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# Maintaining Comfortable Summertime Indoor Temperatures by Means of Passive Design Measures to Mitigate the Urban Heat Island Effect—A Sensitivity Analysis for Residential Buildings in the City of Vienna

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Received: 31 May 2018; Accepted: 31 July 2018; Published: 8 August 2018

**Abstract:** The waste heat generated from the use of air conditioning systems in cities significantly contributes to the urban heat island effect (UHI) during the summer months. Thus, one of the key measures to mitigate this effect is to limit the use of active cooling systems. In the city of Vienna, air conditioning units are common in nonresidential buildings, but have so far been much less installed in residential buildings. This is mainly due to the fact that the Viennese summertime climate is still considered to be relatively comfortable and planning guidelines related to energy efficiency are already strict, resulting in high-quality buildings in regard to thermal performance. However, during the last decade, an increase in summertime temperatures and so called "tropical nights" has been recorded in Vienna and subsequently the postconstruction installation of air conditioning systems in residential buildings has significantly increased. In a study undertaken for the City of Vienna, a series of passive design measures have been simulated with current and future climate scenarios in order to determine the most effective combination of architecturally driven actions to avoid the use of air conditioning systems in residential buildings whilst maintaining comfortable indoor temperatures.

**Keywords:** passive design measures; residential buildings; summertime overheating; indoor thermal comfort; passive cooling; urban heat island effect (UHI)

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## 1. Introduction

The aim of the "Paris Agreement" [1] is to limit the global warming caused by greenhouse gas emissions to well below 2 °C compared to preindustrial times. Summertime overheating is becoming an increasing challenge in this context as climatic conditions are changing and temperatures are steadily on the rise. Especially in densely populated urban areas, the effects of heavily sealed surfaces and built-up areas can be mitigated by microclimatic measures such as green spaces, water areas, and natural ventilation. Air conditioning systems further add to the urban heat island effect (UHI) as the waste heat generated by these systems increases local temperatures in tightly built-up areas. The mostly electrically powered air conditioning systems also contribute to the use of fossil fuels as power generation only slowly shifts towards renewable energy systems. The topic of cooling becomes of increasing importance for the overall energy demand. In Europe, the cooling energy demand is steadily increasing. For 2020, cooling energy demand in the EU-15 was projected to be 115,000 GWh/a, more than 4.5 times higher than in 1990 [2]. In Austria, the electricity consumption for air conditioning and mechanical ventilation increased in the period 1995–2012 from 27.1 GWh/a to 210.3 GWh/a [3]. This is partly due to population growth. However, the purchase of electrically operated small air conditioning systems has increased in recent years. The share of electricity consumed by private air conditioning systems in 2012 amounted to 13% of the electricity consumed per year for air conditioning and mechanical ventilation in Vienna [3].

In Vienna, planning guidelines in regard to thermal performance area already relatively strict, following the Energy Performance of Buildings Directive [4] and subsequently the respective Austrian guidelines [5]. However, there are several aspects to consider in the increasing number of highly insulated buildings. Several studies have shown that the tendency of buildings to overheat during the summer has become a more common problem in the last decade [6]. Even buildings with a highly insulated building shell can have uncomfortable indoor temperatures during the summer. This effect is increased when there is not enough thermal mass to balance the temperature peaks [7]. On the one hand, the high quality of thermal insulation of the opaque building shell and the lower energy transmittance of the transparent envelopes reduce the solar heat gains into the building. On the other hand, heat generated in the building can only slowly dissipate through the building shell. Therefore, the avoidance of direct solar radiation in the summer by means of efficient sun protection and the reduction of internal gains, as well as the possibility of heat efficiently dissipating out of the building, are key factors in order to reduce or completely avoid summer overheating in buildings. Jana et al. [8] have shown that the implementation of effective shading during the day in combination with increased night ventilation proves to be a viable strategy to avoid summertime overheating. In addition, there are some studies addressing future climate scenarios and how they affect the summertime performance of buildings. Gupta et al. [9] have shown that net zero energy dwellings show a projected overheating risk for 2050 climate scenarios. Especially for highly insulated buildings, such as passive houses, additional measures must be taken in order to mitigate the adverse overheating effects of climate change [10]. The urban heat island (UHI) effect similarly impacts the thermal performance of buildings; however, in a study carried out by Oikonomou et al. [11], the results show that the thermal quality of the dwelling has a far greater impact on indoor temperatures than the UHI.

These aspects should be taken into account both for refurbishment as well as for new buildings. In addition, the user behavior needs to be considered, as the efficiency of passive measures heavily relies on the actions of the building user. Therefore, passive cooling strategies and design measures, such as orientation of the building, glazing, shading, and thermal mass, as well as nighttime ventilation, should be exploited in order to reduce or ideally avoid air conditioning systems in residential buildings. These passive design measures have the benefit of being both cost-effective, when considered at an early planning stage, as well as highly effective in terms of energy efficiency.

The Austrian Building Regulation already includes a framework for buildings with a high thermal performance, which are being geared towards minimal heat loss during the colder months. Studies addressing the summertime performance of these high-performance buildings under predicted warmer conditions for Vienna are currently still missing. Climate studies for the City of Vienna show an increase in summertime temperatures as outlined in Section 1.2. Currently, most residential buildings in Vienna are still designed without air conditioning systems; however, it is questionable as to whether the current planning approach adequately covers the requirements of future climate conditions. Thus, the research questions addressed in this study focuses on two main aspects: (1) Does the current planning approach in residential buildings allow for comfortable indoor temperatures, even when summertime temperatures will be increasing over time? (2) Which combination of passive design measures is most effective to address potential future summertime overheating?

In the described study, undertaken for the City of Vienna, the effects of various passive design measures have been simulated with current and predicted climates in order to assess the summertime overheating reduction potential on indoor temperatures. The goal of the study was to quantify the effect of various architecturally driven measures. These passive measures are evaluated in different combinations and compared by means of a sensitivity analysis. The study aims at providing decision-making guidance to developers and planners in order to choose the most suitable combination of passive measures for the application in large-scale residential buildings.

