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Effect of Climate Change and Occupant Behaviour on the Environmental Impact of the Heating and Cooling Systems of a Real Apartment. A Parametric Study through Life Cycle Assessment

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Abstract: Climate change has a strong influence on the energy consumption of buildings, affecting both the heating and cooling demand in the actual and future scenario. In this paper, a life cycle assessment (LCA) was performed to evaluate the influence of both the occupant behaviour and the climate change on the environmental impact of the heating and cooling systems of an apartment located in southern Italy. The analysis was conducted using IPCC GWP and ReCiPe indicators as well as the Ecoinvent database. The influence of occupant behaviour was included in the analysis considering different usage profiles during the operational phase, while the effect of climate change was considered by varying the weather file every thirty years. The adoption of the real usage profiles showed that the impact of the systems was highly influenced by the occupant behaviour. In particular, the environmental impact of the heating system appeared more influenced by the operation hours, while that of the cooling system was more affected by the natural ventilation schedules. Furthermore, the influence of climate change demonstrated that more attention has to be dedicated to the cooling demand that in the future years will play an ever-greater role in the energy consumption of buildings.

Keywords: life cycle assessment (LCA); ReCiPe indicator; global warming potential (GWP) indicator; environmental impact; heating and cooling systems; occupant behaviour; climate change

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Citation: Fajilla, G.; Borri, E.; De Simone, M.; Cabeza, L.F.; Bragança, L. Effect of Climate Change and Occupant Behaviour on the Environmental Impact of the Heating and Cooling Systems of a Real Apartment. A Parametric Study through Life Cycle Assessment. *Energies* **2021**, *14*, 8356. https://doi.org/10.3390/en14248356

Academic Editors: Shi-Jie Cao, Adrian Ilinca and Chi-Ming Lai

Received: 2 November 2021
Accepted: 9 December 2021
Published: 11 December 2021

1. Introduction

According to the Sustainable Development Goals Report 2021 of United Nations [1], global efforts made so far were insufficient and there still is much progress to be made for reaching the objectives of Agenda 2030 [2]. Additionally, the authors of the Sixth Assessment Report of the Intergovernmental Panel on Climate Change pointed out that global warming of 1.5 and 2 °C will be exceeded during the twenty-first century unless significant actions are taken to reduce CO_2 and other greenhouse gases (GHG) emissions in the coming decades [3].

At the European level, new ambitious targets were set with the European Green Deal [4] to reduce GHG emissions and becoming the first climate-neutral continent by 2050. Most of the European buildings present low energy performance and inefficient heating and cooling systems [5,6]. Thus, the building sector still constitutes an important issue to be addressed, being responsible for more than 40% of the worldwide energy consumption and 36% of global GHG [7–10].

1.1. Life Cycle Assessment Applied to Buildings

Life cycle assessment (LCA) is a quantitative method widely known to assess the environmental impacts of products or systems.

The literature on LCA applications to buildings is very extensive, and there is broad agreement in recognizing the importance of the operational stage during the entire cycle of the buildings. Ramesh et al. [11] reviewed 73 buildings across 13 countries and showed that the operational stage is responsible for around 80–90% of the life cycle energy demand of buildings. Similar results were obtained for the Italian context by Asdrubali et al. [12] that assessed to 77% the contribution of the operational stage in the case of detached houses, and up to 85% for office buildings. Sartori and Hestnes [13] analysed the results of 60 LCA of buildings found in the literature highlighting that there is a linear regression between their operational and total energy. Furthermore, a review conducted by Cabeza et al. [14] reported that most of the LCAs are conducted for buildings designed and constructed as low-energy buildings while the percentage of LCA for traditional buildings is lower.

Different authors focused the attention to the environmental impact of the heating and cooling systems because they are the most responsible for emissions during the entire life cycle of a house [15].

Vignali [16] conducted a comparison of the environmental impact of a traditional gas boiler and a condensing gas boiler in three Italian cities obtaining that the impact of the condensing boiler is 23% on average lower than that of the traditional boiler. Additionally, the operational stage of both the systems was responsible, on average, for more than 90% of the total impact. Greening and Azapagic [17] compared the life cycle environmental impacts of domestic heat pumps (air, ground, and water-source) and a gas boiler for the UK context. The impact of the heat pumps was always higher than that of the gas boiler due to the use of electricity. The results showed that the total impact of heat pumps could decrease as the percentage of renewable energy sources in the UK electricity mix increases, while still exceeding the impact of the gas boiler. Llantoy et al. [18] performed an LCA for a lifespan of 30 years to compare the environmental impact of an innovative hybrid energy storage system for heating and domestic hot water production in continental climates with the environmental impact of a traditional system. The results of the analysis, performed through the ReCiPe and the IPCC global warming potential GWP indicators, showed that the total impact of the innovative hybrid energy storage system was lower than the reference one. Zsembinszki et al. [19] compared the environmental performance of an innovative compact hybrid electrical-thermal storage system and a traditional system for cooling, heating, and domestic hot water production in the Mediterranean context. The authors obtained a relevant reduction in energy consumption during the operational stage with the innovative system, despite the environmental impact during its entire life cycle (30-years lifespan) being almost double than that of the traditional system. Shah et al. [15] likened the life cycle impact of three heating and cooling systems (warm-air furnace and air conditioning, hot water boiler and air conditioning, and air–air heat pump) in four cities of the USA considering a lifespan of 35 years. In general, the impact of the heat pump was always higher than that of other systems in a percentage strictly related to the diverse energy mix of the four considered cities. Similar results were obtained by Karkour et al. [20] that performed an LCA to assess the impact of residential air conditioners in Indonesia. The results suggested that the impacts are strongly dependent on the energy mix of the country but could be reduced with diverse solutions, such as introducing refrigerants with low global warming impact and encouraging the recycling of units.

1.2. Problems Related to Climate Change

Among all the mentioned studies, it can be noticed that the attention was mainly focused on the energy demand of buildings by considering the same climatic scenario and the impact of climate change was usually neglected. However, climate change is currently recognized as the most important and critical challenge to mankind globally [21]. Nowadays, just because of climate change, buildings are facing new climatic conditions for which they were not designed [22]. Thus, the impact of climate change on the energy performance of buildings and the environmental impact of the heating and cooling systems cannot be undervalued [23].

For example, Tootkaboni et al. [24] analysed the impact of climate change on the future energy performance of residential buildings in the most populated Italian climate zone. The authors found a decrease of around 30.9% of the heating energy demand and a significant increase in cooling demand up to 255.1%. Similar conclusions were reached by Ciancio et al. [25] that, simulating the energy performance of a building located in three European cities, assessed for 2080 a reduction of the heating energy demand from 36% to 80% and an increase of cooling energy needs from 142% to 2316%. The authors in [26] assessed the influence of climate change on the heating and cooling energy demand of different building prototypes located in Toronto. By 2070, they estimated an average decrease of 18–33% for heating energy use and an average increase of 15–126% for cooling energy use.

Regarding the effect of climate change on the environmental impact of the cooling system in residential buildings of Qatar, Andric and Al-Ghamdi [27] prevised an augmentation of the CO_2 emissions as well as more consumptions of water and fossil fuel, and an increase of the impact on the already strained local marine ecosystem due to the increase of the energy demand for cooling.

1.3. Problems Related to Occupant Behaviour

Another aspect usually overlooked in the studies on LCA is occupant behaviour, whose influence on the energy performance of buildings, and specifically on the heating and cooling systems, is well known [28,29]. Moreover, the AR5 report of the Intergovernmental Panel on Climate Change (IPCC) [30] highlighted that occupant behaviour, such as different thermal control of the indoor environment and natural ventilation usages, determines factors of differences from 3 to 10 worldwide in residential energy use, also in similar dwellings. The literature focused on understanding how people use a space and how their behaviour influences the energy performance of the buildings increased in the last decades [31]. For example, a recent study [32] investigated the impact of occupant behaviour on heating energy consumption and indoor temperature in residential buildings finding that there were outstanding differences in the resulting energy consumption and in the percentage of time in which thermal comfort conditions were met for the different user scenarios.

Fajilla et al. [33] introduced a novelty by analysing the influence of both occupant behaviour and climate change on the energy performance of buildings. The authors showed how the occupant preferences through the control of heating, cooling systems, and natural ventilation impact the energy needs, and how climate change can amplify this impact.

Now, however, a step forward is needed to understand how people influence the environmental impact of the heating and cooling systems.

In fact, despite the importance of the operational stage, it seems that not enough efforts were dedicated to analysing how occupants' behaviour influences the environmental performance of these systems, and the literature in this field is very scarce.

For example, Su et al. [34] performed an LCA to assess the environmental performance of the cooling and heating systems among different houses in China focusing on the families dimension and the age of families' members. The results showed that the larger households, and the families with elderly people or children are more likely to have a higher environmental impact due to the higher cooling and heating demand. The authors highlighted the importance of carrying out further studies to better address the influence of occupant behaviour.

Negishi et al. [35] proposed a framework for a dynamic LCA applied to building systems to discover the influence of the parameters time variation of the building systems such as occupant behaviour, technical performance degradations of the systems, and the variation in the energy mix. Results suggested the need for further investigation for a deeper understanding of the influence of occupant behaviour. Su et al. [36] came to similar conclusions and pointed out that traditional LCA methods have two drawbacks consisting in not considering the time variance of parameters over the entire life cycle of the buildings (e.g., climate), and the behaviours of occupants.

