energies

MDPI

Article

Assessment of the Impact of Occupants' Behavior and Climate Change on Heating and Cooling Energy Needs of Buildings

Gianmarco Fajilla [1,2,*], Marilena De Simone [1], Luisa F. Cabeza [3] and Luís Bragança [2,*]

[1] Department of Environmental Engineering, University of Calabria, 87036 Rende, Italy; marilena.desimone@unical.it
[2] Department of Civil Engineering, University of Minho, 4800-058 Guimarães, Portugal
[3] GREiA Research Group, Universitat de Lleida, 25001 Lleida, Spain; luisaf.cabeza@udl.cat
* Correspondence: gianmarco.fajilla@unical.it (G.F.); braganca@civil.uminho.pt (L.B.); Tel.: +39-393-093-3551 (G.F.); +351-966-042-447 (L.B.)

Received: 9 November 2020; Accepted: 3 December 2020; Published: 7 December 2020

Abstract: Energy performance of buildings is a worldwide increasing investigated field, due to ever more stringent energy standards aimed at reducing the buildings' impact on the environment. The purpose of this paper is to assess the impact that occupant behavior and climate change have on the heating and cooling needs of residential buildings. With this aim, data of a questionnaire survey delivered in Southern Italy were used to obtain daily use profiles of natural ventilation, heating, and cooling, both in winter and in summer. Three climatic scenarios were investigated: The current scenario (2020), and two future scenarios (2050 and 2080). The CCWorldWeatherGen tool was used to create the weather files of future climate scenarios, and DesignBuilder was applied to conduct dynamic energy simulations. Firstly, the results obtained for 2020 demonstrated how the occupants' preferences related to the use of natural ventilation, heating, and cooling systems (daily schedules and temperature setpoints) impact on energy needs. Heating energy needs appeared more affected by the heating schedules, while cooling energy needs were mostly influenced by both natural ventilation and usage schedules. Secondly, due to the temperature rise, substantial decrements of the energy needs for heating and increments of cooling energy needs were observed in all the future scenarios where in addition, the impact of occupant behavior appeared amplified.

Keywords: occupant behavior; climate changes; energy needs; ventilation; residential buildings; DesignBuilder

1. Introduction

In most developed countries, buildings are the major energy consumers, and they may not be able to reach the new energy standards [1,2]. In the EU, most of the buildings have more than twenty years and present low energy performance [1]: The percentage of well-designed buildings is less than 2%, with almost 60% of heating systems inefficient and almost 40% of the windows being single glazed [3]. As recognized by the Energy Performance of Buildings Directive (EPBD) [4], buildings are responsible for 40% of the total energy consumption and 36% of global annual greenhouse gas emissions [3,5–7]; these consumptions could drastically increase double or even triple by 2050 if not faced in the right way [8]. As a consequence, governments worldwide have implemented energy requirements in their building regulations to reduce levels of energy consumed by buildings and to promote more energy-efficient envelopes and systems [9].

2. Literature Review

Nowadays, most researchers agree that occupant behavior plays an increasingly important role in building energy performance [10,11]. Despite the efforts made in improving the envelope of buildings and the efficiency of the systems, reducing energy consumption can be achieved considering also the impact that occupants' behavior (OB) has on buildings consumptions [12–18]. Furthermore, OB is often neglected or too simplified in energy design and assessment, causing large discrepancies between calculated and measured energy performances [12,19,20]. For example, a recent study conducted by Carlucci et al. [19] claimed that occupant behavior related to thermostat control (thermostat setpoints and operation schedules) is often too simplified in the building performance standards and calculation procedures, causing significant uncertainty in the predictions of building energy demand. Moreover, Mora et al. [20] simulated the energy consumption of a residential building considering three occupancy scenarios: Regulations, Current-use, and Statistical. Compared to the Current-use schedules, the Regulation schedules provided a significant underestimation of the heating energy needs, while the statistical schedules led to an overestimation. Different authors [13,14,18] highlighted that OB has an important responsibility in determining the energy consumption of buildings, pointing out that this impact is more significant in the new buildings where the envelope and the systems are optimized. Furthermore, Rouleau et al., in their work [15] claimed that the impact of OB has to be recognized to obtain a reduction in energy consumption. Because OB impacts in many ways on energy consumption (e.g., through heating and cooling systems or the interaction with windows and blinds), they deem that it should be not surprising if there is a huge gap between actual and prevised consumption. Furthermore, Zhang et al. [16] analyzed the role of occupant behavior in building energy performance, concluding that the energy-saving potential of occupant behavior in residential buildings is in the range of 10–25%. Similar results were obtained by [17] that quantify to 20% the achievable energy saving by modifying occupants' behavior using recommendations and feedback. Consequently, occupant behavior in buildings is becoming an increasingly topic so much so that different projects, performed within the framework of the International Energy Agency—Energy in Buildings and Communities Program (IEA-EBC), such as IEA EBC Annex 66 [21] and IEA EBC Annex 79 [22], focused on understanding and studying this issue.

The impact of OB on energy consumption of buildings is also recognized by the Intergovernmental Panel on Climate Change (IPCC) that in the IPCC AR5 [23] reported that factors of 3 to 10 differences can be found worldwide in residential energy use for similar dwellings, due to different usage of natural ventilation and thermal control of the indoor environment.

The reduction of buildings' energy consumption is a growing and global problem, mainly due to the looming threat of climate change. Goal 13 of the 2030 Agenda for Sustainable Development [24] calls for urgent action to tackle climate change and its impacts. Indeed, due to climate change and more frequent extreme events, buildings will have to deal with new climatic conditions for which they were not designed [25]. Thus, an increasing body of literature is now emerging on this topic. A recent work [26] assessed the scientific literature on the energy efficiency of buildings and the climate impact through a comparative analysis of Web of Science and Scopus. It was found that while most of the works focused on technologies for heating, ventilation, air-conditioning, and phase change materials, there is still a knowledge gap in the areas of behavioral changes, circular economy, and some of the renewable energy sources (e.g., geothermal, biomass, wind). The authors in [6] analyzed the impact of climate change on the energy performance of a zero energy building in Valladolid (Spain). Three future weather scenarios (2020, 2050, and 2080) were investigated, and the results showed a drop in the space heating demand and an increase in space cooling. Due to these consumptions' variations, they estimated an increase equal to 25% of the burning biomass to provide more energy to the absorption cooling system. Berardi and Jafarpur [27] assessed the impact of climate change on building heating and cooling energy demand of 16 building prototypes located in Toronto (Canada). Authors estimated for 2070 an average decrease of 18–33% and an average increase of 15–126% for the heating and cooling energy use, respectively. Ciancio et al. [28] simulated the energy performances of a building in three cities (Aberdeen, Palermo, and Prague) considering three climatic scenarios (2020, 2050, and 2080). In general, decreasing trends for heating energy needs and increasing trends for cooling energy needs were obtained. The highest variations were observed for 2080: A reduction of the heating energy needs from −36% to −80% and an increase of cooling energy needs from +142% to 2316%. In another study, Ciancio et al. [29] analyzed the energy needs of a hypothetic building by varying its location in 19 cities with different climate conditions. The simulations performed for 2020, 2050, and 2080 showed, once again, a general decrease in heating energy needs and an increase in cooling energy needs. The authors highlighted that the effects of climate change will be more predominant in the Mediterranean basin than in other European areas. Same results were also found from other studies, such as [25], that argued that Southern Europe will be more vulnerable to climate change than Northern Europe. Furthermore, the authors in [30] studied the climate change-driven increase of energy demand in residential buildings in the area of Qatar, founding an increase equal to around 30%. They stressed how such an increase would cause higher CO_2 emissions, more consumptions of water and fossil fuel, as well as an increase in the impact on the already strained local marine ecosystem. They also suggested renovating the building stocks and substitute fossil fuels with renewable energies (e.g., PV plants, wind farms, and tidal plants) as approaches to reduce the environmental impacts of climate change. Cabeza and Chàfer [8] published a systematic review of the technological options and strategies to achieve zero energy buildings contributing to climate change mitigation. Findings showed that buildings, if properly designed, can help to mitigate the impact of climate change—decreasing both the embodied energy in the materials, used during the construction phase, and the energy demand and use in the operation phase. Moreover, regarding new buildings, authors in [31] proposed an innovative method for designing buildings with robust energy performance under climate change for supporting architects and engineers in the design phase. To the extent of our knowledge, the effect of environmental (climate change) and behavioral variables (such as usage profiles and thermal comfort preferences) on the energy performance of buildings was investigated separately in the literature till now. What is missing are studies that consider both the influencing variables and provide predictions combining the double impact. Table 1 synthesizes the literature review related to this area highlighting: Subject of the study, outcomes and limitations, and considered impacts (occupant behavior/ climate change).

Table 1. Comparison of the Literature review.