### 1.1. Urban Framework Conditions Related to Buildings

The climate is one of the most significant factors affecting the thermal performance of buildings, as we have only limited immediate influence on it. Buildings should provide adequate protection against potentially uncomfortable climatic conditions over the course of the year, which means they have to fulfill the purpose of shelter against cold as well as against overheating. The design and construction typologies of specific regions have adapted over hundreds of years to the local climatic conditions. As a result, local architecture initially was a result of the regional climate. However, the consequences of climate change are already noticeable and local conditions are changing, as demonstrated in several climate studies [12]. In densely populated areas, the immediate effects of changing climatic conditions are even more pronounced. Therefore, care must be taken in the design to adapt buildings to rising summertime temperatures, increasing frequency of high temperatures, limited decrease of temperatures overnight, and the urban heat island effect.

In this context, the urban heat island effect describes the phenomenon where temperatures in urban areas exceed those in rural areas. In comparison to the rural environment, other preconditions exist in the city, which can be mainly summarized as follows: lower evaporative cooling due to sealed surfaces, reduced air circulation and lower wind speeds, larger heat-absorbing surfaces, inadequate shading of buildings due to lack of vegetation, diffused solar radiation due to reflection from other buildings as well as waste heat from air conditioning systems, industrial processes and traffic [13].

For Vienna, a study has been undertaken to predict the number of summer days over the next two decades. The future climate scenarios of the study are based on regional climate models and simulations. A moderate increase (up to 25 days per year) of summer days is expected for the period 2021–2050. For the period 2071–2100, a strong increase (20–50 days per year) is expected. Within this context, summer days were defined as days when the outside air temperature exceeds 25 °C [14].

### 1.2. Thermal Comfort and the Effects of Increased Indoor Temperatures

The individual thermal comfort depends mostly on the thermal equilibrium (heat balance) of the whole body. This balance is strongly influenced by the physiology, as well as physical activity and clothing, in addition to climate parameters, such as air temperature, mean radiation temperature, air velocity, and humidity. The ISO 7730:2005 [15] norm based on studies by Fanger [16] presents methods for predicting the general thermal sensation and degree of discomfort (thermal dissatisfaction) of people exposed to moderate thermal environments. It enables the analytical determination and interpretation of thermal comfort using the calculation of PMV (predicted mean vote), PPD (predicted percentage of dissatisfied), and local thermal comfort.

The Czech meteorologist Jan Kysely defined in a simplified method the "Kysely Day", or the heat wave or heat period. The term "heat period" was defined by Kysely as a " ... *period of time when the maximum temperature exceeds 30 °C for at least 3 consecutive days and lasts as long as the maximum mean temperature during the entire period remains above 30 °C and never falls below a temperature of 25 °C* ... " [17]. This definition allows the comparison of the heat waves based on historical data [18].

In Figure 1, the number of "very hot days" in Vienna for the period from 1954 to 2016 is shown.

It can be seen that there have been more and more heat spells over the last decades and the trend is rising. In addition to this trend, the rising night temperatures in the summer are to be considered. For Vienna, an increase of 0.2 °C per decade was observed for the period 1948–2002 [18]. Especially in inner-city areas and due to the heat island effects, a further increase in nighttime temperatures is to be expected in the future. Nighttime temperatures also have an effect on human health, as comfortable temperatures are prerequisites for recovery during sleep. In a previous study, a relationship between high night temperatures and increased mortality rates was observed for Vienna [19]. The term "warm night" is defined here as the sequence of day–night–day where both days $T_{max} \geq 30$ °C and the night $T_{min} \geq 18$ °C, and shows the greatest risk to human health.

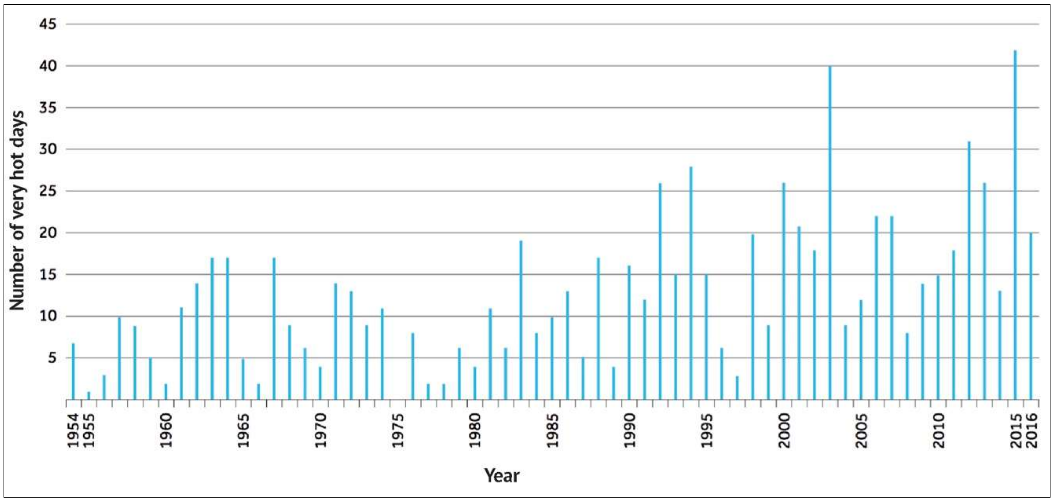


**Figure 1.** Number of "very hot days" (days with equal or higher temperatures than 30 °C) in Vienna in the period 1954–2016; graphic based on data from ZAMG (Zentralanstalt für Meteorologie und Geodynamik) [18].

### *1.3. Passive Design Measures for Maintaining Comfortable Summertime Indoor Temperatures*

The construction technology in buildings has changed gradually over the last decades, and the quality of the building envelope is continuously improving. The increasing demands on the thermal quality of the building envelope leads to an increased internal comfort with a simultaneous reduction of the total energy consumption. To minimize heat losses in winter, the building envelope is usually built with a continuous insulation layer. In summer, this means that the heat generated in the building can dissipate less quickly through the building shell. As a result, additional measures to reduce external heat gain (e.g., by means of shading) and to dissipate the heat generated in the building (e.g., by night ventilation) are of great importance. In practice, these additional measures are often omitted due to cost constraints. However, this can have adverse effects, where the user opts for the installation of a simple air conditioning unit as a cost-effective action to balance the omission of more effective architectural measures. Within this context, the user has a great influence on the indoor climate. By controlling shading devices, ventilation, and internal loads, the functioning of passive design measures depends heavily on the user. It is therefore crucial to make the user aware that his behavior is a deciding factor for a good indoor climate.