1.4. Aim and Objectives of the Study

As emerged from the literature review, the operational stage is the most influencing phase during an LCA of heating and cooling systems or of an entire building. Despite the importance of this stage, it was generally treated with a standard approach and not all influencing factors were investigated. The common procedure of conducting an LCA analysis was to examine the operational stage of the systems considering usage profiles suggested by national standards, with a consequent underestimation of the impact of occupant behaviour [37]. Moreover, the simulation of energy consumption was usually conducted by not considering climatic scenarios, overlooking the effect of climate change that will cause a decrease in the heating energy demand and an increase in the cooling energy demand [25,26]. To fill this gap in the literature, the aim of this study lies in to jointly analyse the effect of occupant behaviour and climate change on the environmental impact of the heating and cooling systems through an LCA analysis. The influence of occupant behaviour and climate change on the energy performance of buildings was already investigated in the literature, but the influence of both these two factors in an LCA analysis has been never explored. This combined investigation is the main novelty of the paper, especially in the study of the environmental impact of heating and cooling systems.

More in detail, chosen an existing building as a case study with heating and cooling systems installed, an environmental analysis is performed by comparing the results obtained conducting firstly an LCA including the influence of occupant behaviour, and secondly an LCA that considers both occupant behaviour and climate change. To achieve these objectives, the paper aims to answer these research questions:

- RQ1: How does occupants behaviour affect the environmental impact of heating and cooling systems' operation phase?
- RQ2: Can occupants behaviour mitigate or amplify the effect of climate change on the total environmental impact of heating and cooling systems? In addition, vice versa?

The approach used in the investigation wants to highlight the importance of considering new and actual variables in the energy simulation and environmental impact evaluation of building systems. In particular, the environmental impacts of heating and cooling systems are analysed by considering the occupant behaviour to bring the evaluations closer to the reality, and climate change to test the validity of technical solutions in future contexts. The findings of this proposed approach could provide new insights to scientists and practitioners for the improvement of design criteria, and also to policymakers for future regulations.

2. Methods

2.1. Case Study

The heating and cooling systems of an apartment located at Rende (Southern Italy), characterized by Mediterranean climate conditions and defined as "Csa" according to the Köppen climate classification [38], were considered for the study. The heating system consists of an autonomous 24 kW wall-mounted gas boiler that works with natural gas. The cooling system is composed of two heat pumps installed in the living room and the bedrooms with a design capacity of 4 kW and 6 kW, respectively.

The apartment has a gross floor area of 80 m^2 and is located on the second floor of a six-story building built in 2008. The rooms of the apartment are south and west facing, with a floor-to-ceiling height equal to 2.7 m and a window-to-wall ratio of 30%. The structure of the building is reinforced concrete, while the external walls (U-value of 0.6 $W/m^2 \cdot K$) are made of double hollow bricklayers with an internal air gap partially filled with expanded polystyrene. The windows consist of double glazing and a frame with thermal break (U-value 2.72 W/m^2·K). The horizontal and vertical overhangs were modelled using standard component blocks considered by the software in shading calculation. Upstairs there is an adiabatic block where there is another heated apartment, while downstairs there is an unconditioned thermal zone. 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 systems, as both activation period and setpoint temperature, and ventilation hourly profiles. The internal heat loads (φ_{int}) were determined through the following relation provided by the Standard UNI/TS 11300-1 [39]:

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

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 calibration of the building model was verified in previous work [40] according to the ASHRAE Guideline 14-2002 [41] through the Normalized Mean Bias Error (NMBE) and the Coefficient of Variation of the Root Mean Square Error (CVRMSE). Errors lower than the limit values were obtained for both metrics (NMBE < 5%, CVRMSE < 15%).

2.2. Energy Simulations

Typical hourly profiles of heating (h1, h2, and h3), natural ventilation in winter (v1, v2, and v3), cooling (c1, c2, and c3), and natural ventilation in summer (v4, v5, and v6) were obtained from a questionnaire survey [33]. The profiles are summarised in Table 1 and shown in Tables 2–5.

Table 1. Daily heating, cooling, and natural ventilation schedules summary.

Heating	**Natural Ventilation in Winter**
h1: Continuous for 24 h	v1: Continuous from 07:00 to 15:00
h2: Limited to the evening (from 19:00 to 22:00)	v2: Limited to the morning hours (from 08:00 to 13:00)
h3: Discontinuous during the day (from 07:00 to 09:00 and from 19:00 to 22:00)	v3: Intermittent but prolonged throughout the day
Cooling	**Natural Ventilation in Summer**
c1: During the hottest hours of the day (from 12:00 to 18:00) in the living zone, and in two-time ranges (from 08:00 to 11:00, and from 14:00 to 17:00) in the bedrooms	v4: Continuous from 07:00 to 19:00
c2: Limited to the afternoon (from 14:00 to 17:00) in the living and bedrooms zones, and the late evening (from 22:00 to 01:00) only in the bedrooms	v5: Concentrated in the coldest hours of the day in the living and bedrooms area, and continuous for 24 h in the bathrooms
c3: Limited to the late afternoon (from 19:00 to 22:00) in the living zone, and from 22:00 to 07:00 in the bedrooms	v6: Prolonged use in the coolest hours in the living and bedrooms area, and continuous for 24 h in the bathrooms

More details about the schedules can be found in a previous work published by the authors [33]. By combining these usage schedules, nine profiles for the heating (h1v1, h1v2, h1v3, h2v1, h2v2, h2v3, h3v1, h3v2, and h3v3) and cooling (c1v4, c1v5, c1v6, c2v4, c2v5, c2v6, c3v4, c3v5, and c3v6) season were adopted to represent different occupants' behaviour. Dynamic energy simulations were conducted for the heating season from 1 October to 30 April with a setpoint temperature of 20 °C, and for the cooling season from 1 May to 30 September with a setpoint temperature of 26 °C (Table 6). Further energy assessments were obtained by varying the heating and cooling setpoint temperatures of ±2 °C. The simulations were conducted through DesignBuilder (v. 6.1.6.008) [42] by using the METEONORM weather data [43] for the current climate (2020) and the data of future climate scenarios (2050 and 2080) obtained with the climate change world weather file generator (CCWorldWeatherGen) [44]. More in detail, CCWorldWeatherGen is a Microsoft Excel-based tool commonly used in this field [9,22,25,26,45] to obtain weather files for future scenarios. It implements the morphing procedure on the current weather file and provides weather files for future scenarios using outputs from the UK Hadley Centre Coupled Model (v.3, HadCM3) [46].

Table 2. Daily heating schedules (On = 1, Off = 0). Adapted from [33].

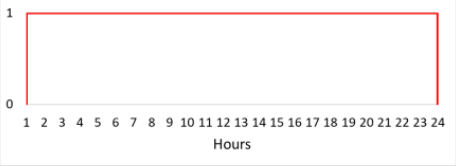
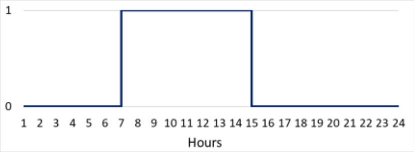
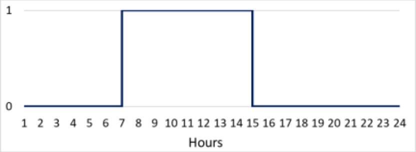
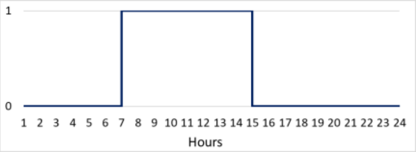
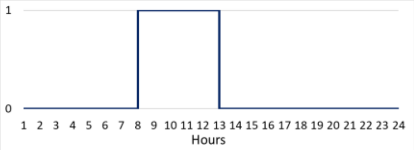
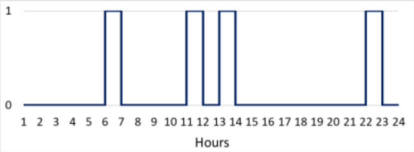
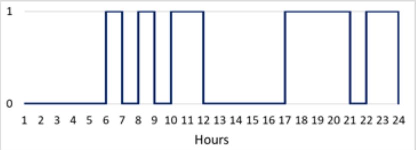
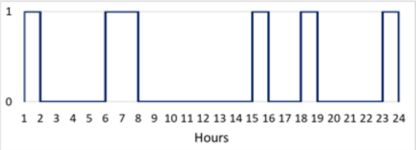
Profile	All Rooms
h1	
h2	
h3	

Table 3. Daily natural ventilation schedules in winter (Open = 1, Close = 0). Adapted from [33].

Profile	Living Zone	Bedrooms Zone	Bathrooms Zone
v1			
v2			
v3			

2.3. LCA Methodology

Life cycle assessment (LCA) is a tool widely common for assessing the environmental impact of a product, process, or system through its complete life cycle [47], including the manufacturing, operational, and disposal stage. The analysis was performed following the four main steps suggested by the ISO 14040 and 14044 guidelines [48,49], as shown in Figure 1.

Table 4. Daily cooling schedules (On = 1, Off = 0). Adapted from [33].

