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# Environmental and energy analysis of the renovation of social housing buildings under various climate change scenarios and user profiles

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## ABSTRACT

The renovation of social housing buildings, a priority for the European Union, must be assessed under a Climate Change (CC) context. This work, centred on the user and the environmental impact, analyses the climate resilience of the renovation of the social housing building stock of the Basque Country, located in Northern Spain. In this region, characterised by cold winters and mild summers, CC projections indicate a moderate warming even in the worst-case scenario. The assessment of passive renovation actions indicates that reducing heating demand is key no matter the CC scenario. The reduction achieved in heating demand with deep passive renovations is up to 82.2 % when the worst CC scenario is considered. Indeed, since low-income tenants occupy these buildings, it has been found that global warming would help users achieve indoor standard conditions in a more effective way than with passive renovation actions. Consequently, to improve indoor conditions independently of the CC scenario, active renovation measures must also be considered. Furthermore, the thermal comfort analysis proved that the risk of overheating in this region is negligible, with less than 4 % of the yearly hours above 26 °C. Finally, the Life Cycle Impact Assessment shows that the environmental impact of the renovation is short when compared to the impact of the operational stage. The use of conventional or ecological materials during renovation would save up to 6.5 % of Non-Renewable Primary Energy Consumption and 3.7 % of $CO_2$ emissions during the life-cycle of the building.

Acronyms:

| | |
|---|---|
| AR5 | Fifth Assessment Report of the Intergovernmental Panel on Climate Change |
| AR6 | Sixth Assessment Report of the Intergovernmental Panel on Climate Change |
| BAU | Business as Usual |
| BMS | Building Management System |
| CC | Climate Change |
| CDD | Cooling Degree Days |

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(*continued*)

| | |
|---|---|
| CIMP | Coupled Model Intercomparison Project |
| CTE DB-HE | Spanish Construction Technical Code - Energy Section |
| DB | Design Builder |
| DHW | Domestic Hot Water |
| EPBD | Energy Performance of Buildings Directive |
| EPC | Energy Performance Certificate |
| EPD | Environmental Product Declaration |
| EPG | Energy Performance Gap |
| ETICS | External Thermal Insulation Composite Systems |
| EU | European Union |
| GCM | Global Circulation Models |
| GHG | Greenhouse Gas |
| HDD | Heating Degree Days |
| HVAC | Heating, Ventilation and Air-Conditioning |
| IPCC | Intergovernmental Panel on Climate Change |
| LCI | Life Cycle Inventory |
| LCIA | Life Cycle Impact Assessment |
| LHV | Lower Heating Value |
| MCV-HR | Mechanically Controlled Ventilation with Heat Recovery |
| MW | Mineral Wool |
| NRPEC | Non-Renewable Primary Energy Consumption |
| RCM | Regional Climate Models |
| RCP | Representative Concentration Pathway |
| RH | Relative Humidity |
| RM | Renovation Measure |
| RQ | Research Question |
| RREE | Renewable Energies |
| RSL | Reference Service Life |
| SHGC | Solar Heat Gain Coefficient |
| SSP | Shared Socioeconomic Pathway |
| TMY | Typical Meteorological Year |
| UP | User Profile |
| WCRP | World Climate Research Programme |
| WGI | Working Group I |

## 1. Introduction

The scientific evidence concerning Climate Change (CC) is overwhelming [1] and recent forecasts provided by the Intergovernmental Panel on Climate Change (IPCC) [2] are pessimistic regarding current global inaction. The scientific community also agrees that anthropogenic Greenhouse Gas (GHG) emissions are the prominent causes of CC. In the Sixth Assessment Report (AR6) of the IPCC [3], released in 2023, buildings have been identified as one of the main sectors with a high potential for demand-side mitigation of GHG emissions options by 2050, followed by land transport and food industry. Consequently, in the European Union (EU), the renovation of the building stock [4] is considered critical to reducing GHG emissions and achieving climate targets.