Ref.	Subject	Outcomes and Limitations	Considered Impact *	
			OB	**CC**
[6]	Effect of CC on the energy performance of ZEBs	Heating/cooling demand registered in future scenarios		√
[8]	Technological options to achieve ZEBs	Gaps in the application of different technologies to reduce CC		√
[10]	Occupant-related energy codes and standards	Considerable variations across the occupancy and usage profiles	√	
[11]	Impact of OB on the energy demands	High variability of OB effect	√	
[12]	Influence of OB on natural ventilation	OB is the reason for discrepancies between calculated and measured energy performance and comfort. The characteristics of the local climate are not considered	√	
[14]	Physical and behavioral factors affecting energy performances	The most significant physical parameters are floor area and climate. Age, number of household members, and income are the most important occupancy variables	√	

Table 1. *Cont.*

Ref.	Subject	Outcomes and Limitations	Considered Impact *	
			OB	**CC**
[15]	Modeling and prediction of the number of occupants, domestic hot water (DHW) use, and non-HVAC electricity use	Acceptable results were obtained from the comparison between simulated and measured values	√	
[16]	Understanding of OB	Gaps: Understand OB in a systematic framework and evaluate its role in building energy policies	√	
[17]	Provide occupants with recommendations to reduce energy consumption	Procedure to develop an energy-efficient Reference Building	√	
[18]	Occupancy patterns on the energy performance of nZEB	Being a nZeB is not related only to the construction and plants, but is also dependent on occupant related factors	√	
[19]	Production and landscape on OPA modeling	Need to develop new studies in climate contexts where models are missing	√	
[20]	Heating and DHW energy consumptions and indoor comfort	Simplified approaches are not suitable to describe adequately the usage scenarios	√	
[22]	Occupant-centric building design and operation	The need of relieving occupants from a passive role in building design	√	
[25]	Impact of CC and variability on thermal comfort	Ventilation and insulation lead to a decrease in internal temperatures		√
[26]	Energy efficiency and CC mitigation	Gaps in the areas of behavioral changes and non-technological measures		√
[27]	Effects of CC on heating and cooling energy demand	Decrease in the heating energy use intensity and increase in the cooling energy use intensity		√
[28]	Resilience to CC of a residential building located in different European cities	CC will affect the heating and cooling energy demands		√
[29]	Impact of CC on heating and cooling energy consumption in different cities	The trends appear more impacting in Southern than Northern Europe		√
[30]	Effect of CC on the residential sector and environmental implications	Importance of renovating the building stocks and use renewable energies		√
[31]	Designing buildings with robust energy performance under CC	OB as a source of variation in combination with CC is indicated as a future work		√

* OB = Occupant behavior, CC = Climate Change.

Aim of the Study

As emerged from the literature review, the impact of occupant behavior, and the effect of climate change on the energy performance of buildings was largely recognized. Their impacts were investigated, highlighting the importance of future scientific contributions to these topics and encouraging more comprehensive studies considering that behavioral variables and climate change were still analyzed separately. Consequently, this paper aims to fill this gap by proposing a study that combines the double effect of these variables on the energy performance of buildings. By considering the information and indications of the available literature, the aim of this study was addressed to assess the impact of both occupants' behavior and climate change on the heating and cooling energy performance of a typical residential unit located in Southern Europe. Here, the energy performance was referred to as the heating and cooling energy needs defined as the heat to be delivered to, or extracted from, a conditioned space to maintain the intended temperature conditions during a given period of time.

Energy needs constitute the base of calculation of the primary energy demand that is determined by the energy supply system and the user types of fuel.

In particular, the authors wanted to answer the following research questions:

- RQ1: How does climate change influence the heating and cooling hours of operation?
- RQ2: How do the daily heating, cooling, and ventilation use profiles affect energy needs?
- RQ3: How does climate change affect the energy performance of buildings in winter and summer?
- RQ4: How do occupants' preferences related to the heating and cooling setpoints temperature affect energy needs in different climate scenarios?

The answers to these research questions can provide useful indications for scientists and policymakers to assess how human factors and environmental conditions can impact the energy consumptions of buildings, and consequently give due weight to them in future regulations and design criteria.

3. Methodology

The general schema and the consecutive steps of the investigation are illustrated in Figure 1.

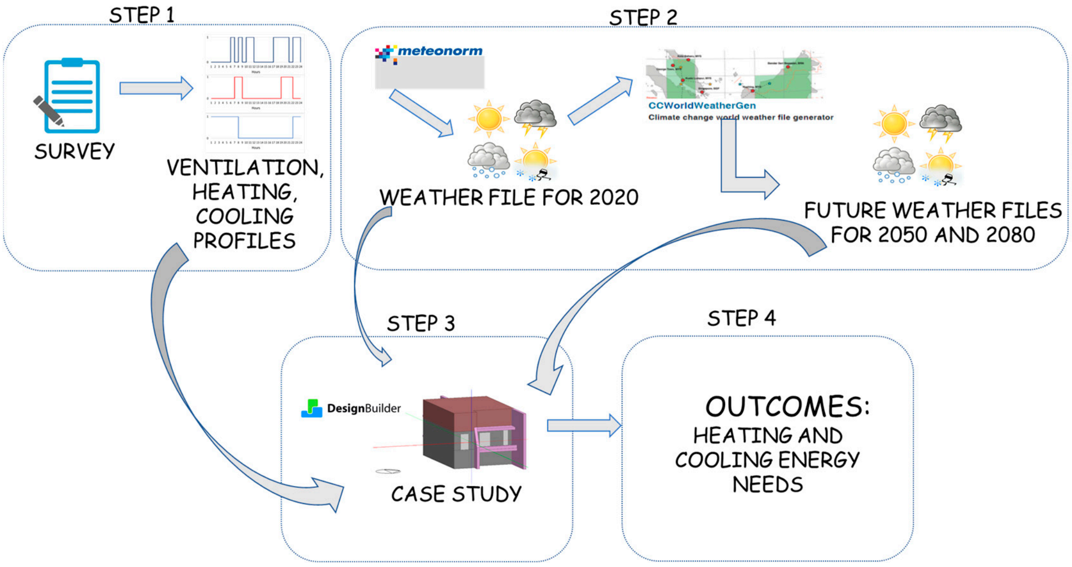


Figure 1. Schema of the adopted methodology.

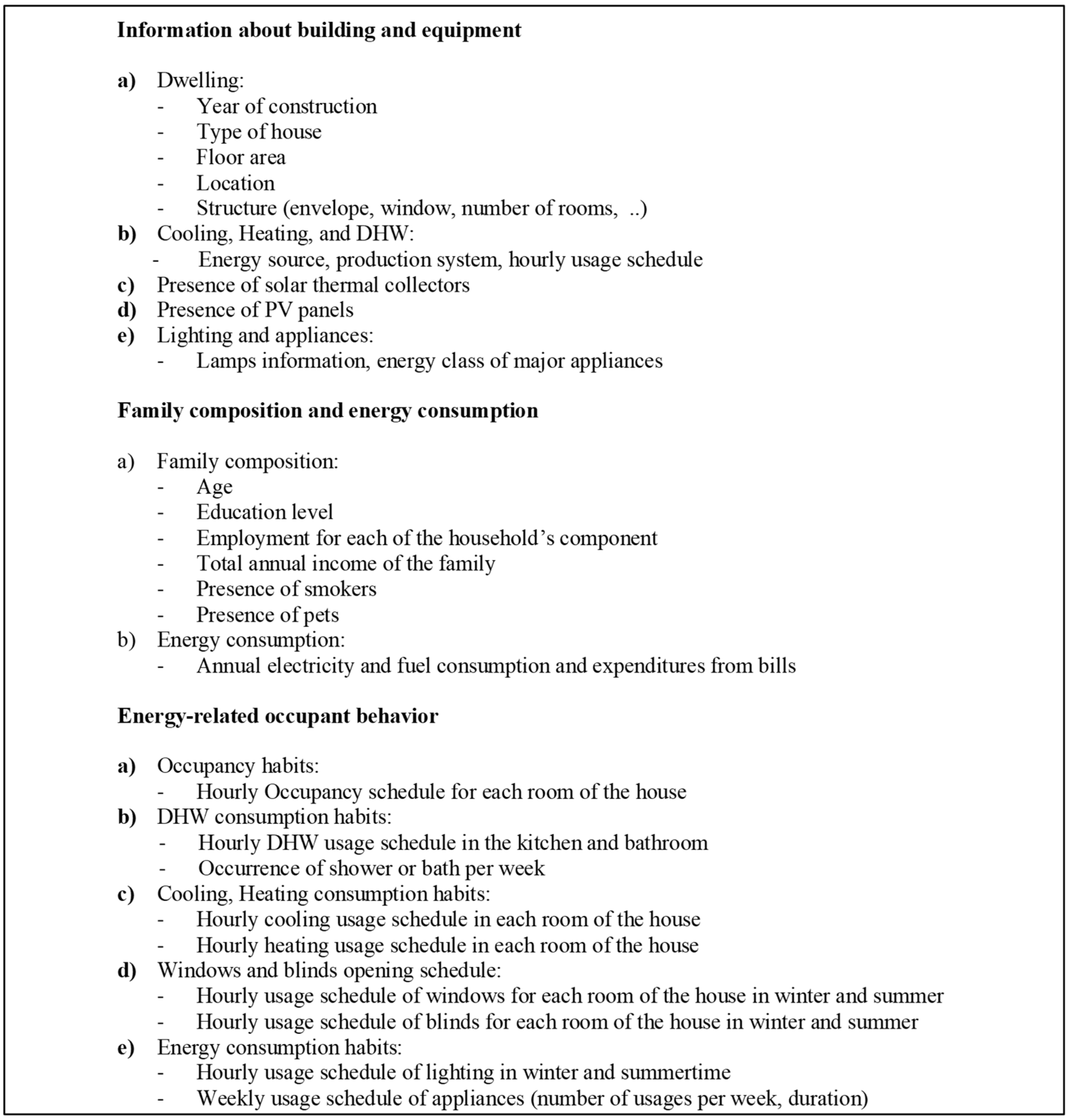
The research can be summarized in four steps:

- step 1: Survey distribution and data for the creation of heating, cooling, and natural ventilation profiles;
- step 2: Weather file for 2020 was downloaded from METEONORM and then adopted in CCWorldWeatherGen tool to obtain the weather files for the future scenarios;
- step 3: An apartment was chosen as a case study and modeled trough DesignBuilder by considering different usage profiles and climate scenarios;
- step 4: Results in terms of heating and cooling energy needs were obtained to assess the impact of occupant behavior and climate change on the energy performance of buildings.

Furthermore, this section introduces more in detail Step 1 to Step 3: The survey to collect information on the occupants' behavior to be used in energy simulations, the energy model of the residential unit investigated in the study, and the tool adopted to obtain the weather files of future climate scenarios.

3.1. Questionnaire Survey

Data of a questionnaire survey delivered in Southern Italy were used to obtain use profiles to be provided as input in energy simulations. During two survey campaigns conducted from 2017 [9] to 2019, 237 surveys were collected, and among them, 193 were accepted as valid for these analyses. The questionnaire presents a total of 64 questions grouped into three main categories, as shown in Figure 2.



Information about building and equipment

a) Dwelling:
  - Year of construction
  - Type of house
  - Floor area
  - Location
  - Structure (envelope, window, number of rooms, ..)

b) Cooling, Heating, and DHW:
  - Energy source, production system, hourly usage schedule

c) Presence of solar thermal collectors

d) Presence of PV panels

e) Lighting and appliances:
  - Lamps information, energy class of major appliances

Family composition and energy consumption

a) Family composition:
  - Age
  - Education level
  - Employment for each of the household's component
  - Total annual income of the family
  - Presence of smokers
  - Presence of pets

b) Energy consumption:
  - Annual electricity and fuel consumption and expenditures from bills

Energy-related occupant behavior

a) Occupancy habits:
  - Hourly Occupancy schedule for each room of the house

b) DHW consumption habits:
  - Hourly DHW usage schedule in the kitchen and bathroom
  - Occurrence of shower or bath per week

c) Cooling, Heating consumption habits:
  - Hourly cooling usage schedule in each room of the house
  - Hourly heating usage schedule in each room of the house

d) Windows and blinds opening schedule:
  - Hourly usage schedule of windows for each room of the house in winter and summer
  - Hourly usage schedule of blinds for each room of the house in winter and summer

e) Energy consumption habits:
  - Hourly usage schedule of lighting in winter and summertime
  - Weekly usage schedule of appliances (number of usages per week, duration)

Figure 2. Questionnaire contents.

Consistently with the aim of this paper, the attention was dedicated to the questions regarding the cooling and heating operation habits and the window opening preferences. The responses collected for the buildings located in Rende, characterized by Mediterranean climate conditions and defined as "Csa" according to the Köppen climate classification [32], were considered.

For the selected buildings, the schedules were first subjected to a cleaning process to verify their reliability. After that, the profiles were clustered based on the timing and length of the usage, and typical hourly profiles were obtained for heating, cooling, and natural ventilation.

3.2. Case Study

Among the collected sample, an apartment built in 2008 located on the second floor of a six-story building, with a gross floor area of 80 m^2 was chosen as a case study. The building structure is made of reinforced concrete, and the external walls consist of double hollow brick layers with an internal air gap partially filled with expanded polystyrene, resulting in a U-value of 0.6 W/m^2·K. The windows are double glazing and a frame with thermal break. The heating system, used both for heating and DHW production, is an autonomous wall-mounted gas boiler. A zone thermostat regulates the operating of the heating system, and the heat emitters are aluminum radiators. The cooling system consists of air conditioners installed in the living room and in the bedrooms. METEONORM weather data [33] were used for the dynamic energy simulations conducted by DesignBuilder [34]. The model of the residential unit is shown in Figure 3.

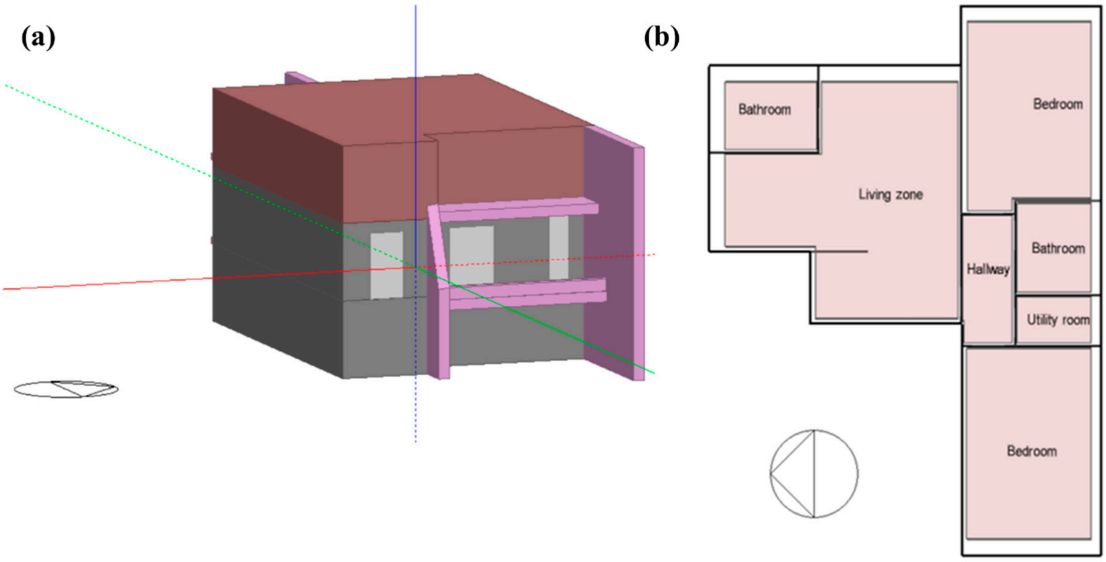


Figure 3. The model of the residential unit: (**a**) DesignBuilder model of the building; (**b**) plan of the apartment.

The reliability of the model was verified by the authors in previous work [20] following the ASHRAE Guideline 14-2002 [35]. The predicted results obtained from the simulation of the actual use and the measured data extracted from the energy bills were compared on a monthly scale through the Normalized Mean Bias Error(NMBE) and the Coefficient of Variation of the Root Mean Square Error (CVRMSE). Values lower than the limit values were obtained for both the parameters.

Downstairs there is an unconditioned thermal zone; while upstairs, there is an adiabatic block, due to the presence of another heated dwelling. Horizontal and vertical overhangs were shaped through standard component block considered by the software in shading calculation. Three thermal zones (living area, bedrooms, and bathrooms) were considered, and the characteristic parameters were changed in terms of management of the heating and cooling system, as both activation period and setpoint temperature, and ventilation hourly profiles. The internal heat loads were determined following the indications of the Standard UNI/TS 11300-1 [36] that uses the relation:

$$\phi_{int} = 7.987\, A_f - 0.0353\, A_f^2 \tag{1}$$

where A_f is the usable floor area of the house [m^2]. The calculated value amounts to 5.56 W/m^2 and groups all contributions of occupancy, miscellaneous equipment, catering process, and lighting. The dynamic simulations were performed by combining different hourly ventilation profiles with heating and cooling operation schedules and setpoints temperature. In the reference case, energy simulations were conducted for the heating (from 1 October to 30 April) and cooling (from 1 May to 30 September) season by considering the current climate data and a setpoint temperature of 20 °C and 26 °C, respectively. Further energy assessments were obtained by varying the climatic scenarios (2050 and 2080) and the internal setpoints temperature (18 °C and 22 °C in the heating season, 26 °C and 24 °C in the cooling season).

3.3. Climate Scenarios

In this study, the climate change world weather file generator (CCWorldWeatherGen) [37] was used to create the weather files of future climate scenarios. Several studies used this tool to obtain future weather files [6,25,27–30], and the authors in [38] presented a critical analysis of it. Specifically, CCWorldWeatherGen is a Microsoft Excel-based tool commonly used that, employing the morphing procedure [39], provides weather files for future scenarios using outputs from the UK Hadley Centre Coupled Model (version 3, HadCM3) [40].