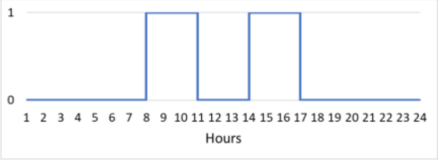
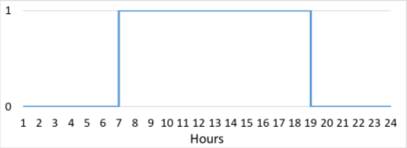
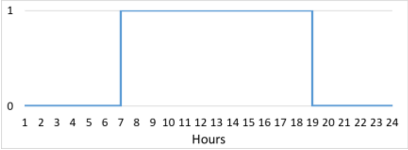
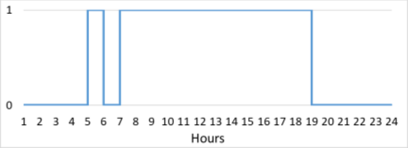
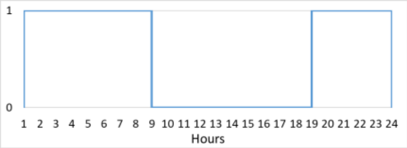
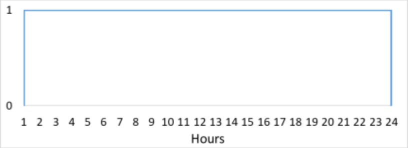
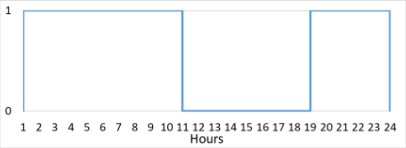
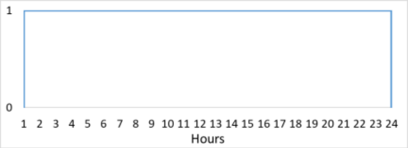
Profile	Living Zone	Bedrooms Zone
c1		
c2		
c3		

Table 5. Daily natural ventilation schedules in summer (Open = 1, Close = 0). Adapted from [33].

Profile	Living Zone	Bedrooms Zone	Bathrooms Xone
v4			
v5			
v6			

The study was carried out through the indicators IPCC 2013 Global Warming Potential for long-term effect (GWP 100 a) and short-term effect (GWP 20 a), and ReCiPe extracted from the Ecoinvent 3.7.1 database [50] by considering data related to the European context. These two indicators were selected based on the evaluation made by the Joint Research Commission of European Union that indicated the GWP indicator as the only indicator representative for all midpoint models currently used in LCA studies [51], and the ReCiPe indicator as the best method for the European context in comparison with EPS2000, Eco-indicator 99, and IMPACT2002+ [52].

2.3.1. Goal and Scope Definition

The goal of the analysis was to assess if and how the occupants' behaviour related to the use of the heating and cooling systems affects the environmental impact of these systems. Consistent with the aim of this paper, the cooling system was considered composed of a single heat pump with a design capacity of 10 kW. The details of the systems are given below in Table 7.

Table 6. Energy consumption [kWh/year] for heating and cooling with setpoint temperatures of 20 °C (heating) and 26 °C (cooling).

Season	**Profiles**	**Consumption [kWh/year]**		
		2020	**2050**	**2080**
Heating	h1v1	2299	1756	1220
	h1v2	2099	1600	1103
	h1v3	2287	1751	1220
	h2v1	720	534	350
	h2v2	682	505	328
	h2v3	771	572	380
	h3v1	1196	906	620
	h3v2	1073	809	544
	h3v3	1185	899	615
Cooling	c1v4	233	367	479
	c1v5	205	310	403
	c1v6	198	314	414
	c2v4	202	312	405
	c2v5	184	271	343
	c2v6	178	276	356
	c3v4	196	322	445
	c3v5	192	343	492
	c3v6	179	323	463

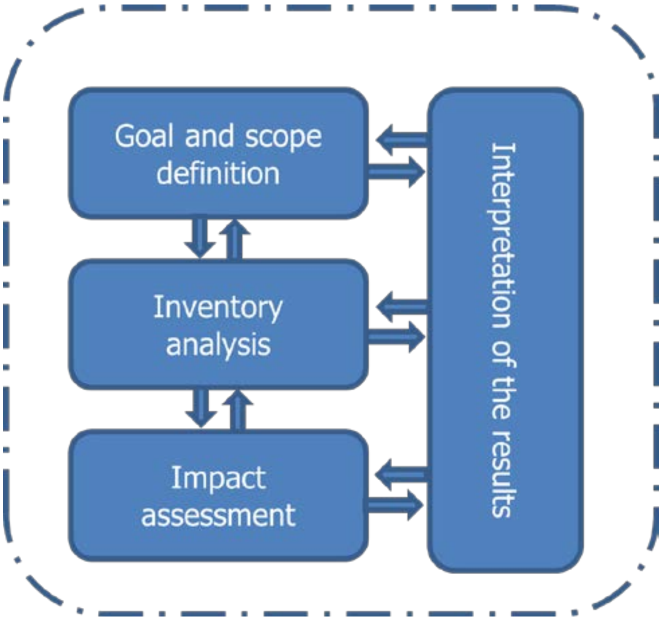
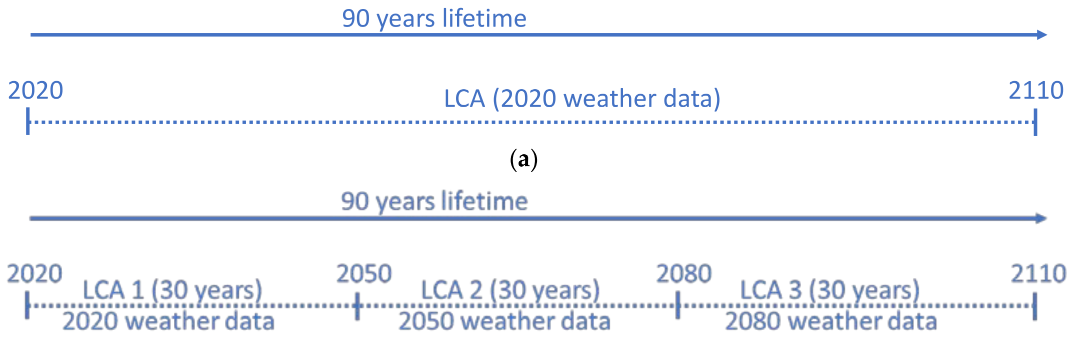


Figure 1. Life cycle assessment framework. Adapted from [48].

Table 7. Heating and cooling systems.

Component	**Variable**	**Value**	**Unit**
Gas boiler	Nominal heat output	24	kW
Air-source heat pump	Capacity	10	kW

Since the reference building is the same in all cases, the study was focused on the systems (operational stage) and not on the building materials; thus, only the gas boiler and the heat pump available in Ecoinvent were included in the LCA study. Failure to consider the individual materials that constitute the systems is the cause of an error. On the other hand, this approximation is reported throughout the analysis and, since it is a comparison, the error is compensated. The lifetime of the entire analysis was assumed to be 90 years, while the lifespan and the number of replacements of each system during the 90 years were calculated according to the lifetime of the various systems. Conventionally, the LCAs of products or buildings are performed with a lifetime ranging from 30 to 50 years [12,18,19,53,54], without considering any external variations (e.g., climate change) to the system boundary that could alter the environmental impact of the systems or the buildings. Following the conventional methodology, the LCA for 90 years (hereinafter referred to as LCA_b) was assessed by considering the same weather data for the entire period, as shown in Figure 2a. LCA_b was considered as a benchmark to compare the results of the LCA proposed in this analysis.



(**a**)

(**b**)

Figure 2. Life cycle assessment: (**a**) Considered as a benchmark (LCA_b); and (**b**) proposed in this study (LCA_{cc}).

This investigation was performed by considering the influence of both occupants' behaviour and climate change by varying the weather data every 30 years. In the end, the LCA for the entire lifetime of 90 years (hereinafter referred to as LCA_{cc}) was calculated as the sum of three contributions: LCA 1, LCA 2, and LCA 3, as shown in Figure 2b.

Based on previous studies carried out in this field [12,18,19,53], the functional unit of 1 m^2 of usable floor area was adopted in this analysis. The scope of the study is from 'cradle to grave'.

2.3.2. Life Cycle Inventory (LCI)

The life cycle inventory (LCI) is the phase of LCA destined to quantify all the inputs and outputs of a product system through its life cycle [48] and consists of three stages, manufacturing, operational, and end-of-life (disposal).

The inventory for the manufacturing stage of the systems is shown in Table 8. For both the gas boiler and heat pump, the disposal stage was included during the manufacturing stage.

Table 8. Inventory of the heating and cooling systems.

Element	Quantity	Unit of Measurement	Lifespan (Years)	Replacement	Total Amount
Gas boiler	1	Unit	20	4.5	4.5
Heat pump	1	Unit	20	4.5	4.5

The input data for the operational stage are the annual energy consumption for the heating and cooling systems shown in Table 6. The energy consumption of the heating and cooling systems was presented separately to consider the different impacts of electricity and natural gas.

2.3.3. Life Cycle Impact Assessment (LCIA)

The life cycle impact assessment (LCIA) is the phase of LCA in which the results of the LCI are associated with specific indicators to assess their potential environmental impacts [48]. Table 9 shows the LCIA during the manufacturing and disposal stage for both gas boiler and heat pump calculated with the GWP [$kgCO_2$-eq/m^2] and ReCiPe indicators [Impact point/m^2]. It can be noticed that the impacts for LCA_b and LCA_{cc} during the manufacturing and disposal stage are the same.

Table 9. Impact assessment during the manufacturing and disposal stage.