To assess the long-term renovation of the EU building stock, a necessary precondition is to properly forecast the different CC scenarios. The World Climate Research Programme (WCRP) [5], created in 1990, has been working over the last few decades to develop models that reliably represent the Earth's climatic behaviour, within the Coupled Model Intercomparison Project (CIMP). In 2021, the Working Group I (WGI) of the IPCC, which assesses the physical science of CC, established different Representative Concentration Pathways (RCPs) [6], which describe four distinct 21st Century trajectories of GHG emissions and atmospheric concentrations, air pollutant emissions, and land use. These trajectories include a strict mitigation scenario (RCP2.6), two intermediate scenarios (RCP4.5 and RCP6.0), and a scenario with a very high level of GHG emissions (RCP8.5). More recently, within the AR6, the IPCC released different Shared Socioeconomic Pathways (SSPs), which are based on the RCPs and take into account the changes in population, economic growth, education, urbanization and technological development [7]. Therefore, the scientific community is committed to establishing a consistent framework and guidelines to model possible future climate scenarios.

To analyse the effect of the possible future weather scenarios on the building sector, it is determinant to work with accurate and reliable future weather files, which is a complex and controversial field of research. These discrepancies are mainly due to the methodology used to generate future weather files and the meteorological models existing within each methodology. Regarding the used methodologies, the most commonly used one is downscaling [8], with the majority of works using the approach of morphing the Typical Meteorological Year (TMY) data with downscaled output data from the Global Circulation Models (GCM) or the Regional Climate Models (RCM). Regarding the models, there is much discussion and a lot depends on the location and detail of the grid required [9]. Another important aspect to consider is which variables (temperature, relative humidity, solar radiation, precipitation, etc.) are estimated or not. The CCWorldWeatherGen tool [10], developed by a research group from the University of Southampton, is one of the most popular morphing tools to downscale and morph the weather data from GCMs to the location of study. Other similar tools are Meteonorm [11] and Weathershift [12], but these are private initiatives. More recently, an interesting open source tool has been developed, FutureWeatherGen [13], which is updated with the latest SPS scenarios of the AR6, and offers the RCM of the region of Portugal while morphing the most important meteorological variables.

The scientific community has been aware for decades that there is a need to analyse the effect of CC on buildings [14]. As indicated before, researchers are also aware that a proper selection of the methodology and model to generate future weather scenarios are vital to obtain the most representative and accurate results as possible [15,16]. Within the literature, there are studies at different building levels and types of buildings, for instance, at a district level [17], in office buildings [18] and in residential buildings [19]. In general, there is a common denominator in all the analysed studies, which is that CC will reduce heating demand and significantly boost cooling demand, due to global warming [20]. An interesting review, elaborated by Andrić et al. [21], highlights the causes of uncertainty when assessing the effect of CC on buildings. They suggest that the share of cooling and heating is strongly influenced by the detail of the model used (GMC or RCM), the time scenario considered (2050 or 2100) and the location of the building.

However, as explained before, the current building stock of the EU is under scrutiny and building renovation needs to be boosted in the upcoming years to contribute to the 2030 Climate Target of reducing emissions by at least 55 % compared to 1990 [22,23]. Thus, the influence of CC on buildings must not be evaluated under the characteristics of the current building stock, rather considering the upcoming renovated buildings. Worldwide, literature can be found regarding the performance of retrofits under climate change [10, 24–27]. A comprehensive review, performed by Liyanage et al. [28], analysed in detail the effect of various Renovation Measures (RM) under a CC framework, differentiating between passive renovations, active renovations and the installation of Renewable Energies (RREE). In this sense, they highlight that passive renovation measures are key to reducing the impact of CC on buildings, and that they are a necessary precondition before attempting to renovate systems or implement RREE. In addition, the results of this study show that the effectiveness of a specific RM mainly depends on the location of the building. In predominantly cold climates, renovation actions are more focused on reducing heating demand, but a risk of overheating has been identified by several researchers [29,30]. On the contrary, in currently hot climates, building renovations are already focused on tackling the cooling demand, mainly with passive solutions [31].

Nevertheless, it is not only important to analyse the performance of building renovations under CC, but also to assess the indoor conditions of the inhabitants. Several of the aforementioned studies indicate that the analysis of user comfort, for which different methodologies are available, is relevant [32]. It is well known that adaptive comfort models are the most trusted, but recent studies highlight that climatic and cultural aspects must also be considered when properly assessing comfort in dwellings. For instance, a study performed by Marco et al. [33], in northern Italy, compared the thermal comfort of the renovation of residential buildings under CC comparing three different comfort models: namely, the Fanger model [34], the UNE-EN 16798 adaptive model [35] and an ad-hoc model developed for the region [36]. One relevant output of the said study is that the three models are not influenced by the building renovation, but strongly influenced by climate change.