The future scenarios selected for this study were 2050 and 2080. The three adopted climate weather files were first analyzed in terms of variations in the external air temperature values. Figure 4a shows the monthly average air temperatures of the current climate, while the ΔT between current and future monthly average air temperatures are reported in Figure 4b for 2050 and in Figure 4c for 2080.

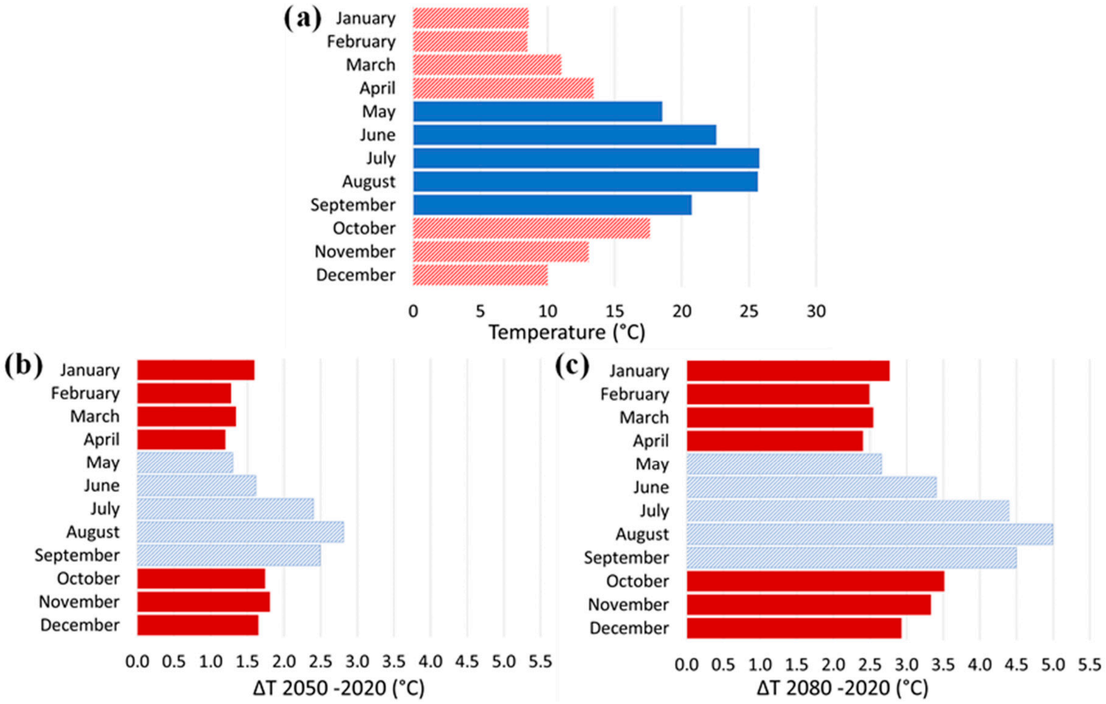


Figure 4. Monthly average air temperature: (**a**) in 2020, and monthly average air temperature increment ΔT (**b**) in 2050 and (**c**) in 2080.

Compared to the current climate, an increase in the monthly average air temperatures for each month of both 2050 and 2080 is projected. In particular, increments from 1.2 °C observed in April to 2.8 °C in August and from 2.4 °C to 5 °C, in the same months, were expected for 2050 and 2080, respectively.

4. Results and Discussion

This section presents the results obtained from the survey and the energy simulations conducted for the heating and cooling season. The results are organized as follow:

- ventilation, heating, and cooling profiles obtained from the survey;

- monthly hours of operation of the heating and cooling systems in 2020, 2050, and 2080 with setpoint temperatures of 20 °C and 26 °C;
- impact of diverse usage schedules of heating, cooling, and natural ventilation on the heating and cooling energy needs in the current climate conditions;
- variations of energy needs in future weather scenarios;
- variations of energy needs by changing the heating and cooling setpoint temperatures of ±2 °C in the different climate conditions.

4.1. Ventilation, Heating, and Cooling Profiles

Tables 2–4 show the typical hourly profiles obtained for heating, cooling, and natural ventilation. Moreover, respondents declared to generally use the heating system from October to April with a typical setpoint temperature of 20 °C, and the cooling system from May to September with a setpoint temperature of 26 °C. Further setpoints temperature ranging from 18 °C to 22 °C in winter, and from 24 °C to 28 °C in summer, were encountered.

Table 2. Daily heating schedules (On = 1, Off = 0).

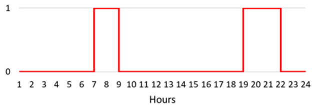
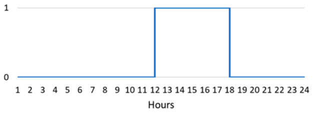
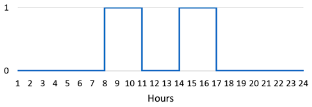
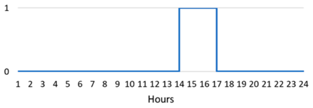
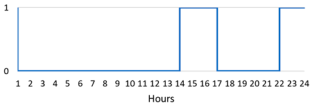
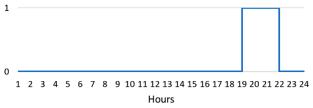
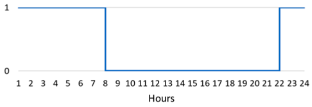
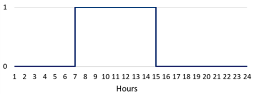
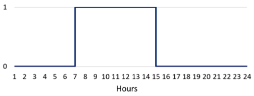
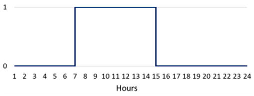
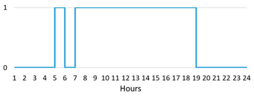
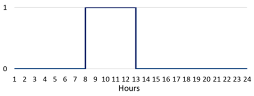
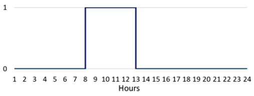
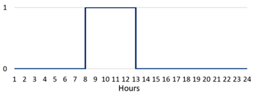
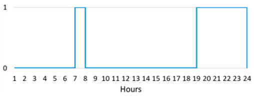
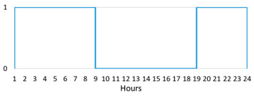
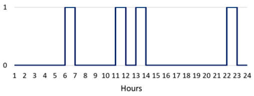
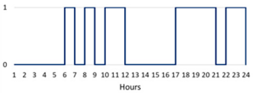
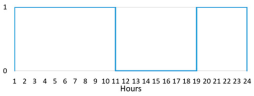
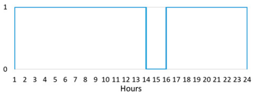
Profile	All Rooms
h1	
h2	
h3	

Table 3. Daily cooling schedules (On = 1, Off = 0).

Profile	Living Zone	Bedrooms Zone
c1		
c2		
c3		

The heating schedules varied in terms of both the duration and time of operation. The heating system could operate for 24 h (profile h1), for three hours during the evening (from 19:00 to 22:00) in profile h2, and during the morning (from 07:00 to 09:00) and in the evening (from 19:00 to 22:00) in profile h3.

Table 4. Daily Natural ventilation schedules (Open = 1, Close = 0).

Profile	Season	Living Zone	Bedrooms Zone	Bathrooms Zone
v1	Winter			
	Summer			
v2	Winter			
	Summer			
v3	Winter			
	Summer			

As shown in Table 3, the cooling system was installed only in the living and bedroom zones and used with diverse daily schedules. In profile c1, it was used in the hottest hours of the day (from 12:00 to 18:00) in the living zone, and for two time ranges in the bedrooms (from 08:00 to 11:00, and from 14:00 to 17:00). The schedules of the cooling system were more similar between the zones with profile c2: In the afternoon (from 14:00 to 17:00) in the two zones, and in the late evening (from 22:00 to 01:00) only in the bedrooms. Profile c3 was different from the others because the cooling operation was only activated during the late afternoon: From 19:00 to 22:00 in the living zone, and from 22:00 to 07:00 in the bedrooms.

Usually, occupants welcome natural ventilation more than mechanical ventilation, where they can only passively accept the system operation [41]. On the other hand, natural ventilation impacts negatively on the energy needs of a building when the external air temperature is lower than the internal air temperature in winter, or higher in summer, producing greater values of heat losses. On the other hand, benefits from window openings can be obtained in summer when the external air is used for natural cooling during the late afternoon or at night.