Element	**Unit**	**GWP 20a**	**GWP 100a**	**ReCiPe**
		[$kgCO_2$-eq/m^2]	**[$kgCO_2$-eq/m^2]**	**[Impact Point/m^2]**
Gas boiler	4.5	29.92	25.89	7.83
Heat pump	4.5	179.81	80.99	16.53

The LCIA during the operational stage of the heating and cooling systems calculated with both LCA_b and LCA_{cc} is presented in Tables 10 and 11.

Table 10. Impact assessment during the operational stage for 90-year lifetime (LCA_b).

Season	**Profile**	**GWP 20a**	**GWP 100a**	**ReCiPe**
		[$kgCO_2$-eq/m^2]	**[$kgCO_2$-eq/m^2]**	**[Impact Point/m^2]**
Heating	h1v1	856.55	694.39	67.04
	h1v2	782.13	634.06	61.21
	h1v3	852.15	690.82	66.69
	h2v1	268.33	217.53	21.00
	h2v2	254.12	206.01	19.89
	h2v3	287.11	232.75	22.47
	h3v1	445.65	361.28	34.88
	h3v2	399.82	324.13	31.29
	h3v3	441.40	357.84	34.55
Cooling	c1v4	119.20	109.38	22.33
	c1v5	104.94	96.30	19.66
	c1v6	101.35	93.00	18.98
	c2v4	103.25	94.74	19.34
	c2v5	93.92	86.18	17.59
	c2v6	90.95	83.46	17.03
	c3v4	100.24	91.98	18.77
	c3v5	97.94	89.87	18.34
	c3v6	91.67	84.12	17.17

Table 11. Impact assessment during the operational stage for 90-year lifetime (LCA_{cc}).

Season	**Profile**	**GWP 20a**	**GWP 100a**	**ReCiPe**
		[$kgCO_2$-eq/m^2]	**[$kgCO_2$-eq/m^2]**	**[Impact Point/m^2]**
Heating	h1v1	655.08	531.06	51.27
	h1v2	596.45	483.53	46.68
	h1v3	653.05	529.42	51.11
	h2v1	199.24	161.52	15.59
	h2v2	188.20	152.57	14.73
	h2v3	213.95	173.45	16.74
	h3v1	338.14	274.12	26.46
	h3v2	301.31	244.27	23.58
	h3v3	335.16	271.70	26.23

Table 11. *Cont.*

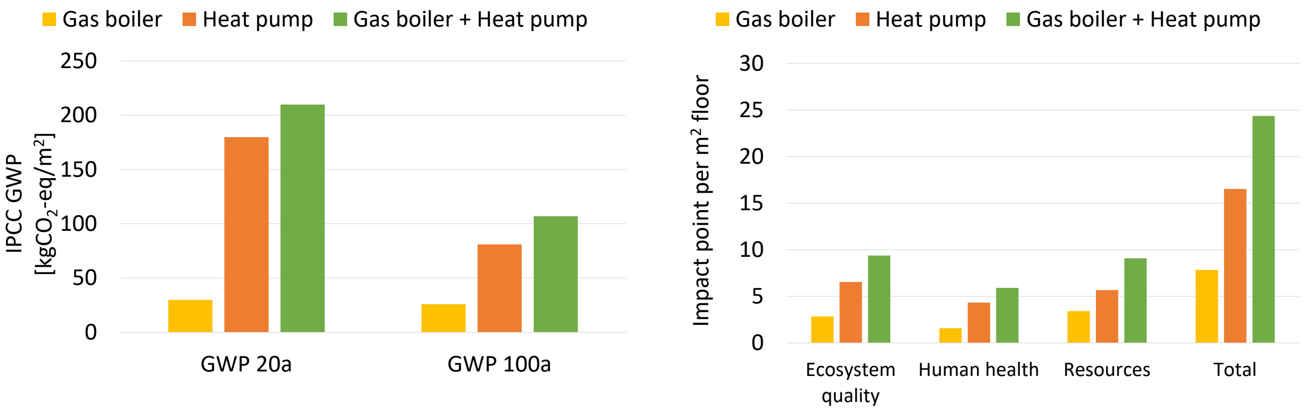
Season	Profile	GWP 20a	GWP 100a	ReCiPe
		[kgCO$_2$-eq/m^2]	[kgCO$_2$-eq/m^2]	[Impact Point/m^2]
Cooling	c1v4	183.79	168.65	34.42
	c1v5	156.54	143.64	29.32
	c1v6	157.88	144.88	29.57
	c2v4	156.24	143.37	29.26
	c2v5	135.82	124.64	25.44
	c2v6	138.03	126.66	25.85
	c3v4	164.09	150.57	30.73
	c3v5	174.92	160.52	32.76
	c3v6	164.48	150.93	30.81

3. Results and Discussion

The last step of the LCA, namely the interpretation of the results, is presented in this section.

3.1. Manufacturing and Disposal Stage

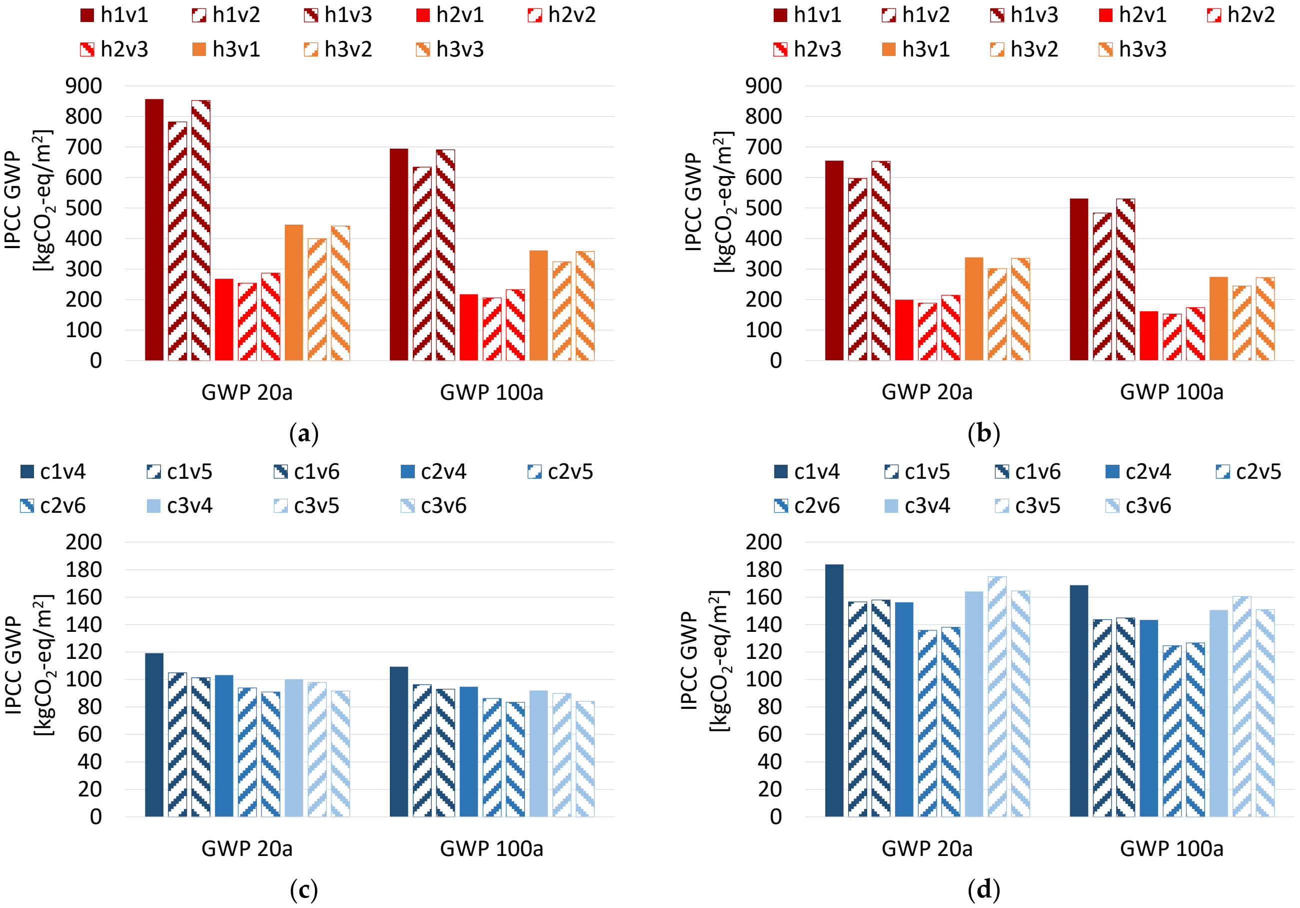
Figure 3 shows the impact of the gas boiler and the heat pump during the manufacturing and disposal stage calculated through the indicator IPPC GWP for short-term (GWP 20a) and long-term (GWP 100a) (Figure 3a), and the ReCiPe indicator (Figure 3b).



(**a**) (**b**)

Figure 3. Results per m^2 of floor area during the manufacturing and disposal stage using the indicators: (**a**) IPCC GWP 20a and GWP 100a; and (**b**) ReCiPe.