Besides the performance of the renovation and user comfort, other indicators can also be found within the literature to analyse the effect of CC on buildings, such as economic, social, thermal-resilience and environmental indicators [28]. Since the main aim of renovating a building is to reduce GHG emissions, the authors consider that the environmental assessment should also be a key indicator. Life Cycle Impact Assessment (LCIA) is a comprehensive and complex tool that has been widely used to assess the environmental impact of the construction of new buildings [37–40]. A recent review conducted by Leichter et al. [41] performs a comprehensive analysis of the life cycle sustainability assessment in buildings and highlights that the number of researches on this topic regarding the renovation of buildings has significantly increased in the past years. Other outcomes of this research are that the environmental impact is the most used parameter within the life cycle assessment, followed by the economic impact; and that the majority of the reviewed studies conclude that building renovation is more environmentally efficient than demolishing old buildings and constructing new ones.

Regarding the building aggregation level, Leichter et al. [41] indicate that the majority of the studies focus on assessing the environmental impact of the renovation of the external envelope. Although in recent years studies considering different combinations of HVAC and RREE systems have arisen [42–48], it is highlighted that there is still a significant lack of data and that it is needed to harmonize the methodology, especially regarding the service life of the systems and the boundaries definition. Regarding the renovation of buildings in a CC context, the reviews analysed [37–40] do not reference any study concerning CC together with LCIA; and within the review conducted by Leichter et al. [41], there is only one reference [49] considering this aspect. Nevertheless, all such studies agree that the importance of LCIA lies in the usefulness of such indicators as the calculation of the Non-Renewable Primary Energy Consumption, the amount of $CO_2$ emissions and CC indicators [28,50], both for the renovation process and for the remaining life cycle of the building.

To sum up, it is agreed within the reviewed literature that the analysis of the resilience of buildings under a CC context is an uncertain field that must be carefully assessed. Most of the studies coincide in that, due to global warming, there will be a generalised increase in cooling demand. Consequently, it is important to assess the renovation of buildings as well as the thermal comfort of users. In addition, several studies suggest that the analysis of the environmental impact, using the LCIA, is important. The vast majority of the reviewed studies focus on office buildings or private residential buildings. In the EU, social housing buildings are considered, within the framework of the European Green Deal [51], as a strategic sector to prioritize renovation. The characteristics of the tenants of social housing buildings depend on the model established in each country [52–54]. In Spain, social housing is a targeted model, in which housing is allocated according to a set of vulnerability indicators, particularly income. Consequently, low-income tenants are overrepresented in the Spanish social housing stock [55,56]. Specifically, in previous studies conducted by the authors [57], it has been found that the real heating consumption ranges from 0.32 to 0.40 times the calculated heating needs.

However, the number of research studies focusing on social housing buildings, while considering their real consumption in the renovation process under a CC framework, is very limited. From the reviewed literature, only the aforementioned study conducted by

Marco et al. [33] analysed social housing buildings, but they do not consider the influence of the real consumption of the tenants. In Spain, several studies have been done on social housing buildings [15,58–61], but these works are rather focused on analysing thermal comfort, some considering CC, but none account for the dwellings' real consumption. In the case of the social housing stock of the Basque Country, a comprehensive work of research has been conducted from 2018 to 2024 [62,63], led by the manager of the housing stock, Alokabide S.A. They found that the real consumption of the dwellings differs greatly from the predicted consumption. With all of this in mind, this work aims to analyse how the difference between predicted and real consumption, mainly in heating consumption, affects the renovation of social housing buildings of the Basque Country under a CC framework. To do so, the following Research Questions (RQs) have been established, following the key aspects highlighted in the literature:

- How will CC affect the renovation of social housing buildings in this specific region?
- What kind of renovation is the most suitable for social housing buildings under a CC framework?
- How do the real consumption and CC affect the thermal comfort of users in social housing buildings?
- Is the LCIA an appropriate tool to assess the renovation of social housing buildings in a CC context?