Looking at the graphs, shown in Table 4, it can be seen the variations of the occupants' preferences related to ventilation through the seasons. Profile v1 was typical of families who preferred to use continuous hours of ventilation during the day from the morning to the afternoon. The daily schedules were equal among the rooms, but different in duration between the seasons: From 07:00 to 15:00 and from 07:00 to 19:00 in winter and summer, respectively. Profile v2 showed the use of the natural ventilation limited to the morning hours in winter (from 08:00 to 13:00) and concentrated in the coolest hours in the summer. Finally, profile v3 presented an intermittent, but prolonged use throughout the day in winter, and continuous use in the coolest hours in the summer (from 19:00 to 11:00). Similar habits could be seen in the bathrooms area in both v2 and v3 profiles where people used to leave the windows open for the entire day. Natural ventilation profiles, as well as heating and cooling profiles, are linked to occupancy. Generally, it is noted that in homes with greater hours of daily occupancy, there is a more frequent occupant-window interaction and prolonged use of the heating and cooling systems (e.g., heating schedule h1 with continuous activation).

The heating and cooling schedules were combined with the natural ventilation profiles, and nine profiles, both for winter and summer seasons, were applied to perform the energy simulations of a residential unit.

4.2. Monthly Hours of Operation of the Heating and Cooling System in the Climate Scenarios

Due to the increase of the monthly average air temperature, it is also interesting to analyze how the hours of operation of the heating and cooling systems vary from the current climate to the future scenarios. In this study, "monthly hours of operation" was the sum of the hours in which the heating/cooling system provides the energy necessary to reach and maintain the indoor temperature at the setpoint value.

In particular, Figure 5 shows the monthly hours of operation of the heating system in the current climate (Figure 5a) and the differences (Δ*h*) with respect to 2050 (Figure 5b) and 2080 (Figure 5c), by setting the internal air temperature value equal to 20 °C. The energy simulations were performed by considering all the heating schedules (h1, h2, h3) coupled with the ventilation profiles (v1, v2, v3).

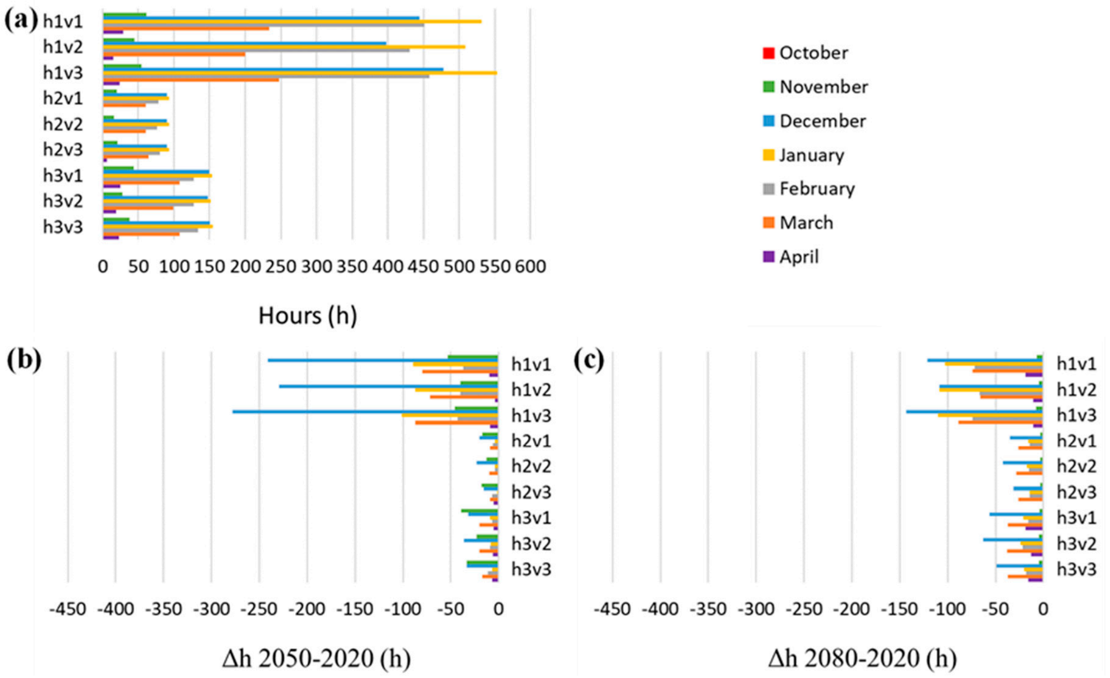


Figure 5. Monthly hours of operation of the heating system: (**a**) in the current climate, and differences Δ*h* in the year (**b**) 2050 and (**c**) 2080.

The study shows a decreasing trend in the operation hours of the heating system for each month of the future climate scenarios. The major differences arose when the three profiles of the natural ventilation were combined with the heating schedule h1 characterized by continuous activation. In general, December was the month where more variations from 2020 to the future scenarios were observed.

The results for the cooling season, in terms of monthly hours of operation, were obtained with a setpoint temperature of 26 °C and are shown in Figure 6.

As a consequence of the external temperature rise, it is possible to observe an increasing trend of the monthly hours of operation of the cooling system in the future climate conditions. May, June, and September registered the main increases with the schedules c1 and c2. This growth was more visible with profile c1 because the cooling system could operate for more hours and mainly in the hottest hours. Considering the schedule c3, the operation of the cooling system was from June to September in 2020, and also needed in May during the future climate scenarios. It mainly happened when the cooling schedule c3 was coupled with the natural ventilation profile v1 because the ventilation occurred in the hottest hours of the day, producing an increase of the internal air temperature, and consequently, a prolonged cooling system operation.

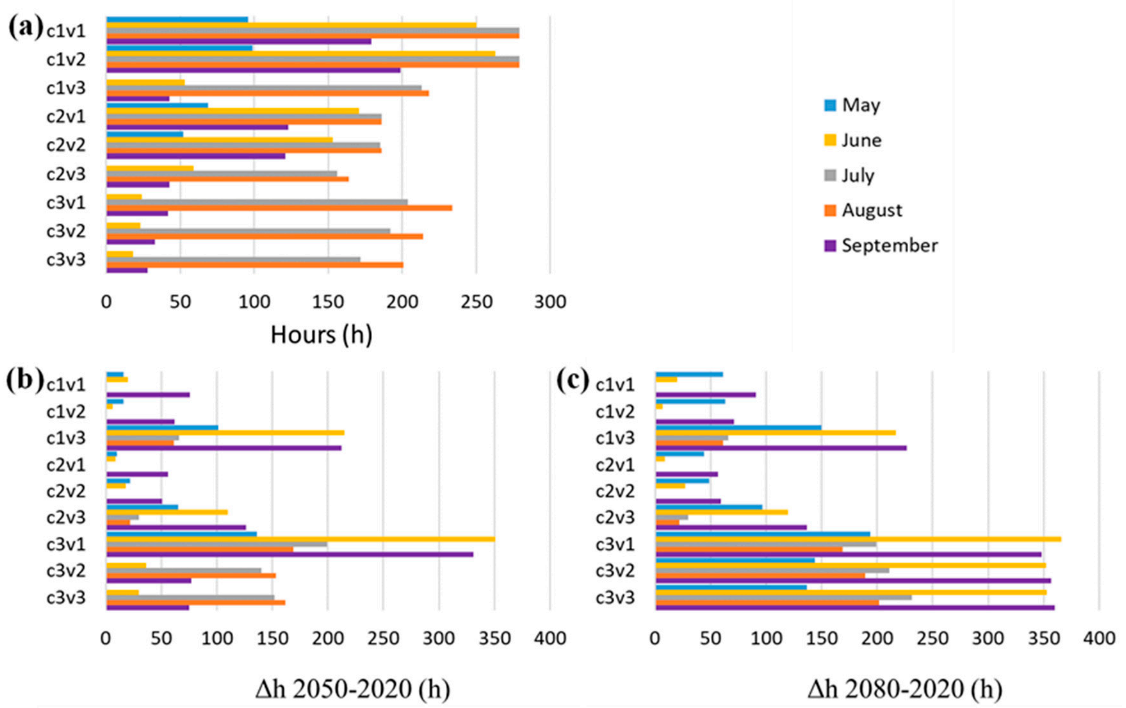


Figure 6. Monthly hours of operation of the cooling system: (**a**) in the current climate, and differences Δ*h* in the years (**b**) 2050 and (**c**) 2080.

4.3. Impact of Occupant Behavior on Energy Needs

Figure 7 shows the heating and cooling energy needs in the current climate with a heating setpoint temperature of 20 °C and a cooling setpoint temperature equal to 26 °C.