In general, the impact of the heat pump appears to be always higher than that of the gas boiler. It is in accordance with previous studies, such as [17,19]. In fact, the environmental impacts of the heat pump ranged from 180 kgCO$_2$-eq/m^2 (GWP 20a) to 81 kgCO$_2$-eq/m^2 (GWP 100a), far higher than those of the gas boiler that reached 30 kgCO$_2$-eq/m^2 for GWP 20 and 26 kgCO$_2$-eq/m^2 for GWP 100a. Regarding the ReCiPe indicator (Figure 4b), around 16 and 8 impact point/m^2 were obtained for the heat pump and the gas boiler, respectively. More in detail, the impact of the heat pump mainly affects the ecosystem quality (around 7 impact point/m^2), while the gas boiler has a higher impact in the category of resources with an environmental impact of around 3 impact point/m^2. The higher damage of the heat pump to the ecosystem could be caused by the presence of refrigerant in the system. The heat pump found in the Ecoinvent database includes the R134a refrigerant that is one of the most damaging, by varying the typology of the refrigerant it could be possible reducing the impact of the heat pump [18]. Additionally, the damage due to the gas boiler may be reduced by decreasing the quantity of material used for manufacturing. The impacts obtained for the manufacturing and disposal stage are in line with the values of existing researches, e.g., [18,19].



(**a**) (**b**) (**c**) (**d**)

Figure 4. Comparison of the results per m^2 of floor area during the operational stage using the indicator IPCC GWP 20a and GWP 100a calculated: For heating with (**a**) LCA$_b$; and (**b**) LCA$_{cc}$; and for cooling with (**c**) LCA$_b$; and (**d**) LCA$_{cc}$.

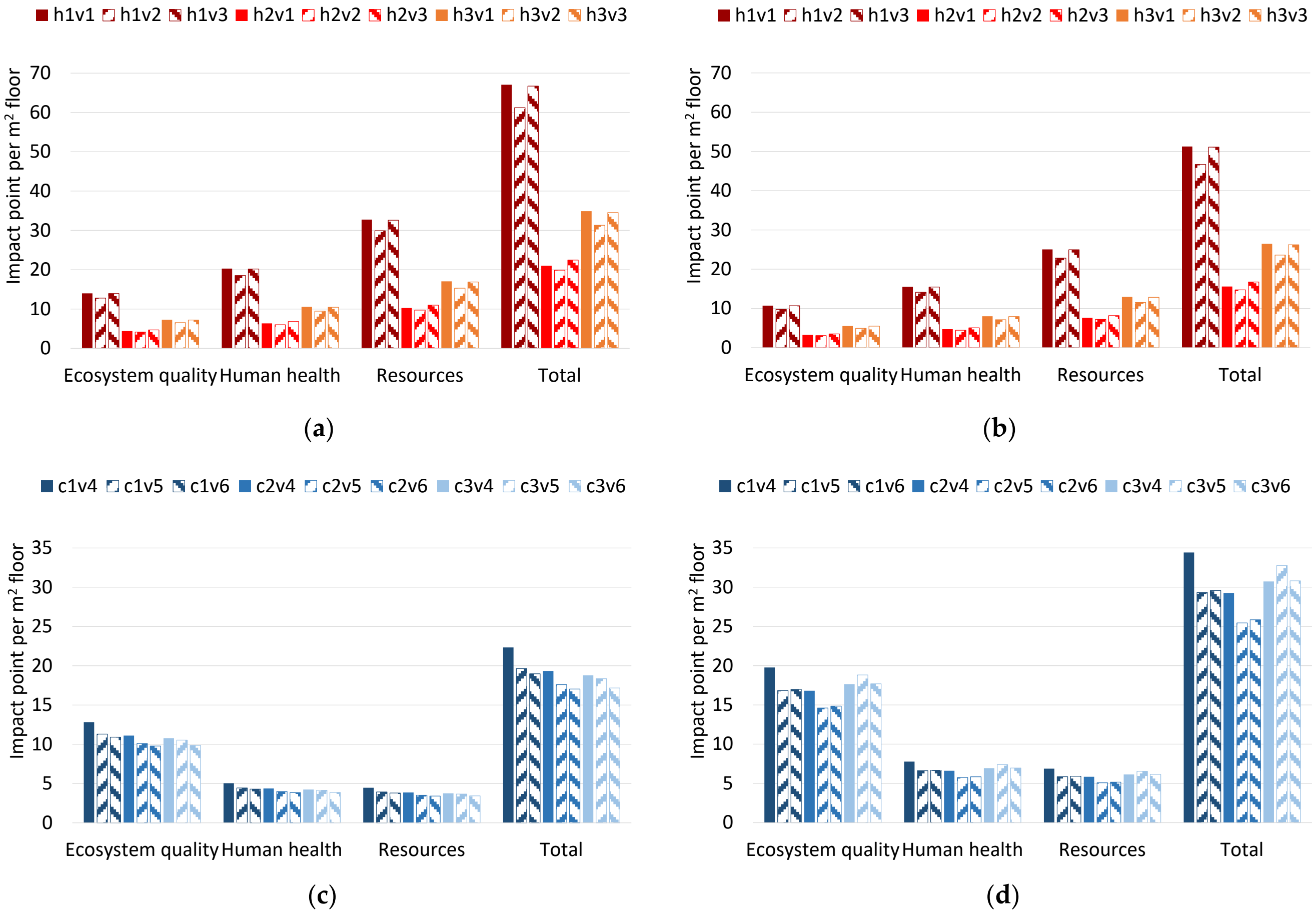
3.2. Operational Stage

The results of the impacts of the heating and cooling systems during the operational stage calculated with the GWP indicator are shown in Figure 4.

LCA$_b$ and LCA$_{cc}$ provided different results: the impacts of the heating were higher for LCA$_b$ (Figure 4a) than those calculated with LCA$_{cc}$ (Figure 4b), and opposite trends were observed for the cooling (Figure 4c,d). These results can be explained by the fact that climate change, which will cause a decrease in heating consumption and an increase in cooling consumption [33,45], was included only in the LCA$_{cc}$ analysis. Moreover, it can be seen how a different occupant behaviour can influence the impact of these systems, at first glance.

Regarding the heating environmental impact, it was possible to observe variation mainly among the heating profiles. Maximum impact variations equal to −70% and −53% were obtained between the profile h1v1 and the profiles h2v2 and h3v2. For the LCA$_b$, the highest impact was obtained for the profile h1v1 (857 kgCO$_2$-eq/m^2 for GWP 20a and 694 kgCO$_2$-eq/m^2 for GWP 100a), while the lowest impact was observed for the profile h2v2 (254 kgCO$_2$-eq/m^2 for GWP 20a and 206 kgCO$_2$-eq/m^2 for GWP 100a). With LCA$_{cc}$ the maximum and minimum impacts were also found for h1v1 and h2v2, with values 24% and 26% lower than those found with LCA$_b$.

The environmental impact of the cooling system varied among the three cooling usage profiles and from one ventilation profile to another. Additionally, while the impacts calculated with LCA$_b$ decreased moving from c1 to c3 and from v4 to v6, this trend was not found with LCA$_{cc}$. The maximum impact was due to the profile c1v4 with both LCA$_b$ (Figure 4c) and LCA$_{cc}$ (Figure 4d); the minimum impact was obtained for the profile c2v6 with LCA$_b$ and the profile c2v5 with LCA$_{cc}$. The discrepancy between the results of LCA$_{cc}$ and LCA$_b$ was caused by climate change that influenced the energy consumptions of the profiles and engendered a different augmenting of the hours of operation of the cooling system during the considered 90 years. LCA$_b$ provided the maximum and minimum impact values equal to 119 and 91 kgCO$_2$-eq/m^2 for the short-term effect GWP 20a and equal to 109 and 84 kgCO$_2$-eq/m^2 for long-term effect GWP 100a, respectively. With LCA$_{cc}$, values equal to 184 kgCO$_2$-eq/m^2 (GWP 20a) and 169 kgCO$_2$-eq/m^2 (GWP 100a) for the profile c1v4 and equal to 136 kgCO$_2$-eq/m^2 (GWP 20a) and 124 kgCO$_2$-eq/m^2 (GWP 100a) for the profile c2v5 were obtained. Figure 5 shows the results of the impacts during the operational stage of the two considered systems calculated with the indicator ReCiPe. The trends observed among the usage profiles with the GWP indicator were also encountered with the indicator ReCiPe. According to the results of Figure 3b, the damage caused during the operational stage of the heating system (Figure 5a,b) mainly affects the resources category, while the impact of the cooling operation (Figure 5c,d) was particularly damaging for the ecosystem quality.



(**a**) (**b**)

(**c**) (**d**)

Figure 5. Comparison of the results per m^2 of floor area during the operational stage using the indicator ReCiPe calculated: For heating with (**a**) LCA$_b$; and (**b**) LCA$_{cc}$; and for cooling with (**c**) LCA$_b$; and (**d**) LCA$_{cc}$.