As the human comfort in buildings depends strongly on the actual internal climatic frameworks conditions, these in turn are heavily influenced by factors relating to the construction and architecture of the built environment. In this context, it is important to implement measures to reduce the summer temperatures in the buildings by means of passive design measures. In preparation for the sensitivity analysis, several architecturally relevant measures that have a high impact on the summertime behavior of buildings have been selected and are briefly described in the following subsections.

#### 1.3.1. Shading

Shading systems are crucial elements for supporting internal thermal comfort. The control is usually manual, with automatic control systems being used for larger residential buildings. On a general level, sun protection systems can be mainly divided into three categories: (1) External shading: These systems have the highest impact on the indoor climate, as the solar radiation can be effectively reflected from the external surfaces and heat gains in the building can be reduced. These systems should be wind-and weather-resistant and should require as little maintenance as possible. (2) Intermediate shading: An intermediate sunscreen is better suited than an internal sunscreen, but worse than an external sunscreen. The heat protection glazing (inside) reduces the radiation from entering the building, and the single glazing (outside) offers wind protection and can potentially fulfill requirements on listed buildings. (3) Internal shading: These systems have a much lower sun protection effect as the solar radiation has already passed the thermal boundary of the glazing.

#### 1.3.2. Thermal Mass

The heat storage capacity (Q) indicates how much heat a material can store and is determined by the density, thickness, and specific heat storage capacity of a material. The thermal mass of a building is decisive for the inertia as the higher the storage capacity, the more heat it can absorb without the temperature being changed significantly. A building with a heavyweight construction has longer reaction times on temperature changes and can therefore reduce the temperature peaks. However, it is always necessary to dissipate the stored heat at night, when the temperatures are cooler. A high thermal mass can have a negative effect if night ventilation is not planned appropriately or cannot be used due to high night temperatures. To increase the effect, thermal mass activation systems can be applied for heating and cooling purposes.

A lightweight construction reacts faster to temperature changes than a heavyweight construction. It thus has lower reaction times and heats up faster, and as a result the high temperatures cannot be reduced so easily, which recent studies with lightweight timber constructions have shown [20]. Rapid cooling of the component due to lower night temperatures thus cannot be expected with current insulation standards [21]. If a lightweight construction is chosen, phase change materials (PCMs) can counterbalance the limited storage capacity as the heat stored in the form of latent heat. Care must however be taken that the heat can be dissipated at night, when cooler temperatures prevail. Especially with superinsulating walls, PCMs must be planned carefully in order to exploit their beneficial effect [22].

#### 1.3.3. Orientation

The orientation of the building and subsequently of the opaque and transparent elements is a key aspect in supporting comfortable temperatures in the interior. In densely populated urban areas, while there is often no choice to turn the buildings to optimize the orientation, various façade elements can be effectively applied. Solar radiation can be best controlled in south-facing windows, as horizontal elements provide highly effective protection. East- and west-facing façades are consequently the most critical for overheating, and effective shading must be provided for low-angled sun. The orientation is one of the aspects which is best taken into account at the urban planning level.

#### 1.3.4. Ventilation

The cooling potential with natural ventilation depends on the temperature difference, airflow rate, and the storage capacity of the building. The required temperature difference is usually only predominant during the night. A high thermal mass of the building allows a reduction of the temperature peaks during the day, provided that the stored heat can be dissipated during the night (see Section 1.3.2). Conversely, night ventilation has little influence on the daily indoor temperature without thermal mass. Even only with natural ventilation, air exchange rates of over 10 $h^{-1}$ can be achieved; however, a minimum temperature difference of 2 K between the inside and outside temperature is necessary. In residential buildings, the natural ventilation is usually controlled by the user; however, there are automatic control systems on the market that optimally control the opening of the windows depending on the outside temperature and weather conditions. In a study which considered the potential for cooling by means of natural ventilation for different buildings types, 20% of existing and 50% of new low-energy buildings were considered to be able to be effectively cooled by natural means alone [23].

#### 1.3.5. Greening of Building Surfaces

Green roofs and façades can significantly contribute to the reduction of the urban heat island effect. In Vienna, only 2–3% of the roofs are currently green roofs, whereas about 45% of roof areas could be landscaped and could thus contribute to the reduction of the heat island effect with an estimated reduction of 1 to 2 K in the city [24]. Greening the buildings also protects the construction from solar radiation and reduces the indoor temperatures. Green roofs reach surface temperatures of about 20–25 °C, compared to bitumen and gravel roofs with an average surface temperature of above 80 °C [25]. When looking at future climate scenarios, retrofitting roofs with green roofs can contribute to easing the effect of summertime overheating, as shown in [26]. In addition to the evaporative cooling effect caused by greened surfaces, plants support sound absorption and dust binding. Nevertheless, care should be taken to ensure that the passive use of solar energy in winter is not hindered; therefore, climbing plants are recommended for south-facing walls, which shed their foliage in autumn [27].

## 2. Methodology

The aim of the sensitivity analysis carried out in the context of the study was to quantifiably assess which combination of measures could have a positive or negative effect on the indoor room temperatures and subsequently on the thermal comfort of the occupants. In order to allow for comparable results, a highly simplified one-room model has been chosen. Based on a thermal building simulation, various passive measures to avoid summer overheating are analyzed and compared. The simulation is performed with the software package TRNSYS (TRaNsient SYstems Simulation, The University of Wisconsin, USA), a simulation program that analyzes the dynamic thermal behavior of buildings [28]. Using a one-zone model, the effects of different measures are evaluated and presented. The model is a 20 $m^2$ room with a ceiling height of 2.5 m and 30% window area on the south façade. This corresponds to a typical living room in residential buildings. Since the one-room model approach considers a room with only one façade, cross ventilation, which can be far more effective than ventilation from one side only, has not been taken into account. However, in multistorey residential buildings, apartments usually face only one orientation due to single-tier access on two sides. Thus, the model represents the worst-case scenario for natural ventilation. Similarly, the south orientation has been chosen as the worst-case scenario for overheating. Even though west and east orientations can have higher solar gains during shoulder seasons, highest outdoor temperatures during the summer months in combination with a south-facing façade deliver the highest internal solar gains, when unshaded.