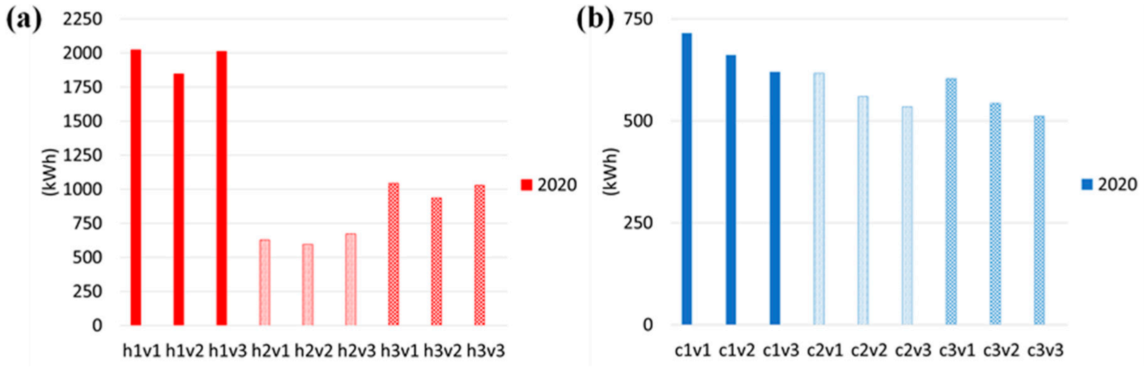


Figure 7. Energy needs in the current climate for: (**a**) the heating season; (**b**) the cooling season.

In winter, the energy requirement (Figure 7a) was more influenced by the heating schedules than the natural ventilation type. In particular, values of the order of 2000 kWh, 1000 kWh, and 700 kWh were registered for the heating schedule h1, h3, and h2, respectively. These differences in energy needs were due to the diverse duration of the heating system operation.

On the other hand, the cooling energy need seems to be affected by both the operation type and natural ventilation schedules. A decreasing trend of the energy requirement from the cooling schedule c1 to c3 and from the natural ventilation schedule v1 to v3 was observed. In more detail, the cooling energy need ranged from 714.8 kWh to 619.7 kWh, from 616.4 kWh to 534.7 kWh, and from 606.4 kWh to 511.7 kWh for c1, c2, and c3, respectively. These results can be explained by analyzing the cooling and ventilation profiles. In fact, the cooling system could operate for more hours and in the hottest hours of the day with the schedule c1.

Also, the natural ventilation with profile v1 mainly occurred in the hours in which the external air temperature can be higher than the internal one leading to greater cooling energy needs. In contrast, the schedules v2 and v3 produced a positive effect the energy balance.

In the current climate, h2v2 and c3v3 were the less heating and cooling energy-demanding profiles, while h1v1 and c1v1 were those with the most heating and cooling energy requirement.

4.4. Impact of Climate Changes on the Energy Needs

The use profiles were also used to assess their impact on future climate scenarios characterized by temperature rise. Figure 8 illustrates the relative differences of the energy needs in 2050 and 2080 compared to 2020.

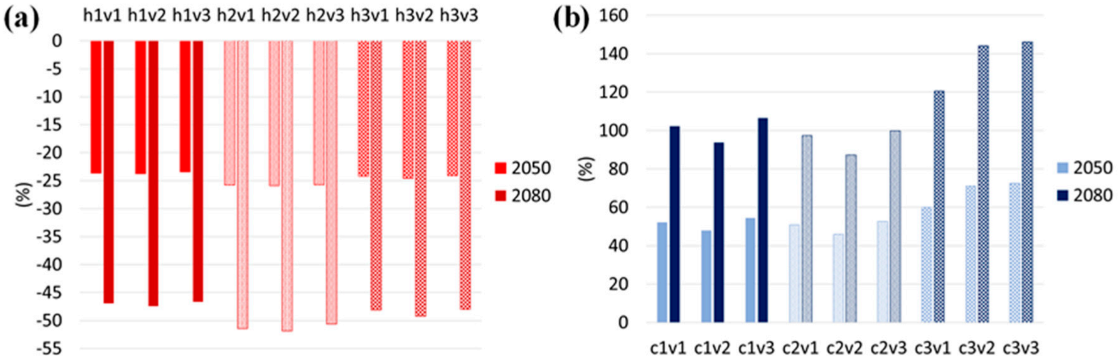


Figure 8. Relative differences between the energy needs calculated in the current climate and in future climate scenarios for: (**a**) the heating season; (**b**) the cooling season.

For all future scenarios, energy needs reductions were observed in the heating season, and energy needs increments in the cooling season. In winter, the impact of climate change was more predominant than the impact of occupant behavior (Figure 8b). In fact, significant variations were found from one year to the next and not in different heating and ventilation profiles. The differences varied from −24% to −26%, and from −47% to −52% in 2050 and 2080, respectively.

In summer, visible variations were observable varying the use profiles and passing from a climatic scenario to another (Figure 8b). In fact, energy requirements increased from +48% to +54%, from +46% to +53%, and from +60% to +73% with the cooling schedule c1, c2, and c3 in 2050, respectively. Moreover, for 2080, cooling need increased from +94% to +107%, from +87% to 100%, and from +121% to +146% with the schedule c1, c2, and c3, respectively.

4.5. Impact of the Heating and Cooling Setpoint Temperatures on Energy Needs

Occupants can impact the energy performance of buildings also by varying the setpoint temperature of the heating and cooling system.

Figures 9–11 present, for the different climate scenarios, the variations of the heating and cooling energy needs when the setpoint temperatures were modified of ±2 °C.

As expected, the decrease in the heating setpoint temperature by 2 °C led to a reduction in energy requirements, and the increase in temperature consequently produced an increase in energy need (see Figure 9a). Opposite trends in thermal behavior were observed by varying the cooling setpoint temperature (see Figure 9b).

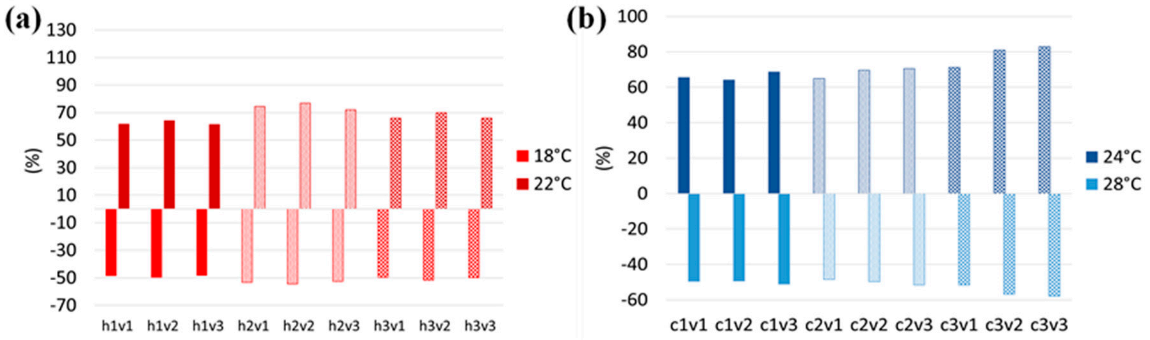


Figure 9. Relative differences of the (**a**) heating and (**b**) cooling energy needs caused by a variation of the setpoint temperature of ±2 °C in 2020.

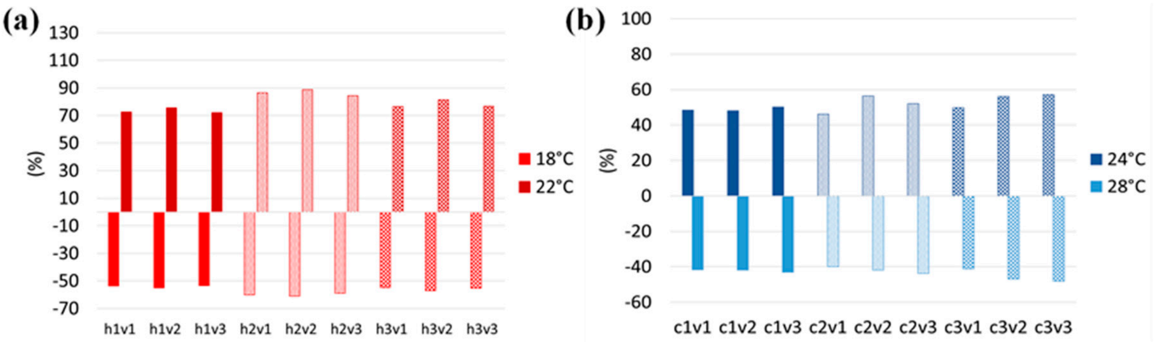


Figure 10. Relative differences of the (**a**) heating and (**b**) cooling energy needs caused by a variation of the setpoint temperature of ±2 °C in 2050.