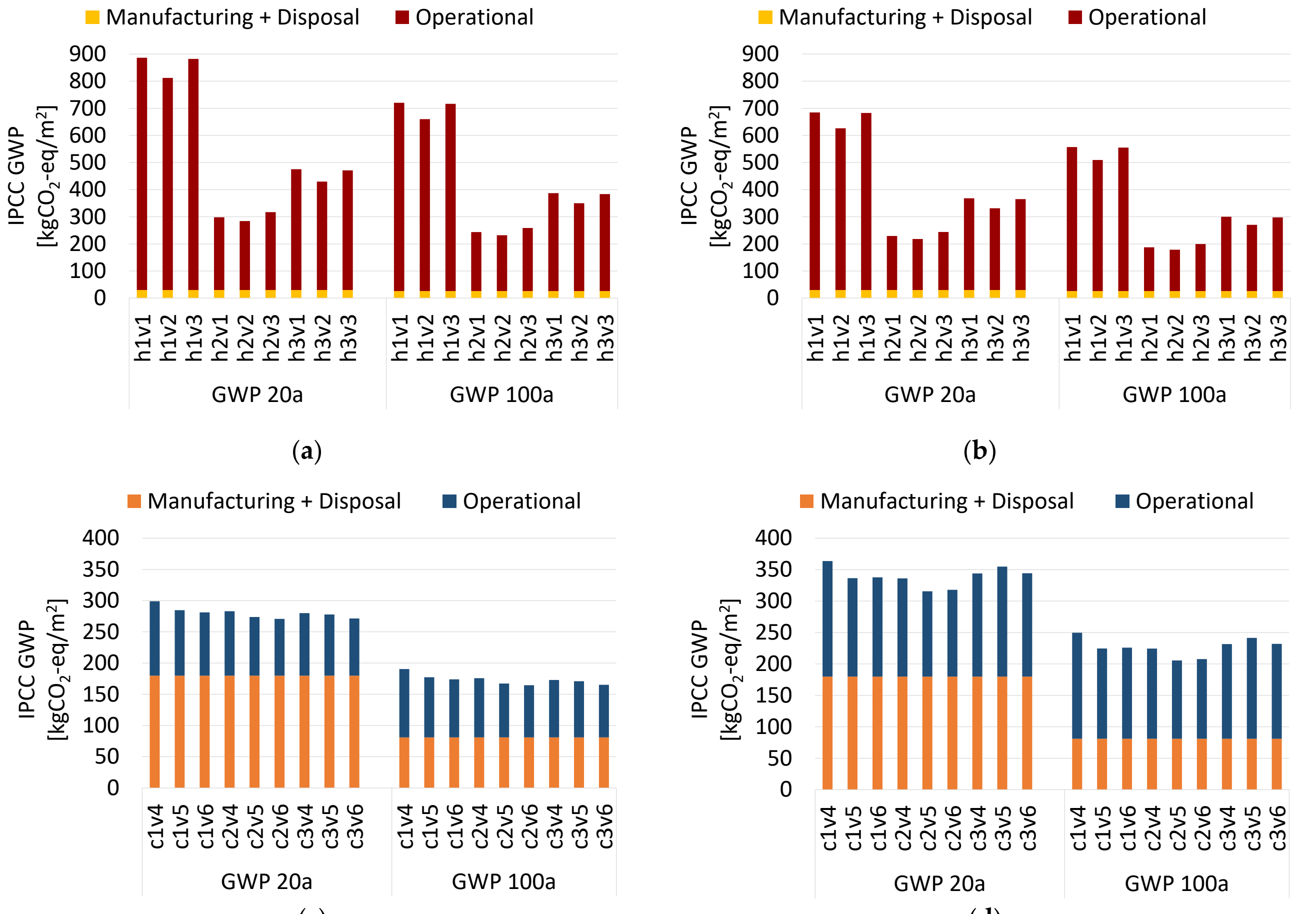
The impact caused by heating in the category of resources reached peaks of 33 and 25 impact point/m^2 with LCA$_b$ and LCA$_{cc}$, respectively. Regarding the cooling operation, maximum impact points per m^2 of about 13 and 20 were obtained from LCA$_b$ and LCA$_{cc}$ in the ecosystem quality category.

The effect of climate change produced a reduction of the total impacts caused by the heating system for LCA_{cc}, if compared with those obtained with LCA_b. In particular, impact values from 20 to 67 impact point/m^2 (Figure 5a) and from 15 to 51 impact point/m^2 (Figure 5b) were obtained through the indicator ReCiPe.

An opposite effect was produced to the impact of the cooling system that was higher for LCA_{cc}. Impact values from 17 to 22 impact point/m^2 and from 25 to 34 impact point/m^2 were obtained with LCA_b and LCA_{cc}, respectively.

3.3. Total Impact (Manufacturing, Operational, and Disposal Stage)

The total impacts of the heating and cooling systems, namely the impact caused during the manufacturing, operational, and disposal stage, calculated through the GWP indicator are shown in Figure 6.



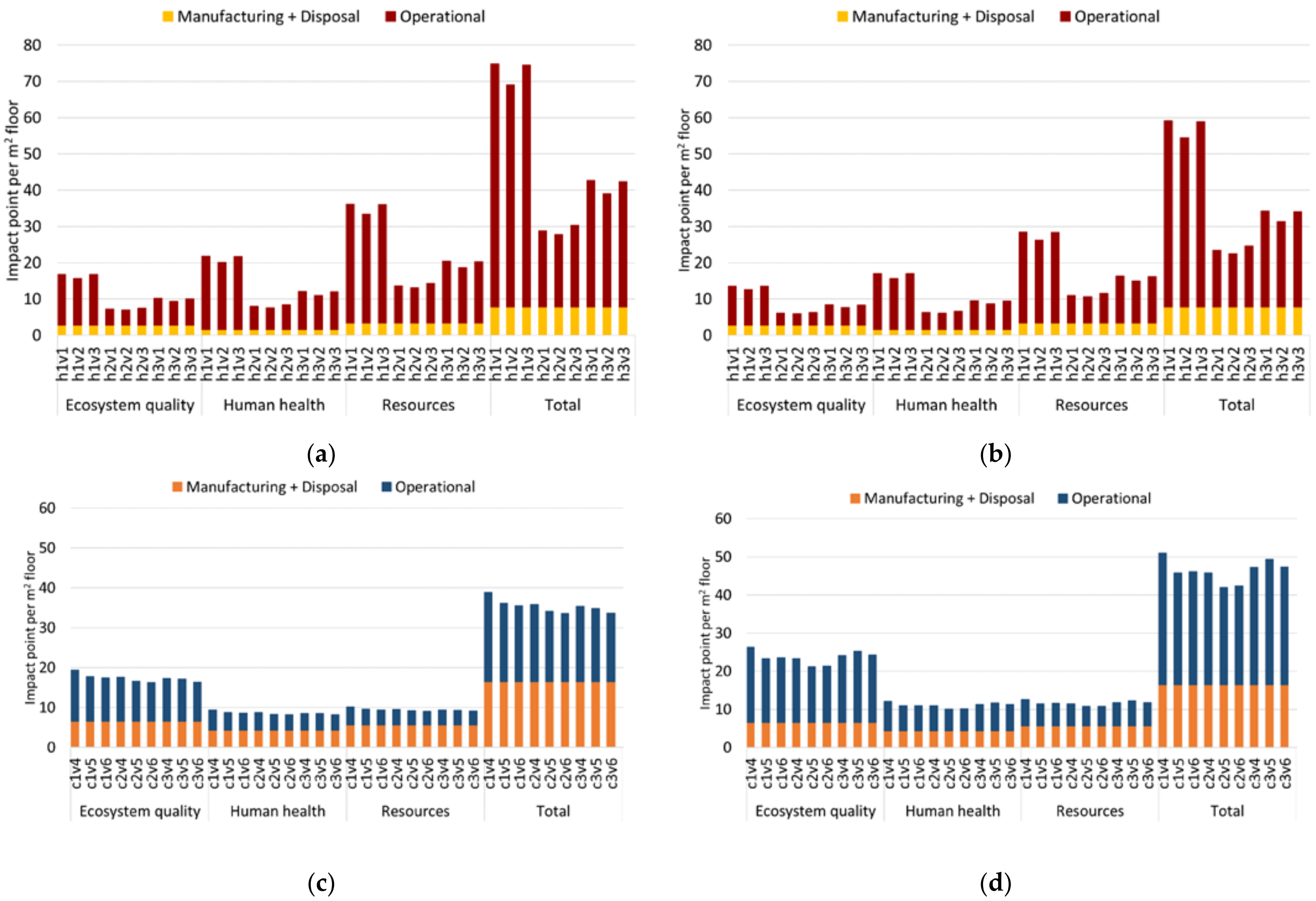
(**a**) (**b**)

(**c**) (**d**)

Figure 6. Comparison of the total results per m^2 of floor area (manufacturing and disposal + operational stage) using the indicator IPCC GWP 20a and GWP 100a calculated: For heating with (**a**) LCA_b; and (**b**) LCA_{cc}; and for cooling with (**c**) LCA_b; and (**d**) LCA_{cc}.

It is interesting to notice that, while for the heating system (Figure 6a,b) the total impact is almost completely due to the operational stage (more than 90%), the impact related to cooling (Figure 6d) changed between GWP 20a and GWP 100a. In fact, for all the nine cooling profiles the impact for short-term effect (GWP 20a) is mainly due to the manufacturing and disposal stage, while for the long-term effect the environmental damage related to the operational stage is predominant.

Similar results were obtained with the indicator ReCiPe (Figure 7a–d). The total impact due to heating was mainly caused by the operational stage.



(**a**) (**b**)

(**c**) (**d**)

Figure 7. Comparison of the total results per m^2 of floor area (manufacturing and disposal + operational stage) using the indicator ReCiPe calculated: For heating with (**a**) LCA$_b$; and (**b**) LCA$_{cc}$; and for cooling with (**c**) LCA$_b$; and (**d**) LCA$_{cc}$.