The model is greatly simplified to focus on the impact of different passive design measures only. Measures that have a significant influence on summer overheating are analyzed and the impact of the individual measures and combinations of measures is quantitatively presented. Within the simulation, a number of assumptions have been made, which are described in the boundary conditions in Table 1.

**Table 1.** Boundary conditions for the thermal dynamic simulation.

| **Boundary Conditions** | |
|---|---|
| Model dimensions | 5.0 m × 2.5 m × 4.0 m (length × height × width) |
| Location | Vienna, Austria |
| Proportion of window-to-wall ratio | 30% of the façade |
| Window frame | Uf = 1.1 W/($m^2$K), 25% of the window area |
| Exterior walls U-values | U = 0.21 W/($m^2$K) |
| Internal loads | According to ÖNORM B 8110-5 [29] |
| Ventilation | According to ÖNORM B 8110-5 [29] |

For the simulation, two different climate scenarios created from the program Meteonorm [30] are used. The climate data for the current climate scenario is based on long-term measurements (1991–2010) for the location Wien Hohe Warte. The data for the future climate is developed by Meteonorm and is a prediction for the year 2050 for the location of Vienna. Table 2 shows the monthly mean temperature and the global radiation for the climate scenarios used for the subsequent thermal dynamic simulations.

**Table 2.** Climatic data for the current and future climate scenario.

| Climate Data | | |
|---|---|---|
| | **Current Climate Scenario** | **Future Climate Scenario** |
| Maximum temperature | 33.75 °C | 36.50 °C |
| Monthly mean temperature in July | 21.10 °C | 23.70 °C |
| Median global radiation in July | 240 W/m$^2$ | 267 W/m$^2$ |

The mean temperature for the future climate scenario in July is 2.6 °C above the current climate scenario, and therefore, fewer hours where night cooling can take place are possible (see Figure 2). Also, the global radiation in the summer month is about 10% higher in the future climate scenario than in the current climate scenario (see Figure 3).

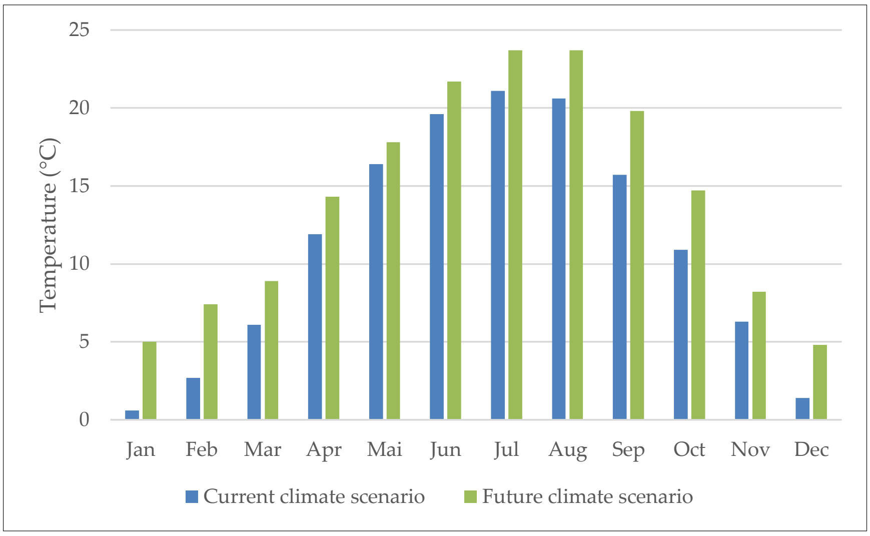


**Figure 2.** Monthly mean temperature based on long-term measurements (1991–2010) for the location Wien Hohe Warte [30].

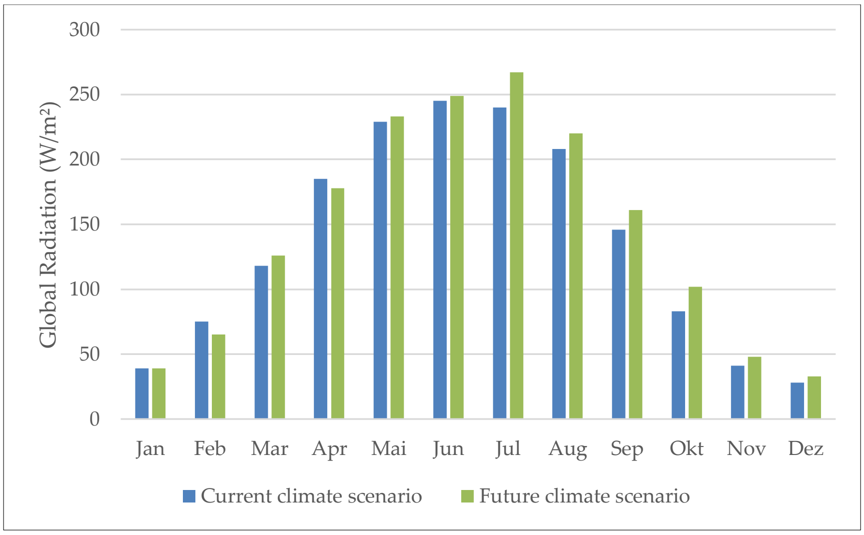


**Figure 3.** Monthly global radiation based on long-term measurements (1991–2010) for the location Wien Hohe Warte [30].

The boundary conditions and scenarios are based on a thesis, which has been carried out as a basis for this study. The thesis is focused on the topic of summertime overheating on large-scale housing units and defines various framework and boundary conditions which are considered to be most effective to reduce summertime overheating [31]. The variable boundary conditions and scenarios which had the most impact on thermal comfort during the summer are summarized in Table 3. For the different variants, the thermal mass, the sun protection, and the night ventilation are combined in different combinations.