The main contribution of this work is the analysis of the influence of the real consumption of dwellings on the renovation assessment under a CC framework. To answer these RQs, a building of the social housing stock in the Basque Country, which has been monitored in detail since 2020, has been used as a demonstrator building. First, the influence of CC under different weather and time scenarios is analysed. Then, different RMs and their effects under CC scenarios are analysed. We then compare the influence of the real consumption on both the energy performance of the renovation measures and the thermal comfort of the users. Finally, the LCIA is used to assess the importance of using ecological or conventional materials for these social housing building renovations. With this work, a comprehensive assessment of the resilience of social housing building renovation is performed, under the scope of different CC and RM scenarios, considering the real consumption, while also using the LCIA to analyse the improvement potential with ecological materials.

## 2. Materials

As explained in the Introduction Section, the main contribution of this study is to understand the influence of the real consumption users on the renovation of buildings within a CC framework. To do so, a building located in the city of Vitoria-Gasteiz, in the north of Spain, has been used as a demonstrator building. The real consumption of the users of this building has been collected since 2020, as well as the indoor temperature of each dwelling. Thus, the real energy performance of the building and the actual indoor conditions of the dwellings can be evaluated; with this information being used to assess the resilience of the building in different future weather scenarios.

The development, constructed in 2010, has 126 dwellings and is made up of two rectangular blocks with a north-south orientation. Each block is made up of three different halls. The north block is higher with eight apartment floors, whereas the south block has six apartment floors. This building is included in the social housing building stock of the Basque Country, managed by Alokabide S.A., with around 14,000 dwellings [64]. About 24 % of the buildings of this social housing stock are similar to the demonstrator building used in this study [62], in terms of constructive characteristics and Heating, Ventilation and Air-Conditioning (HVAC) systems. In addition, around 66 % of the buildings are located in the same climate region as this building. Thus, the results obtained from the analysis of this demonstrator building may be extrapolated to a high percentage of the total social housing stock. In Fig. 1a, an aerial view of the demonstrator building in shown, and a summary of the main construction characteristics and a description of the HVAC systems are presented in Table 1.

To simplify the analysis and the energy simulations performed in this study, the calculations and simulations have focused on one intermediate hall of the demonstrator building, as shown in Fig. 1b. The analysed hall consists of eight floors with three dwellings per floor, two of 84 $m^2$ of conditioned area, with three bedrooms facing north and the kitchen and living room facing south; and one of 64 $m^2$ of conditioned area and the whole dwelling orientated to the south. The layout of each floor is shown in Fig. 1c. The analysed hall has a total conditioned area of 1798 $m^2$ and a high compactness ratio of 2.68 $m^3/m^2$. The window-to-wall ratio of the façades is high,

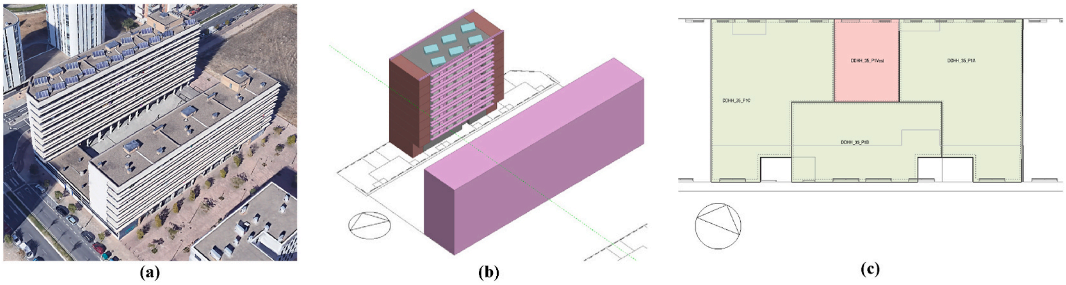


**Fig. 1.** **(a)** Satellite view (Source: Google Maps 2024) of the demonstrator building, (b) picture of the Design Builder model and (c) layout of the type floor of the modelled building.

