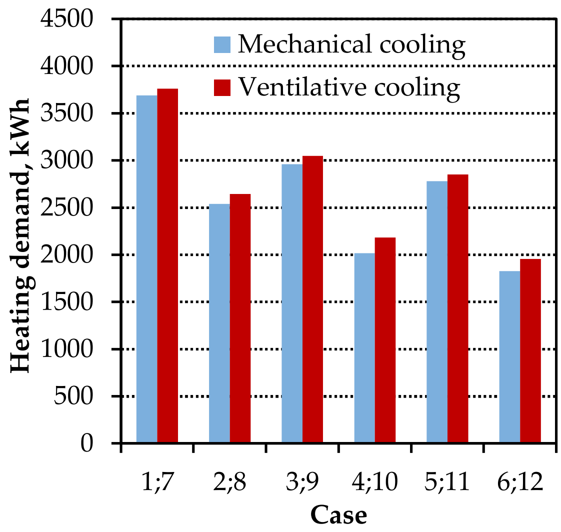
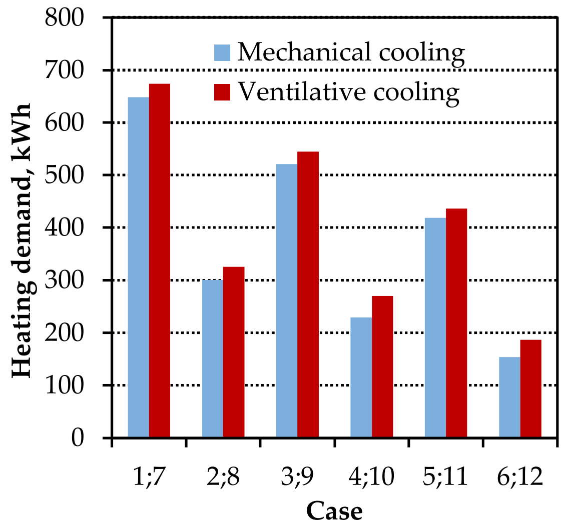


Figure 8. Variation of indoor air temperature in the living room (hourly step): (**a**) TMY weather data; (**b**) real weather data; (**c**) future weather data; theoretical comfort line is operative comfort temperature with −1.5 °C offset (see Section 2.6).

On the basis of the comparison of annual heating demand for mechanical cooling and ventilative cooling (Figure 9) the higher values of this parameter for ventilative cooling for all cases were noted, which are associated with greater heat demand for ventilation. However, the differences were not significant (from 2% to 8%).



(a)



(b)

Figure 9. The annual heating demand for cases with mechanical cooling and ventilate cooling: (**a**) the whole building, (**b**) living room.

In single-family houses heat and cold are usually produced by various sources, so the costs of energy consumption for heating and cooling were calculated and compared. It was assumed that a gas boiler was the heat source (the most popular solution in Poland) and electric split air conditioners were the source for cooling. The efficiency of the systems was assumed in accordance with the Polish standard [51]. The market prices were used to assess the heating and cooling costs as follows: 0.12 EUR/kWh for electricity and 0.04 EUR/kWh for gas [50]. Results are presented in Table 8. The costs of heating a building with ventilative cooling were higher from 2% to 8% depending on the case. However, considering both annual heating and cooling costs, the total costs were higher for buildings with mechanical cooling (from 5% to even 21% depending on the case).

Table 8. Annual costs for heating and cooling.

Case	Heating Costs, EUR	Cooling Costs, EUR	Total Costs, EUR
1	195	13	208
2	134	24	158
3	156	23	179
4	107	37	143
5	147	22	168
6	96	34	130
7	199	0	199
8	140	0	140
9	161	0	161
10	115	0	115
11	151	0	151
12	103	0	103

4. Conclusions

Based on the simulations carried out, it was found that:

- With the current climatic conditions, in Poland (Central Europe, the Baltic Sea region) ventilative cooling is a good solution. It causes a sufficient reduction of energy demand to provide thermal comfort conditions in dwellings. Therefore, it is a lower-cost option than mechanical cooling. Moreover, it is environmentally friendly because it does not contribute to CO_2 emissions to the atmosphere. Moreover, using only ventilative cooling can cause discomfort during only no more than 2% of the occupied time in rooms in the summer period. To obtain the lowest number of hours of discomfort, especially in summer, the air exchange rate significantly increased, up to 7 h^{-1}. However, these cases are extreme. On the other hand, ventilative cooling has greater inertia of work, and it is not possible to reach the required internal temperature as quickly as in the case of mechanical cooling;

- In the future, global warming may render the ventilative cooling itself, without mechanical cooling ineffective. Especially in summer, residents may complain about excessively high indoor temperatures. In the most pessimistic variant, for a highly sunny room, the number of discomfort hours may be as much as 20% of the occupied time. A compromise solution would be to combine ventilative cooling with mechanical cooling. Mechanical cooling would only be turned on if ventilative cooling would not be able to provide comfort conditions, so that the costs of energy consumption would be as low as possible. However, such a solution would involve the introduction of the control system;
- Typical meteorological data, commonly use in energy analyses, are not actual. The results of 30-years-old data differed from current data. During several decades the climate has warmed up considerably. Therefore, particular attention should be given to the selection of climate data for building performance simulations. The obtained differences in the calculated heating demand between standard climate data and real data can reach even 8 kWh/m^2;
- Very well-insulated buildings have more cooling demand however taking into account the sum of cooling and heating energy consumption, they generate lower operating costs compared to standard single-family houses; but in opposite in well-insulated houses without mechanical cooling thermal comfort conditions are significantly worse in current and future warmer climate. The use of insulation of passive building standard, causes greater overheating of the building, hence the higher the number of discomfort hours.

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