In Table 3, the different variants each have a specific abbreviation to be referred to in this paper. V x.n, where *x* (1–12) indicates the variants for the different scenarios and n indicates the current climate scenario (*n* = 1) or, alternatively, the future climate scenario (*n* = 2). For the variants V 1.n to V 6.n, three different wall constructions are combined with two types of sun protection, whereas the night ventilation (tilted windows) remains the same. For the variants V 7.n to V 12.n, two types of sun protection are combined with three different night ventilation types, whereas the thermal mass (heavyweight construction) remains the same. In order to provide a distinct overview, where only one parameter is altered at a time, the scenarios are simulated in groups. Thus, scenarios V 5.n are equal to V 8.1 and scenarios V 6.n are equal to V 11.n.

The wall constructions differ in their storage capacity and their material layers as well as their thickness, however the U-value for the overall wall construction remains the same (U = 0.21 W/(m$^2$K)) for all three construction types. The shading factor (Fc) is Fc = 0.3 for the internal sun protection (representing, e.g., an internal blind or curtain) and Fc = 0.7 for the external sun protection (representing, e.g., an external blind or shutter). The three types of night ventilation differ in their air change rate per hour (ACPH) and are ACPH = 0 for no ventilation, ACPH = 2 for tilted windows, and ACPH = 8 for fully open windows during the night, following the principles as described in the respective norms [32]. All variants use the same double-glazing window type with a U-value of 1.10 W/(m$^2$K) and a g-value of 62%.

The simulation is performed for one year. For the results, the focus is on a five-day period in July (18th to 22nd July), which reflects a typical hottest Austrian summer period, based on the long-term measurements from 1991–2010.

**Table 3.** Examined variants and boundary conditions for the current and future climate scenarios.

| Future climate scenario | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Thermal mass | | | Sun protection | | Night ventilation | | | |
| | Variants | Lightweight construction | Medium construction | Heavyweight construction | Internal sun protection | External sun protection | No ventilation | Tilted windows | Fully Opened windows | Double glazing |
| | | Wood construction | < | Concrete construction | Fc = 0.3 | Fc = 0.7 | ACPH = 0 (1/h) | ACPH = 2 (1/h) | ACPH = 8 (1/h) | U = 1.10 W/(m$^2$K), g = 0.62 |
| Combinations of thermal mass and sun protection | V 1.2 | x | | | x | | | x | | x |
| | V 2.2 | x | | | | x | | x | | x |
| | V 3.2 | | x | | x | | | x | | x |
| | V 4.2 | | x | | | x | | x | | x |
| | V 5.2 | | | x | x | | | x | | x |
| | V 6.2 | | | x | | x | | x | | x |
| Combinations of sun protection and ventilation | V 7.2 | | | x | x | | x | | | x |
| | V 8.2 | | | x | x | | | x | | x |
| | V 9.2 | | | x | x | | | | x | x |
| | V 10.2 | | | x | | x | x | | | x |
| | V 11.2 | | | x | | x | | x | | x |
| | V 12.2 | | | x | | x | | | x | x |

## 3. Results

Based on the TRNSYS simulation, the operative temperature in the room is evaluated without considering a cooling capacity in the building. This means that only the passive design measures are considered within the calculations. Within the analysis of a whole year, the temperatures during a five-day period are analyzed in detail. The results are divided into the current climate scenario (see

Section 3.1) and the future climate scenario (see Section 3.2). The limiting temperature for acceptable thermal comfort in Austria for living rooms is defined at 27° [32]). This temperature is shown in the Figures to indicate which variants still achieve the thermal comfort requirements.

### *3.1. Results for the Current Climate Scenario*

#### 3.1.1. Combinations of Thermal Mass and Sun Protection

In these variants (V 1.1–V 6.1), the influence of the thermal mass and the sun protection is examined. Three wall materials (wood, brick, and concrete construction) and two sun protection solutions (internal and external sun protection) were defined and analyzed. The detailed results are shown in Figure 4, with the key findings:

- In the variants with an internal sun protection (V 1.1, V 3.1, and V 5.1), the room temperature is almost always above the outside temperature. Despite the high thermal mass in V 5.1, no comfortable temperature can be achieved because the solar gains through the windows are too high to be compensated by the thermal mass of the concrete.
- The variants with a wooden construction (V 1.1 and V 2.1) have the highest temperature peaks. A means of reducing these peaks would be to add more thermal mass (brick, concrete) to the construction. This shows that for thermal comfort during the summer, the thermal mass of a building plays an important role.
- An external sun protection (in V 2.1, V 4.1, and V 6.1) is the most effective measure. These variants all have significantly lower operative internal temperatures, with the difference between wood (V 2.1) and concrete (V 6.1) temperatures being only about 2 K. In conclusion, one can remark that the influence of the thermal mass decreases with the application of external sun protection.