**Table 1**
General, HVAC and external envelope characteristics of the demonstrator building.

| | | Whole building | Modelled block |
|---|---|---|---|
| Location | | Vitoria-Gasteiz, Basque Country, Spain (42.85° N 2.6727° W) | |
| Year of construction | | 2010 | |
| General description | | 2 building blocks, arranged as:<br>- North block: ground floor as common areas and 8 floors of dwellings<br>- South block: ground floor as common areas and 6 floors of dwellings | Intermediate hall of the north block |
| Types of dwellings | | −76 dwellings of 3 bedrooms and 84 $m^2$<br>−54 dwellings of 2 bedrooms and 64 $m^2$ | −2 dwellings of 3 bedrooms and 84 $m^2$ per floor<br>−1 dwelling of 2 bedrooms and 64 $m^2$ per floor |
| Conditioned area | | 12,025 $m^2$ | 1798 $m^2$ |
| Compactness ratio | | 2.50 $m^3/m^2$ | 2.68 $m^3/m^2$ |
| External envelope | | Concrete prefabricated façade, U = 0.31 $W/m^2{\cdot}K$<br>Roof, U = 0.33 $W/m^2{\cdot}K$<br>Windows, U = 3.30 $W/m^2{\cdot}K$ | |
| Windows-to-wall ratio in façades | | 40 % | 45 % |
| Heating and DHW system descriptions | | Centralised natural gas boiler, nominal performance of 90.4 % | |
| Ventilation system | | Natural ventilation, stack effect and windows | |
| Air Conditioning system | | No air conditioning system is installed | |
| RREE system | | Solar thermal panels to support the DHW production (designed for 30 % annual DHW needs) | |
| Energy Performance Certificate | Non-Renewable Primary Energy Consumption (NRPEC) | 99.8 $kWh/m^2{\cdot}yr$ – Label D | 92.4 $kWh/m^2{\cdot}yr$ – Label D |
| | $CO_2$ emissions | 21.1 $kgCO_2/m^2{\cdot}yr$ – Label D | 19.5 $kgCO_2/m^2{\cdot}yr$ – Label D |
| | Heating demand | 55.1 $kWh/m^2{\cdot}yr$ – Label D | 50.0 $kWh/m^2{\cdot}yr$ – Label D |

with 45 % of openings. Nevertheless, as depicted in Fig. 1a, the south façade of the building has passive solar protections, consisting of eaves along the entire façade. Table 1 summarises the specific characteristics of the analysed hall.

Considering the HVAC systems, due to the location of the building (northern Spain), and as will be analysed in detail in Section 3.1, the heating need is the most significant, and no cooling system is available. Solar thermal panels to support the Domestic Hot Water (DHW) production were installed, but are currently out of service. As depicted in Table 1, the Energy Performance Certificate (EPC) data of the modelled hall indicates a Non-Renewable Primary Energy Consumption (NRPEC) of 92.4 $kWh/m^2{\cdot}yr$ (rating D in the Spanish EPC scale) and GHG emissions of 19.5 kg $CO_2/m^2{\cdot}yr$ (also rating D). The EPC indicators of the whole building are slightly