Regarding the cooling system, the operational was also the most damaging stage. Only for human health and resources categories, manufacturing appeared to be the most impacting stage. This can be explained by the fact that the impact of the cooling system in these categories was very low if compared with that of the ecosystem quality category.

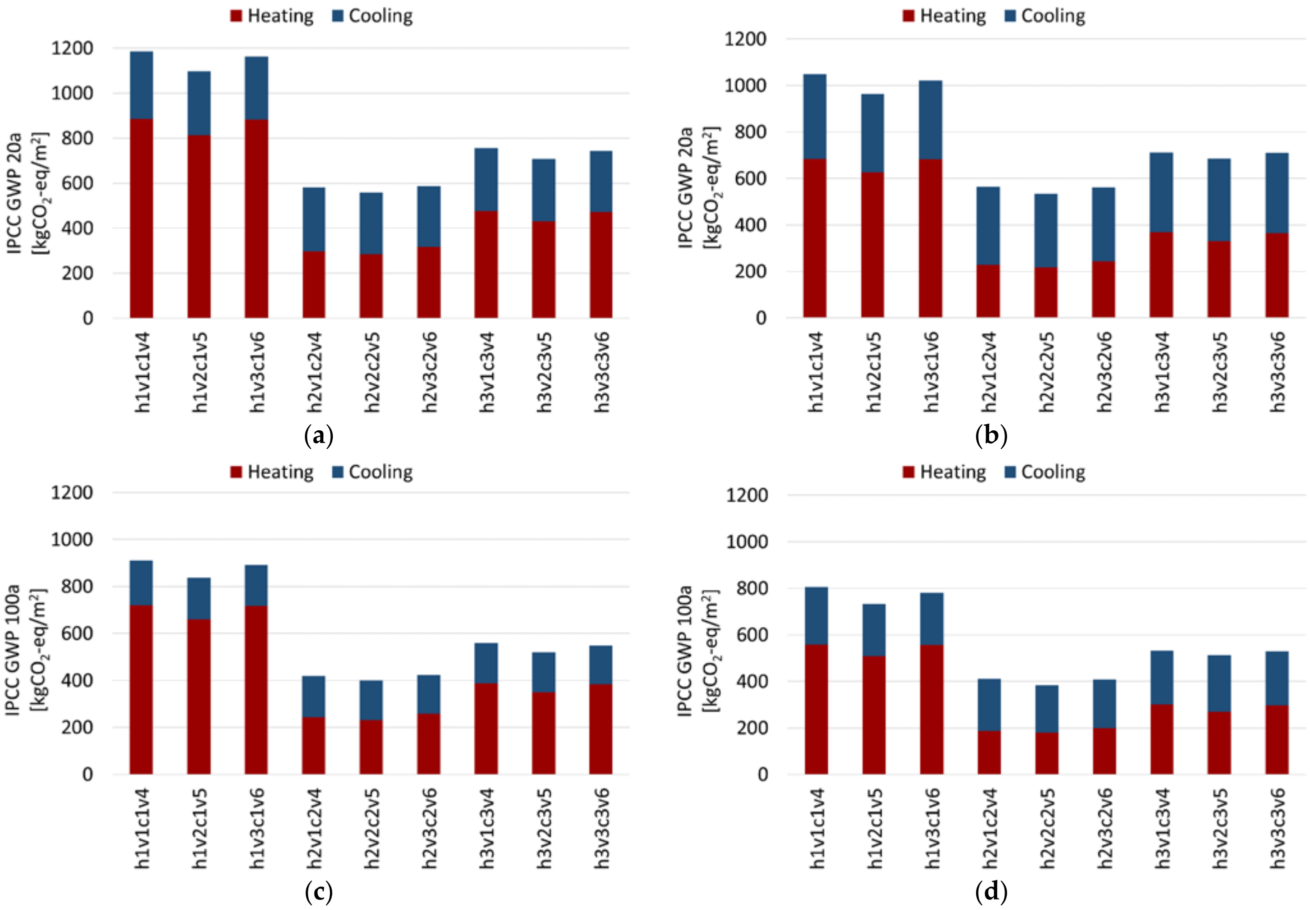
3.4. Annual Impact of the Two Systems

Figures 8 and 9 show the comparison between the annual results per m^2 of floor area calculated with LCA$_b$ and LCA$_{cc}$ through the indicators GWP and ReCiPe.

In general, LCA$_b$ provided impact values ranging from 1185 to 558 kgCO$_2$-eq/m^2 with GWP 20a (Figure 8a) and from 911 to 419 kgCO$_2$-eq/m^2 with GWP 100a (Figure 8c). The results obtained with LCA$_{cc}$ (Figure 8b,d) were always lower than the previous, in a measure ranging from −3% (with profiles h2v1c2v4 and h3v2c3v5) to −12% (with profiles h1v1c1v4, h1v2c1v5, and h1v3c1v6).

Analysing more in depth the results, for LCA$_b$ the impact due to heating operation was always higher than that caused by cooling. In contrast, the cooling impact appeared to be predominant in three profiles (h2v1c2v4, h2v2c2v5, and h2v3c2v6) with LCA$_{cc}$.

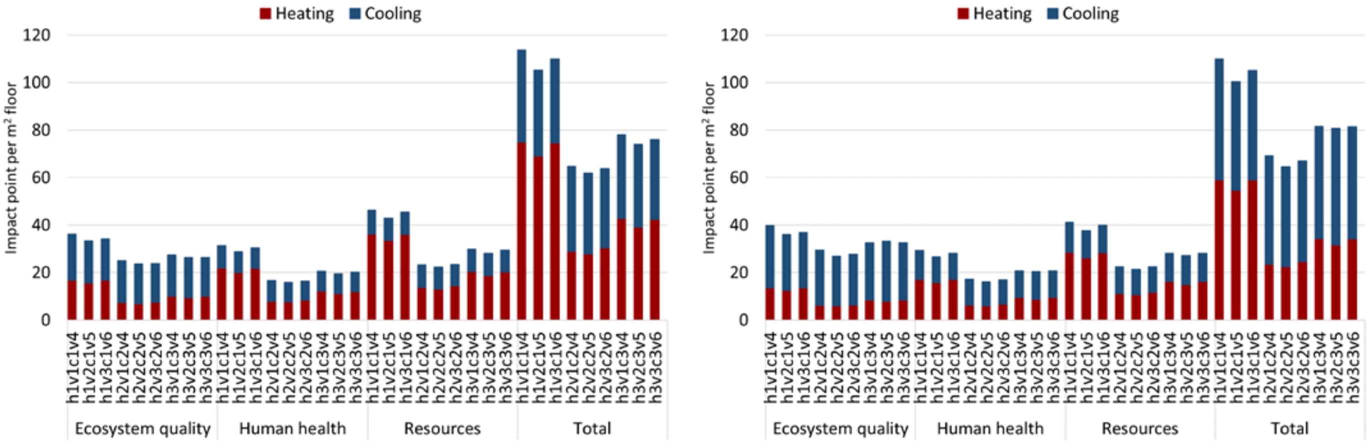
Regarding the annual results obtained with the ReCiPe indicator, it should be noticed that LCA$_b$ provided impacts higher than those of LCA$_{cc}$ only for the first three profiles. Furthermore, LCA$_b$ (Figure 9a) attributed to the heating system the main percentage of the total impact for six out nine profiles (h1v1c1v4, h1v2c1v5, h1v3c1, h3v1c3v4, h3v2c3v5, h3v3c3v6). In the case of LCA$_{cc}$ (Figure 9b), the impact of the heating system is the major contributor of the total impact only for the first three profiles (h1v1c1v4, h1v2c1v5, and h1v3c1v6).



(**a**) (**b**)

(**c**) (**d**)

Figure 8. Comparison of the annual results per m^2 of floor area (manufacturing and disposal + operational stage) for heating and cooling calculated: using the indicator IPCC GWP 20a with (**a**) LCA$_b$; and (**b**) LCA$_{cc}$; and using the indicator IPCC GWP 100a with (**c**) LCA$_b$; and with (**d**) LCA$_{cc}$.

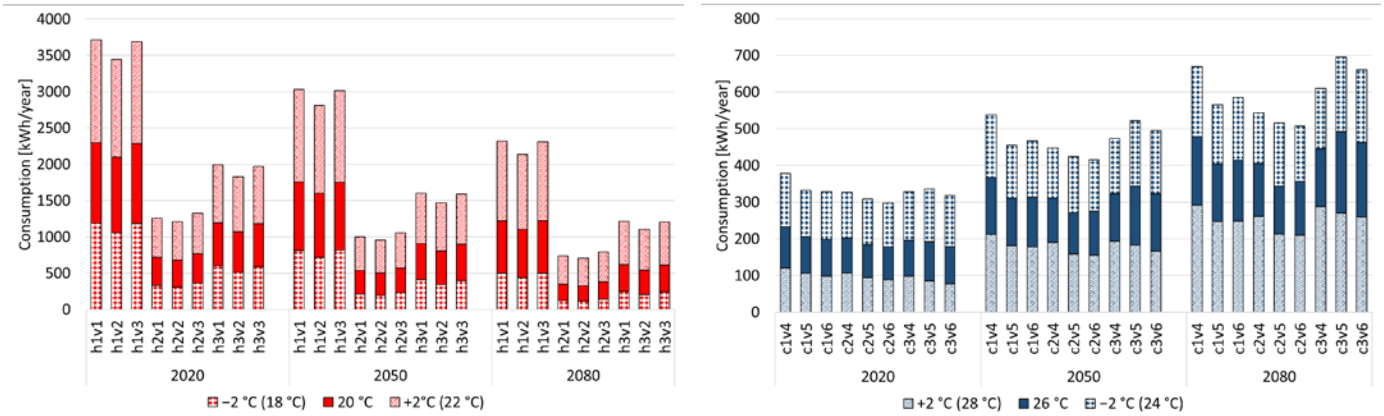


(**a**) (**b**)

Figure 9. Comparison of the annual results per m^2 of floor area (manufacturing and disposal + operational stage) for heating and cooling using the indicator ReCiPe calculated with: (**a**) LCA$_b$; and (**b**) LCA$_{cc}$.