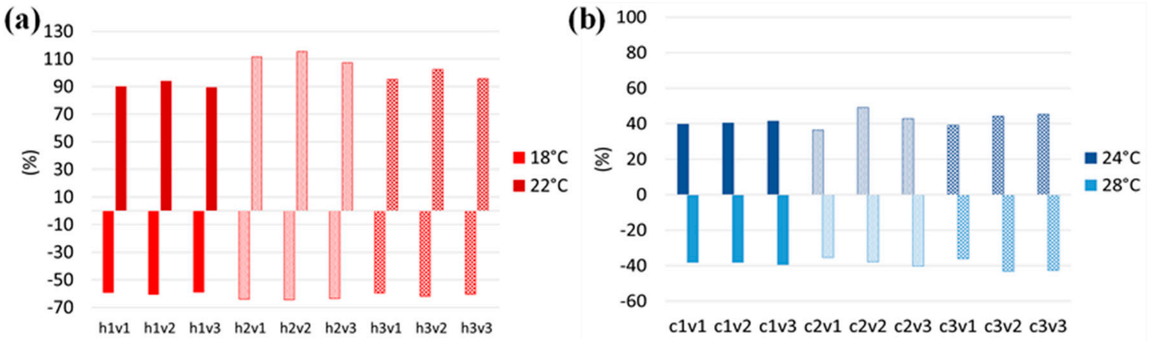


Figure 11. Relative differences of the (**a**) heating and (**b**) cooling energy needs caused by a variation of the setpoint temperature of ±2 °C in 2080.

More in detail, regarding the heating season in the current climate, the energy need decreased from −48% to −54% when the internal air temperature was set equal to 18 °C and increased from +62% to +77% when 22 °C was the selected setpoint. The maximum variation was found for profile h2v2, for which the energy need was 595.2 kWh at 20 °C, and 271 kWh and 1052 kWh at 18 °C and 22 °C, respectively.

In summer, the energy need increased from +65% to +83%, when the setpoint temperature was 28 °C and decreased from –48% to –58% when it was equal to 24 °C, with a maximum variation for profile c3v3 with both 24 °C and 28 °C. In particular, the greatest variations were found for the c3v3 profile that registered an energy requirement of 511.7 kWh at 26 °C, and of 935.5 kWh and 215 kWh at 24 °C and 28 °C, respectively.

The same information as above, but referring to 2050, is shown in Figure 10. For both the heating (Figure 10a) and cooling needs (Figure 10b), the general trends were similar to those noticed in 2020, what changes were the magnitude of the variations.

Specifically, in 2050, the heating energy need encountered higher fluctuations by varying the setpoint temperature (decrement from −53% to −61% and increment from +72% to +89%). The maximum variation, also in 2050, was observed in both cases for profile h2v2. Instead, in summer, the variations due to the occupants' preferences had a minor impact: The energy need increased from +46% to +57% and decreased from −40% to −48%. The results for 2080 are shown in Figure 11.

In 2080, the reduction and increase of the heating setpoint temperature led to remarkable changes in energy requirements (from −59% to −65% for 18 °C, and from +90% to +114% for 22 °C). In the cooling season, the variations of the setpoint temperature determined more limited modifications in terms of energy needs that increased from +36% to +45% and decreased from −35% to −43%. As happened in 2020, also in 2050 and 2080, the maximum variations were observed for profile h2v2 in winter and c3v3 in summer.

4.6. Discussion

Energy simulations were first performed with setpoint temperature equal to 20 °C in winter and 26 °C in summer. In 2020, the heating energy needs were more influenced by heating schedules than ventilation profiles, and values of the order of 2000 kWh, 1000 kWh, and 700 kWh were registered for the continuous and the two intermittent operations, respectively. In summer, the cooling energy needs were affected by both cooling and ventilation operations. They ranged from 511.7kWh to 606.4 kWh, from 534.7 kWh to 616.4 kWh, and from 619.7 kWh to 714.8 kWh in the three operation modes.

In future scenarios, the temperature rise determined the decrement of the heating energy needs and the augmentation of the cooling energy needs, in agreement with the results of the previous studies. Specifically, during the heating season, energy needs reductions from −24% to −26% in 2050, and from −47% to −52% in 2080 were obtained. In summer, energy requirements increased from +48% to +54%, from +46% to +53%, and from +60% to +73% by changing the cooling schedule in 2050. Moreover, the increments obtained in 2080 were around double then those registered in 2050.

In addition to natural ventilation habits and systems operation mode, the occupants' can have different preferences in thermal comfort conditions, thus, variations of the setpoint temperature of ±2 °C were considered.

In particular, in 2020, the heating energy needs decreased from −48% to −54% and increased from +62% to +77% when the setpoint temperature was set equal to 18 °C and 22 °C, respectively. On the other hand, cooling energy needs increased from +65% to +83% and decreased from −48% to −58% with setpoint temperature equal to 28 °C and 24 °C, respectively.

From 2020 to 2080, the variations of energy needs were smaller for the heating and greater for the cooling. In any case, occupants' behavior in controlling and personalizing the indoor thermal conditions had a consistent impact in each climatic scenario.

To the extent of our knowledge, this study was the first that jointly assessed both the impact of occupant behavior and climate change on the energy performance of buildings. The results of this study can be considered indicative of what could be predicted in other Mediterranean countries.

A limitation of this study consists in the fact that energy evaluations were carried out in one location and for a type of building. Thus, the results are contextual and suggest further investigations to address the implication of both occupant behavior and climate change on the heating and cooling energy needs in diverse building typologies and climatic conditions.

Furthermore, this initial study provided informative results for scientists and policymakers as both human factors and environmental conditions can consistently affect the energy consumptions of buildings. Moreover, if the temperature rise determines the reduction of the energy needs in winter and the increment in summer, different preferences and behavior of occupants can lead to better managing of the systems' operation following energy-saving intentions in every season.

Therefore, adequate attention is needed for the aforementioned aspects in future regulations and design criteria.

5. Conclusions

Dynamic simulations were conducted to assess how the heating and cooling energy needs of a residential unit were affected by occupants' behavior and climate change. In particular, the impact of occupants' behavior was investigated by applying nine usage profiles of heating, cooling, and natural ventilation in winter and summer. Moreover, the influence of occupant behavior was taken into account by varying the indoor setpoint temperature. Regarding climate changes, three scenarios were considered—2020, 2050, and 2080.

The heating energy needs in 2020 were more influenced by heating schedules than ventilation profiles, while the cooling energy needs were consistently affected by both cooling and ventilation operations.

As expected, reducing the energy needs in winter and a rise in summer were noticed in future scenarios. In addition, due to the temperature increase, the variations of energy needs in 2080 were doubled than those obtained in 2050. More relevant results were highlighted concerning the impact of the setpoint temperature. In fact, the variations of energy needs registered from 2020 to 2080 were higher for the cooling than those for the heating, indicating that standards and codes should place more attention to future prescriptions about this control parameter.

In general, this study quantified how occupant preferences related to heating, cooling, and natural ventilation affect the energy performance of buildings. It was also demonstrated that due to climate change, buildings could be subjected to more critical climate conditions, which will lead them to have higher energy needs and to emit more CO_2. In future scenarios, the impacts of occupant behavior will be amplified, and especially the preferences related to the cooling system will have a consistent impact in Mediterranean countries.

Author Contributions: Conceptualization, G.F. and M.D.S.; methodology, G.F. and M.D.S.; software, G.F. and M.D.S.; validation, M.D.S.; formal analysis, G.F. and M.D.S.; investigation, G.F. and M.D.S.; data curation, G.F. and M.D.S.; writing—original draft preparation, G.F.; writing—review and editing, M.D.S, L.F.C., and L.B.; visualization, G.F. and M.D.S.; project administration, M.D.S.; funding acquisition, M.D.S. and L.F.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Calabria Region Government with the Gianmarco Fajilla's Ph.D. scholarship (POR Calabria FSE/FESR 2014–2020) grant number H21G18000170006. A part of this publication has received funding from Secretaria Nacional de Ciencia y Tecnologia (SENACYT) under the project code FID18-056. This work was partially funded by the Ministerio de Ciencia, Innovación y Universidades de España (RTI2018-093849-B-C31 - MCIU/AEI/FEDER, UE). This work was partially funded by the Ministerio de Ciencia, Innovación y Universidades - Agencia Estatal de Investigación (AEI, RED2018-102431-T). This work is partially supported by ICREA under the ICREA Academia program.

Acknowledgments: The authors would like to thank the Catalan Government for the quality accreditation given to their research group (GREiA 2017 SGR 1537). GREiA is certified agent TECNIO in the category of technology developers from the Government of Catalonia.

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

References

1. Almeida, M.; Ferreira, M. Ten questions concerning cost-effective energy and carbon emissions optimization in building renovation. *Build. Environ.* **2018**, *143*, 15–23. [CrossRef]
2. Ferreira, M.; Almeida, M.; Rodrigues, A. Impact of co-benefits on the assessment of energy related building renovation with a nearly-zero energy target. *Energy Build.* **2017**, *152*, 587–601. [CrossRef]
3. de Fátima Castro, M.; Colclough, S.; Machado, B.; Andrade, J.; Bragança, L. European legislation and incentives programmes for demand Side management. *Sol. Energy* **2020**, *200*, 114–124. [CrossRef]
4. European Union. Directive (EU) 2018/844 of the European Parliament and of the Council of 30 May 2018 amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency. *Off. J. Eur. Union* **2018**, *156*, 75–91.