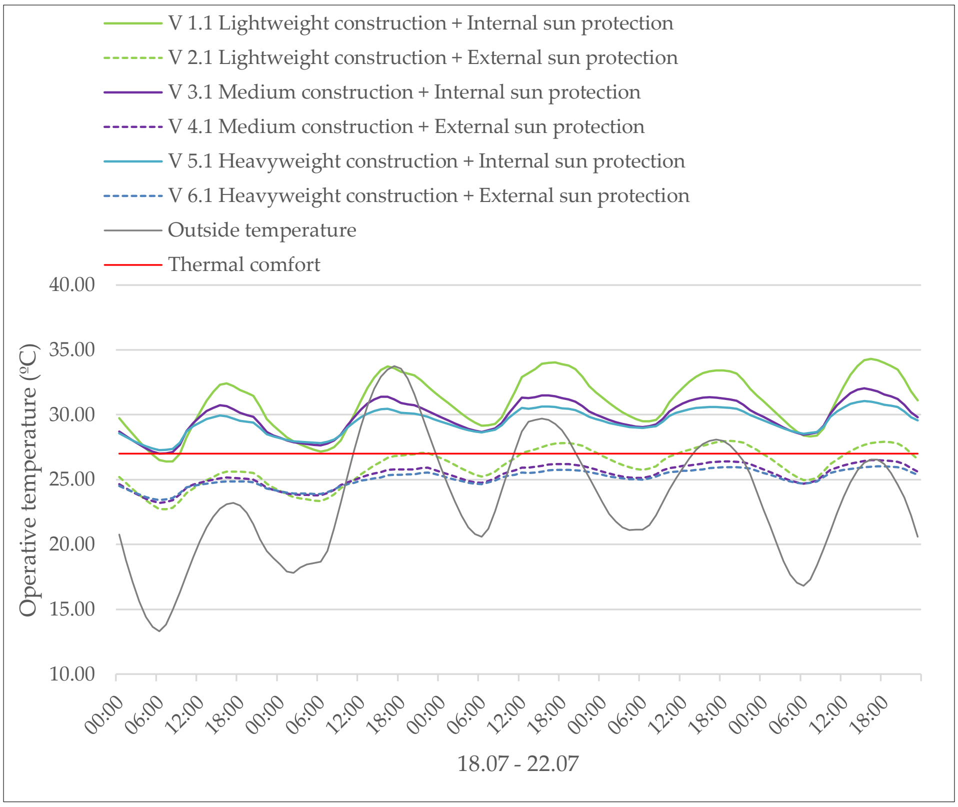


**Figure 4.** Current climate scenario—Variants of thermal mass and sun protection, based on [33].

### 3.1.2. Combinations of Sun Protection and Ventilation

In these variants (V 7.1–V 12.1), the influence of sun protection and night ventilation is examined. Internal and external sun protection is combined with no ventilation, tilted windows, and fully opened windows.

The detailed results are shown in Figure 5. The key findings are:

- Night ventilation (V 9.1 and V 12.1) is a very effective measure. With fully opened windows (ACPH = 8), the room temperature during the day can be kept below the outside temperature for both sun protection systems.
- At lower air change rates (ACPH = 2), the sun protection is crucial to provide enough thermal comfort. A difference of 5 K can be recognized between the variant with external and internal sun protection.
- During a heat wave, external sun protection is not enough to reduce the internal room temperature. Some kind of night ventilation is necessary to maintain thermal comfort.

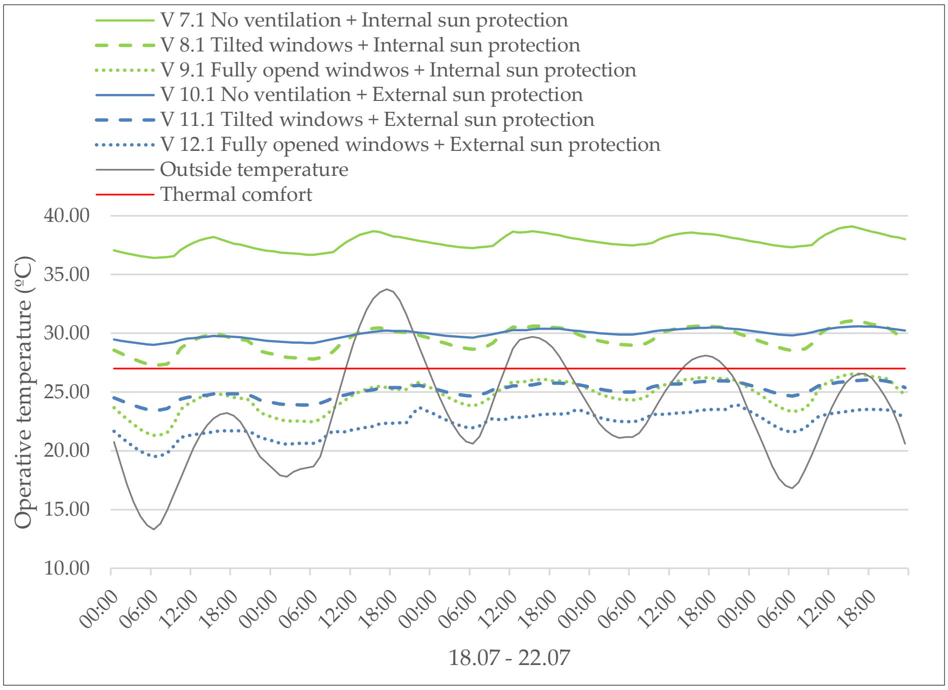


**Figure 5.** Current climate scenario—Variants of sun protection and night ventilation, based on [33].

## 3.2. Results for the Future Climate Scenario

For the future climate scenario as shown in Figures 6 and 7, it can be seen that the outside temperature remains consistently high and does not fall below 20 °C during the heat period. Effective cooling is therefore hardly possible even during the night.

In general, the following results can be seen:

- In all scenarios, a similar temperature profile can be seen as compared to the current climate scenario.
- Due to the increasing outside temperatures, these profiles shift 2–3 K upwards in the scale.
- The best solution is to combine a high thermal mass construction, an external sun protection, and fully opened windows during the night (V 12.2).

Not every variant with external sun protection manages to reach the requirements of adequate thermal comfort. This means that the room temperature can only be maintained below 27 °C by applying a combination of measures.