3.5. Influence of Occupant Behaviour by Varying the Setpoint Temperature

As already mentioned in Section 2.2, energy simulations were also performed by varying the heating and cooling setpoint temperatures of ±2 °C and, hence, considering occupants preferences in thermal comfort. The energy consumption obtained by varying the setpoint temperatures during the three climatic scenarios is shown in Figure 10.



(**a**) (**b**)

Figure 10. Energy consumption [kWh/year] by varying the setpoint temperatures of ±2 °C for (**a**) heating; and (**b**) cooling.

These changes in energy consumption will have a consequence on the environmental impact of the heating and cooling systems. The impact variations, expressed as the percentage difference between the impacts calculated with setpoint temperature at 20 °C (heating) and 26 °C (cooling) and the impacts with a setpoint variation of ±2 °C, are shown in Table 12.

Table 12. Impact variations by varying the setpoint temperatures of ±2 °C.

Season	Profiles	LCA_b		LCA_{cc}	
		−2 °C	+2 °C	−2 °C	+2 °C
		[Variations (%) of Both GWP and ReCiPe]			
Heating	h1v1	−48	+62	−53	+72
	h1v2	−50	+64	−54	+75
	h1v3	−48	+61	−52	+71
	h2v1	−54	+75	−58	+87
	h2v2	−55	+77	−59	+90
	h2v3	−53	+72	−57	+84
	h3v1	−50	+66	−54	+77
	h3v2	−52	+70	−56	+82
	h3v3	−50	+66	−54	+77
Cooling	c1v4	+62	−49	+47	−42
	c1v5	+62	−48	+47	−42
	c1v6	+66	−50	+49	−43
	c2v4	+62	−47	+44	−40
	c2v5	+68	−49	+57	−42
	c2v6	+67	−51	+51	−44
	c3v4	+68	−50	+47	−40
	c3v5	+75	−56	+51	−48
	c3v6	+77	−57	+53	−48

It can be inferred that LCA_b provided percentage variations of the heating impacts lower than those obtained with LCA_{cc}, opposite trends were found for the environmental impact of the cooling system. In general, the reduction of 2 °C of the heating setpoint temperature led to a reduction of the heating impact ranging from −48% to −55% with LCA_b and from −52% to −59% with LCA_{cc}. In both cases, the maximum reduction was obtained for the profile h2v2. This profile registered the maximum variation also with the increase of setpoint temperature of +2 °C. In this case, impact variations from +61% to +77% and from +71% to +90% were obtained for LCA_b and LCA_{cc}, respectively.

With cooling, percentage variations of the impact from +62% to +77% and from +44% to +57% were encountered by reducing the setpoint temperature of 2°C with LCA_b and LCA_{cc}. Additionally, an augmentation equal to +2 °C of the cooling setpoint temperature produced an impact drop ranging from −47% to −57% and from −40% to −48%, for LCA_b and LCA_{cc}, respectively.

Unlike heating, the maximum variations were found for different profiles: c3v6 with LCA_b, and for c2v5 (−2 °C) and the profiles c3v5 and c3v6 (+2 °C) with LCA_{cc}.

4. Conclusions

A life cycle assessment was conducted for the heating and cooling systems of a residential building located in southern Italy. The indicators IPCC 2013 Global Warming Potential for short and long-term effect (GWP 20a and GWP 100a) and ReCiPe were adopted to perform the study, for a functional unit of 1 m^2 of usable floor area.

The novelty of the paper consists in the consideration of the effect of two factors usually neglected in such studies. In particular, the analysis was carried out for a lifetime of 90 years by considering the influence of both occupant behaviour and climate change on the operational stage of the systems (LCA_{cc}). The comparison was made with the results of an LCA conducted in a conventional way (LCA_b), namely ignoring the external influences such as climate change. In general, the percentage differences encountered with the GWP during the different stages were also found with the ReCiPe indicator.

Concerning the manufacturing and disposal stage, the results of the LCA_b and LCA_{cc} were the same. For both indicators, the environmental impact of the gas boiler was lower than that of the heat pump. This result is in accordance with that of previous studies (e.g., [17]). In particular, with the ReCiPe indicator, the heat pump appeared to be more degrading for the ecosystem quality, while the gas boiler for the resources category.

Nine usage profiles for the heating season and the same for the cooling were adopted, and significant differences were observed from one profile to another in both LCAs, with similar trends but different magnitude. The impacts caused by the heating operation were highest for LCA_b, while those of cooling resulted greatest for LCA_{cc}. These results can be justified by the fact that the effects of climate change were not considered in LCA_b leading to an overestimation of the heating impacts and an underestimation of those caused by cooling. Regarding heating, the differences were more among the heating profiles (h1, h2, h3) than between one natural ventilation profile to another (v1, v2, v3). Impact values of the order of 800 $kgCO_2$-eq/m^2, 400 $kgCO_2$-eq/m^2, and 200 $kgCO_2$-eq/m^2 were found with LCA_b for h1, h3, and h2, respectively. Maximum and minimum variations were observed between h1v1 and h2v2 (−70%), and between h1v1 and h3v1 (−48%). With LCA_{cc} the maximum and minimum impacts were also found for h1v1 and h2v2, with values 24% and 26% lower than those found with LCA_b, respectively. Unlike the heating system, the environmental impact of the cooling system varied among the three cooling usage profiles and from one ventilation profile to another. Only with LCA_b it was possible to observe a decreasing trend of the impacts moving from c1 to c3 and from v4 to v6. Additionally, while the maximum impact with both LCA_b and LCA_{cc} was encountered for the profile c1v4, the minimum impact was found for the profile c2v6 with LCA_b and the profile c2v5 with LCA_{cc}. In general, the impact caused by the cooling operation with LCA_b was always lower than that calculated with LCA_{cc} in a measure ranging from −33% to −44%.

Regarding the total impact calculated during the entire lifetime, there is a huge difference between the cause of the heating and cooling impacts. In fact, while more than 90% of the heating impact is sourced from the operational stage, that of the cooling is mainly due to the manufacturing and disposal stage for the short-term effect (GWP 20a) and due to operational stage for long-term effect (GWP 100a). With the ReCiPe indicator, the operational stage was predominant for both heating and cooling systems.

The analysis of the annual impact of the system allowed a better understanding of the differences between LCA_b and LCA_{cc} and between the results of GWP and ReCiPe.

According to the GWP indicator, the annual impact provided by LCA_b was always higher than that obtained with LCA_{cc}. Impact variations between LCA_b and LCA_{cc} ranging from 3% to 14% were found. Additionally, the environmental impact of the heating was the main contributor of the annual impact for all the nine usage profiles with LCA_b, and for six out nine profiles with LCA_{cc}. With the ReCiPe indicator, the total impact calculated with LCA_b was higher than LCA_{cc} only with the first three profiles. Additionally, while with LCA_b the impact of the heating was greater than the cooling impact for the first and last three profiles, with LCA_{cc} the heating impact was predominant only for the first three profiles.

This study was the first attempt of including the influence of occupant behaviour and climate change on the assessment of the environmental impact of the heating and cooling systems. Both occupants' behaviour and climate change appeared to highly affect the environmental performance of the systems. With the ongoing concern with climate change, more attention needs to be dedicated to the cooling demand that showed an increasing impact during the LCA analysis. These findings are important and informative for scientists and policymakers for future regulations and design criteria. A limitation of this investigation consists in the fact that one system typology for heating and cooling were considered and the energy simulations were carried out for a building. Moreover, the study was developed on a real case and conducted for its location in terms of climatic conditions. On the other hand, the outcomes of this study can be considered indicative of what could happen in other Mediterranean countries with similar systems. Moreover, the results of this study encourage further studies to analyse more in deep the influence of the occupant behaviour and consider different typologies of heating and cooling systems, the integration of renewable energy sources, and more climatic zones. As a consequence of these results, future studies on the environmental impacts of heating and cooling systems will have to carefully analyse the operational phase, adopting more realistic and contextualised usage profiles and also considering the influence of climate change.

Author Contributions: Conceptualization, G.F., E.B. and L.F.C.; methodology, G.F., E.B. and L.F.C.; software, G.F.; validation, L.F.C.; formal analysis, G.F.; investigation, G.F. and E.B.; resources, L.F.C. and M.D.S.; data curation, L.F.C.; writing—original draft preparation, G.F.; writing—review and editing, E.B., L.F.C., M.D.S. and L.B.; visualization, G.F.; supervision, L.F.C.; project administration, L.F.C. and M.D.S.; funding acquisition, L.F.C. and M.D.S. 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 research was partially funded by the Ministerio de Ciencia, Innovación y Universidades de España (RTI2018-093849-B-C31—MCIU/AEI/FEDER, UE) and 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 programme.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: Data are available upon request to the corresponding author.

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

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

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