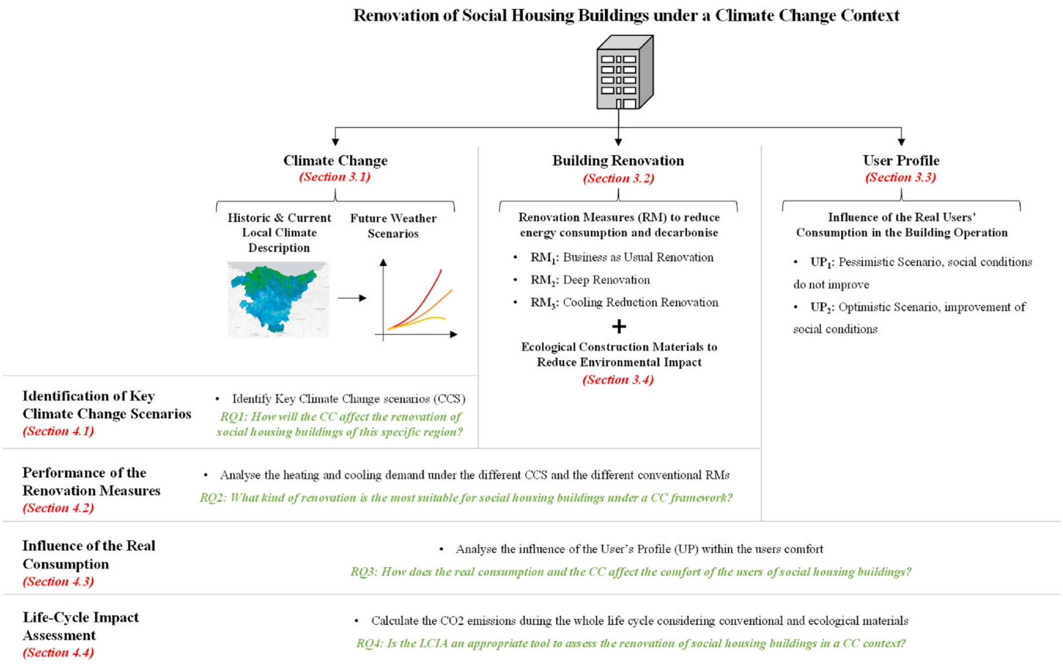
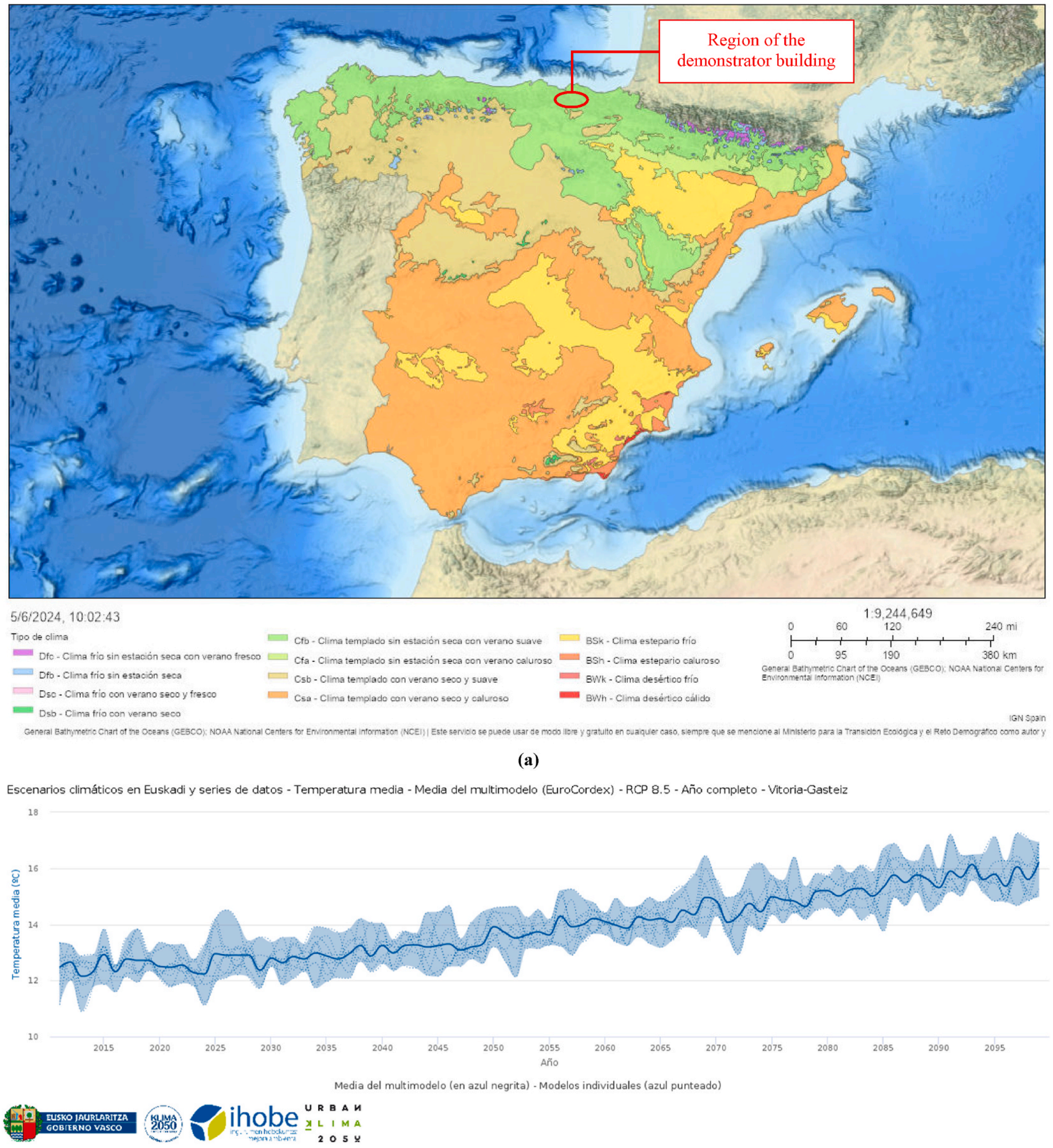