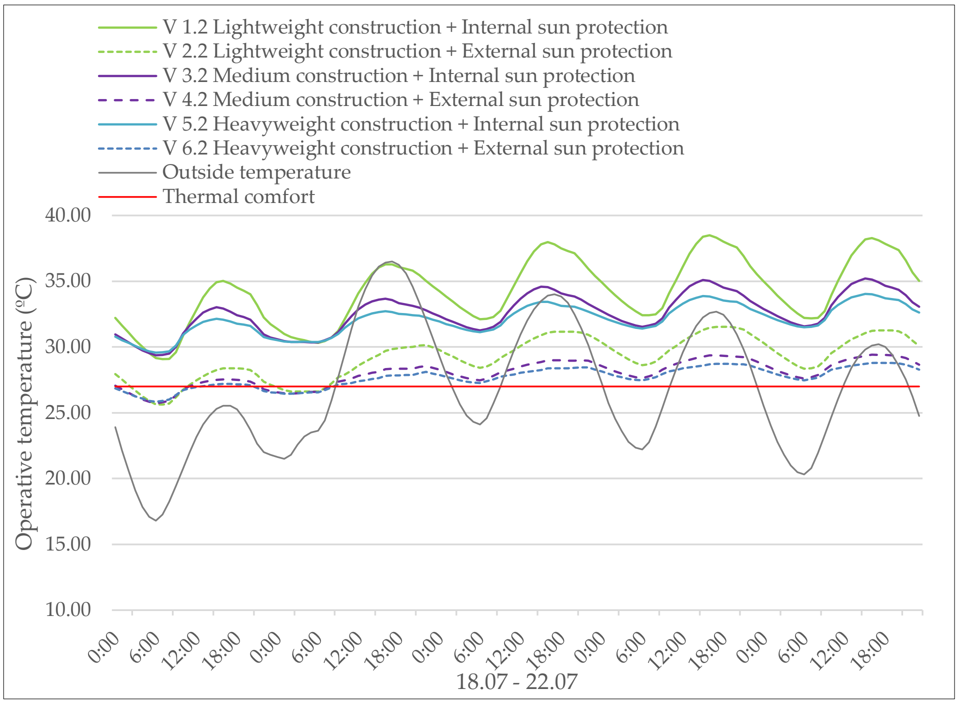


**Figure 6.** Future climate scenario—Variants of thermal mass and sun protection, based on [33].


**Figure 7.** Future climate scenario—Variants of sun protection and night ventilation, based on [33].

### 3.3. Cooling Demand for the Current Climate Scenario

For the current climate scenario, in addition to the temperatures as shown above, the cooling energy demand is evaluated for the exemplary room. An unlimited cooling capacity with a fixed nominal air temperature of 26 °C is assumed. When the room temperature exceeds 26 °C, the cooling system is turned on, regardless of the time of the day and the presence of persons. It is therefore only a theoretical cooling energy demand, which allows a comparison of the different variants. Figure 8 shows the cooling energy demand of each examined variant for the current climate scenario. The calculation of the cooling energy demand confirms the results for the operative temperature as described above.

- The variants with external sun protection measures have a significantly lower energy demand because the solar gains through the windows are lower.
- The use of air conditioning in residential buildings can be avoided by combining an external sun protection for south-oriented windows with night ventilation and high thermal mass.
- The cooling energy demand is, for some variants, higher than the heating energy demand during the winter.

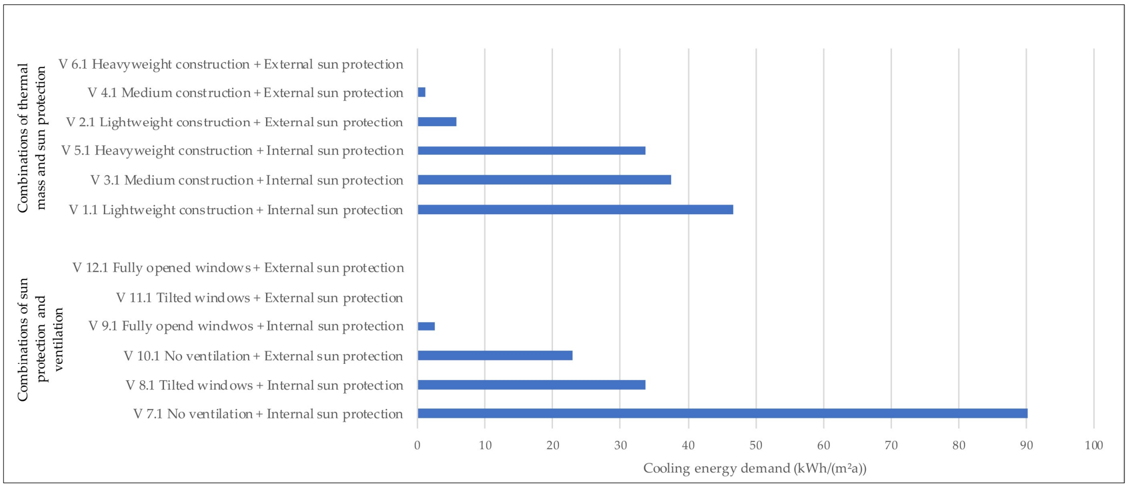


**Figure 8.** Current climate scenario—Cooling energy demand, based on [33].

### 3.4. Cooling Demand for the Future Climate Scenario

As for the future climate scenario, the theoretical cooling energy demand is evaluated for the exemplary room. Figure 9 shows that in the future climate scenario, each of the examined variants has a cooling energy demand, mainly because the temperature during the night is higher and therefore night ventilation is not as effective. The key findings are:

- Although night ventilation is not as effective as in the current climate scenario, it is still critical for reducing the cooling energy demand because it is the most effective way to reduce the indoor temperature.
- Buildings benefit from massive construction and the ability to compensate periods of high temperatures.
- External sun protection can reduce the cooling energy demand by 40% to more than 80%.
- Active cooling of the buildings will be required due to high inside temperatures in the future, and the cooling energy demand for some variants will be higher than their heating energy demand during the winter.

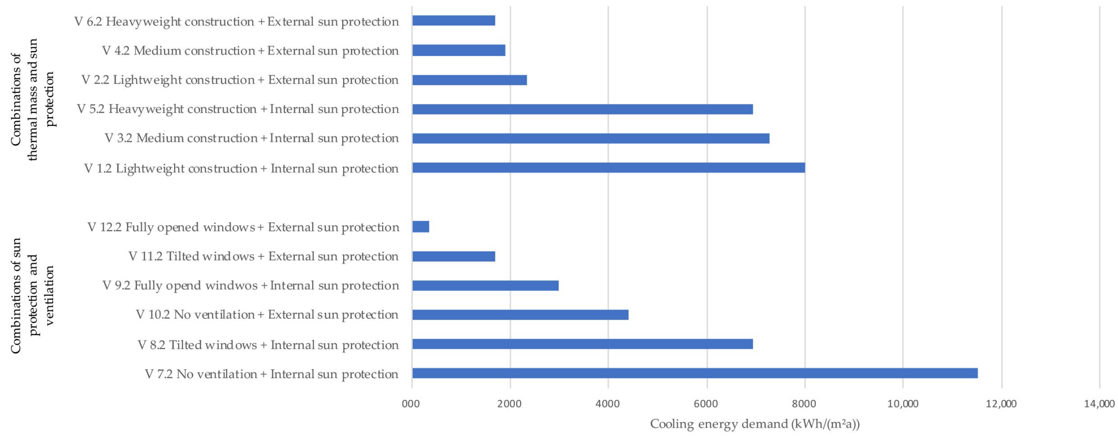


**Figure 9.** Future climate scenario—Cooling energy demand, based on [33].

## 4. Discussion

The study addresses the key question of if and how residential buildings in Vienna can be designed so that energy-intensive air conditioning systems can be avoided under the aspects of current and future climate conditions. The study highlights potential passive design measures within an exemplary case study. Although the model is very simplified for the purpose of the simulation and in order to allow an effective comparison between the different variants, several remarks can be discussed as an outcome from this study:

Active cooling systems can—under specific architectural framework conditions—be avoided in residential buildings within the current climate of the city of Vienna. By means of good advanced planning and the use of passive measures, the cooling energy requirement can be limited and the temperatures can be kept within the comfort range. It can be seen from the results that external sun protection and night ventilation are the most effective measures. A low g-value cannot easily replace the effect of external sun protection.

In addition, the future boundary conditions in the city have to be considered. The comparison of the two climate data sets (current and future climate scenario) shows that the effect of external sun protection is becoming ever more important, especially in the case of very high outside temperatures and increased solar radiation. On very warm nights, night ventilation is less effective. In addition, the potential noise problem with open windows within the city has to be taken into account when the building is located within the vicinity of busy roads.

For refurbishment actions, similarly, passive design measures should be taken into account. Increasing the thermal mass can be more complex as well as cost-intensive to install in existing buildings when it is not already available. Other measures, such as window sizing and orientation, can similarly be easily included in the planning of new buildings, but are usually not feasible to be adapted in existing buildings. Therefore, retrofitting buildings with external sun protection becomes the most important factor when trying to avoid summertime overheating in existing buildings, if a suitable architectural integration can be achieved. Listed buildings and buildings in protected zones, as well as buildings where the external façade cannot be adapted for external shading, would need alternative solutions, such as internal reflective shading elements or shading elements between glass panes.

The assessment focuses on the benefits and drawbacks of various combinations of passive design measures. The simplification of the model provides several limitations, which could potentially be addressed in a subsequent study. For the orientation and ventilation, only worst-case scenarios have been assumed; thus, a more distinct assessment with a higher number of combinations could be done when also altering, for example, cross ventilation and east/west façades. Since the study focused on summertime overheating, the heating energy demand for the various scenarios has not been assessed. However, assuming that shaded elements and ventilation are not applied during the heating season, only the effect of the thermal mass remains as a variant, as the thermal properties of the walls and windows remain the same.

The assessment should provide guidance on the suitability of various measures; it does not, however, substitute a detailed assessment for a specific planning case. Although the study focuses on climate data for the city of Vienna, the results can be applied to regions with similar climate conditions within the Central and Eastern European regions.

## 5. Conclusions

The increasing population in cities promotes urban development strategies such as the densification of areas within existing buildings or the use of previously undeveloped and unsealed areas for construction development. In order to address the urban heat island effect and the subsequent challenge of overheating in residential buildings, it is necessary to implement measures at different hierarchical levels within the urban context. Building orientation, site area, green spaces, and potential water surfaces are already defined at the urban level within the urban land use plans. Considering the aspect of shading, the greening of buildings, and the potential for ventilation and densification already at this planning stage is crucial for the future development of buildings which allow for comfortable summer indoor temperatures. The reduction of the urban heat island effect thus already starts at the level of urban planning.

The use of air conditioning systems in residential buildings and the associated power consumption can be reduced by different strategies. A series of passive design measures have been quantified and presented in this study. Effective architectural means include external shading, nighttime ventilation, and a high thermal mass of the construction materials. The detailed analysis shows that a combination of these three measures provides the best results. Nevertheless, external shading proves to be the most crucial element, which must not be omitted at any cost.

New developments in residential buildings, such as thermal mass activation in combination with the application of renewable energies, can provide further means of reducing the cooling energy demand with increased thermal comfort. Looking at the building from the perspective of the city's supply network, the need to reduce peak loads becomes a relevant factor as the topic of load shifting is becoming ever more important. The connection of buildings with different uses allows the displacement of thermal and electrical loads across the building boundaries. The thermal mass of the buildings can be used in combination with renewable energies as urban energy storage. The heating and cooling supply of the buildings is significantly influenced by the increasing quality of low-energy and passive buildings. Thus, for thermal networks, a supply of low temperatures in the heating case and moderately low temperatures in the cooling case are sufficient to achieve a high thermal comfort.

As a summary, the results of the study show that adequate planning, which primarily includes passive design measures with little or no additional cost, can achieve adequate thermal comfort in residential buildings also during the summer months without energy-intensive air conditioning units, even for future climate scenarios. Thus, the current planning approach of avoiding air conditioning systems in residential buildings can still adequately cover the requirements of comfortable indoor temperatures even with potentially higher future summertime temperatures. However, it must be taken into account that only a combination of measures, which must include external shading, can provide adequate indoor temperatures for future climate scenarios. Therefore, buildings currently being planned must already consider these aspects in order to avoid future postconstruction installation of technical building systems. If these aspects are taken into account, the use of passive design measures instead of air conditioning systems provides a feasible way forward in the current urban and building planning approach.

In the future, "plus-energy" and smart buildings, which can use, generate, and store energy more easily within the building's constraints, will offer more efficient and economical solutions. Making buildings that are currently being built future-proof with adequate passive design measures is a prerequisite in order to mitigate the urban heat island effects and to reduce the consequences of climate change.

**Author Contributions:** Author D.Ö. contributed mainly to the Conceptualization, Methodology, Analysis, Writing, and Project Management. Author S.S. contributed mainly to the Analysis and Writing.

**Funding:** The study "Avoiding summertime overheating in residential buildings" has been funded by the Municipality of Vienna, Municipal Department 20, Energy Planning [33].

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

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