5. Araújo, C.; Almeida, M.; Bragança, L.; Barbosa, J.A. Cost-benefit analysis method for building solutions. *Appl. Energy* **2016**, *173*, 124–133. [CrossRef]
6. Rey-Hernández, J.M.; Yousif, C.; Gatt, D.; Velasco-Gómez, E.; San José-Alonso, J.; Rey-Martínez, F.J. Modelling the long-term effect of climate change on a zero energy and carbon dioxide building through energy efficiency and renewables. *Energy Build.* **2018**, *174*, 85–96. [CrossRef]
7. Streimikiene, D.; Balezentis, T.; Alebaite, I. Climate change mitigation in households between market failures and psychological barriers. *Energies* **2020**, *13*, 2797. [CrossRef]
8. Cabeza, L.F.; Chàfer, M. Technological options and strategies towards zero energy buildings contributing to climate change mitigation: A systematic review. *Energy Build.* **2020**, *219*, 110009. [CrossRef]
9. Carpino, C.; Fajilla, G.; Gaudio, A.; Mora, D.; De Simone, M. Application of survey on energy consumption and occupancy in residential buildings. An experience in Southern Italy. *Energy Procedia* **2018**, *148*, 1082–1089. [CrossRef]
10. O'Brien, W.; Tahmasebi, F.; Andersen, R.K.; Azar, E.; Barthelmes, V.; Belafi, Z.D.; Berger, C.; Chen, D.; De Simone, M.; D'Oca, S.; et al. An international review of occupant-related aspects of building energy codes and standards. *Build. Environ.* **2020**, *179*, 106906. [CrossRef]
11. Gaetani, I.; Hoes, P.J.; Hensen, J.L.M. Estimating the influence of occupant behavior on building heating and cooling energy in one simulation run. *Appl. Energy* **2018**, *223*, 159–171. [CrossRef]
12. Roetzel, A.; Tsangrassoulis, A.; Dietrich, U.; Busching, S. A review of occupant control on natural ventilation. *Renew. Sustain. Energy Rev.* **2010**, *14*, 1001–1013. [CrossRef]
13. Balint, A.; Kazmi, H. Determinants of energy flexibility in residential hot water systems. *Energy Build.* **2019**, *188–189*, 286–296. [CrossRef]
14. Mora, D.; Carpino, C.; De Simone, M. Behavioral and physical factors influencing energy building performances in Mediterranean climate. *Energy Procedia* **2015**, *78*, 603–608. [CrossRef]
15. Rouleau, J.; Ramallo-González, A.P.; Gosselin, L.; Blanchet, P.; Natarajan, S. A unified probabilistic model for predicting occupancy, domestic hot water use and electricity use in residential buildings. *Energy Build.* **2019**, *202*. [CrossRef]
16. Zhang, Y.; Bai, X.; Mills, F.P.; Pezzey, J.C. V Rethinking the role of occupant behavior in building energy performance: A review. *Energy Build.* **2018**, *172*, 279–294. [CrossRef]
17. Ashouri, M.; Fung, B.C.M.; Haghighat, F.; Yoshino, H. Systematic approach to provide building occupants with feedback to reduce energy consumption. *Energy* **2020**, *194*, 116813. [CrossRef]
18. Carpino, C.; Mora, D.; Arcuri, N.; De Simone, M. Behavioral variables and occupancy patterns in the design and modeling of Nearly Zero Energy Buildings. *Build. Simul.* **2017**, *10*, 875–888. [CrossRef]
19. Carlucci, S.; De Simone, M.; Firth, S.K.; Kjærgaard, M.B.; Markovic, R.; Rahaman, M.S.; Annaqeeb, M.K.; Biandrate, S.; Das, A.; Dziedzic, J.W.; et al. Modeling occupant behavior in buildings. *Build. Environ.* **2020**, *174*, 106768. [CrossRef]
20. Mora, D.; Carpino, C.; De Simone, M. Energy consumption of residential buildings and occupancy profiles. A case study in Mediterranean climatic conditions. *Energy Effic.* **2018**, *11*, 121–145. [CrossRef]
21. Yan, D.; Hong, T.; Dong, B.; Mahdavi, A.; D'Oca, S.; Gaetani, I.; Feng, X. IEA EBC Annex 66: Definition and simulation of occupant behavior in buildings. *Energy Build.* **2017**, *156*, 258–270. [CrossRef]
22. O'Brien, W.; Wagner, A.; Schweiker, M.; Mahdavi, A.; Day, J.; Kjærgaard, M.B.; Carlucci, S.; Dong, B.; Tahmasebi, F.; Yan, D.; et al. Introducing IEA EBC Annex 79: Key challenges and opportunities in the field of occupant-centric building design and operation. *Build. Environ.* **2020**, *178*, 106738. [CrossRef]
23. Lucon, O.; Ürge-Vorsatz, D.; Zain Ahmed, A.; Akbari, H.; Bertoldi, P.; Cabeza, L.F.; Eyre, N.; Gadgil, A.; Harvey, L.D.D.; Jiang, Y.; et al. *Climate Change 2014: Mitigation of Climate Change*; Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change Chapter 9, Buildings; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2014; pp. 671–738.
24. UN General Assembly. *Transforming Our World: The 2030 Agenda for Sustainable Development*; A/Res/70/1; Division for Sustainable Development Goals: New York, NY, USA, 2015.
25. Barbosa, R.; Vicente, R.; Santos, R. Climate change and thermal comfort in Southern Europe housing: A case study from Lisbon. *Build. Environ.* **2015**, *92*, 440–451. [CrossRef]
26. Cabeza, L.F.; Chàfer, M.; Mata, É. Comparative analysis of web of science and scopus on the energy efficiency and climate impact of buildings. *Energies* **2020**, *13*, 409. [CrossRef]

27. Berardi, U.; Jafarpur, P. Assessing the impact of climate change on building heating and cooling energy demand in Canada. *Renew. Sustain. Energy Rev.* **2020**, *121*, 109681. [CrossRef]
28. Ciancio, V.; Falasca, S.; Golasi, I.; de Wilde, P.; Coppi, M.; de Santoli, L.; Salata, F. Resilience of a building to future climate conditions in three European cities. *Energies* **2019**, 12. [CrossRef]
29. Ciancio, V.; Salata, F.; Falasca, S.; Curci, G.; Golasi, I.; de Wilde, P. Energy demands of buildings in the framework of climate change: An investigation across Europe. *Sustain. Cities Soc.* **2020**, *60*, 102213. [CrossRef]
30. Andric, I.; Al-Ghamdi, S.G. Climate change implications for environmental performance of residential building energy use: The case of Qatar. *Energy Rep.* **2020**, *6*, 587–592. [CrossRef]
31. Moazami, A.; Carlucci, S.; Nik, V.M.; Geving, S. Towards climate robust buildings: An innovative method for designing buildings with robust energy performance under climate change. *Energy Build.* **2019**, *202*, 109378. [CrossRef]
32. Köppen, W.P.; Geiger, R. *Handbuch der Klimatologie*; Gebrüder Borntraeger: Berlin, Germany, 1930.
33. Meteonorm. *Meteonorm Global Meteorogical Database Version 7.1.8*; METEOTEST: Bern, Switzerland, 2012.
34. DesignBuilder. DesignBuilder Version 6.1.6.008. DesignBuilder Software Ltd. 2020. Available online: http://www.designbuilder.co.uk/ (accessed on 1 February 2020).
35. ASHRAE. *ANSI/ASHRAE Guideline 14-2002 Measurement of Energy and Demand Savings*; ASHRAE: Peachtree Corners, GA, USA, 2002.
36. Italian Standardization Body, UNI/TS 11300-1. *Energy Performance of Buildings, Part 1: Evaluation of Energy Need for Space Heating and Cooling*; Italian Standardization Body: Milan, Italy; Rome, Italy, 2014.
37. Jentsch, M.F.; Bahaj, A.B.S.; James, P.A.B. Climate change future proofing of buildings-Generation and assessment of building simulation weather files. *Energy Build.* **2008**, *40*, 2148–2168. [CrossRef]
38. Moazami, A.; Carlucci, S.; Geving, S. Critical Analysis of Software Tools Aimed at Generating Future Weather Files with a view to their use in Building Performance Simulation. *Energy Procedia* **2017**, *132*, 640–645. [CrossRef]
39. Belcher, S.E.; Hacker, J.N.; Powell, D.S. Constructing design weather data for future climates. *Build. Serv. Eng. Res. Technol.* **2005**, *26*, 49–61. [CrossRef]
40. Met Office. Met Office HadCM3: Met Office Climate Prediction Model. Available online: https://www.metoffice.gov.uk/research/approach/modelling-systems/unified-model/climate-models/hadcm3 (accessed on 15 March 2020).
41. Day, J.K.; McIlvennie, C.; Brackley, C.; Tarantini, M.; Piselli, C.; Hahn, J.; O'Brien, W.; Rajus, V.S.; De Simone, M.; Kjærgaard, M.B.; et al. A review of select human-building interfaces and their relationship to human behavior, energy use and occupant comfort. *Build. Environ.* **2020**, *178*, 106920. [CrossRef]