**Fig. 2.** Schematic summary of the methodology of this study, indicating the sections in which each part is explained and the research questions.

worse due to the greater exposure of the adjacent halls to the external environment, but the rating is also D. The values of these indicators represent an average building in terms of building envelope, energy systems and consumption, but with much room for renovation, considering the zero-energy balance horizon of the recently approved Energy Performance of Buildings Directive (EPBD) recast [65].

Regarding the collected data, this building is equipped with a Building Management System (BMS) that monitors the energy consumption of the dwellings and the consumption of the centralised boiler, as well as the indoor temperature of the dwellings. These data were collected for the past three years (2021–2023) and analysed to obtain the real performance, including indoor conditions and energy consumption of all the dwellings, and so derive specific heating profiles for the apartments. This information has been used to perform calibrated simulations of the intermediate hall, using the well-known energy simulation software Design Builder (DB), based on the EnergyPlus engine [66]. The conditions of the simulations are explained in detail in Section 3.3. With all the analyses of this demonstrator building, the influence of the real consumption of social housing buildings on different CC and RM scenarios can be analysed.



(a)

(b)

**Fig. 3. (a)** Köppen-Geiger climate classification of Spain (Source: [77]) and **(b)** mean outdoor temperature under the worst climate change scenario (RCP-8.5) in the municipality of the demonstrator building (Source: [74]).

## 3. Methodology

As drawn from the reviewed literature, the resilience of buildings in different future climate scenarios is mainly affected by three factors. Firstly, and evidently, by the CC forecasted scenarios. Then, by the characteristics of the RM performed in the building. And last but not least, by the user energy profile of the inhabitants. The novelty of this work is to analyse the influence of the latter factor. Fig. 2 summarises the methodology developed in this study, which is aligned with the recommendations of the scientific community, such as [21]. The aspects considered within the CC analysis in the demonstrator building location are explained in Section 3.1; the characteristics of the considered RM are explained in Section 3.2; and the details of the user profiles are explained in Section 3.3. Finally, to have a broader view of the impacts in the long term, and following the suggestions of the reviewed literature, the environmental impacts of the renovations using the LCIA are assessed, whose methodology is explained in Section 3.4. To analyse the influence of these different aspects, four RQs have been identified, which are answered in each subsection of the Results and Discussion Section of this document. As indicated in Fig. 2, to answer RQ1, the CC scenarios are studied; to answer RQ2, DB simulations of different proposed RMs are performed; and to answer RQ3 and RQ4, the real consumption of the users of the demonstrator building is incorporated into the evaluation. To help the readers with the interpretation of this work, descriptions of the different cases and their main characteristics, as well as the nomenclature list, are presented in Table A 1 of Appendix A.

### 3.1. *Climate change*

To understand the possible future weather scenarios that will affect the performance of renovations and users' thermal comfort, it is first important to analyse the historical and current climate of the region. The demonstrator building is located in northern Spain, in the city of Vitoria-Gasteiz, in the Autonomous Community of the Basque Country. According to the Köppen-Geiger climate classification, the demonstrator building is located in a region with a Cfb climate, as indicated in Fig. 3a. This category corresponds to an oceanic climate without dry seasons and with soft summers. Historically, from the 1970s to the 2000s, the average temperature ranged between 11 °C and 12 °C, mainly due to cold nights; whereas outdoor temperature during the summer would reach a maximum of around 30 °C. The historical weather data can be consulted as open source data both in national [67] and regional meteorological agencies [68]. Besides, within the ARCAS project [69], a climate and air quality map [70] was developed, in which detailed historical weather of the region can be consulted.

Nevertheless, recent studies have shown that the region in which the demonstrator building is located may be changing its Köppen-Geiger classification to Csb [71], which also consists of an oceanic climate, but with dryer summers. This, of course, is due to CC, which is a complex science with plenty of different scientific and political points of view. As explained in the Introduction Section, the IPCC and its associates are working on establishing different future climate scenarios, represented by the RCPs [3]. To understand the characteristics of the possible future climate scenarios for this region, the forecasts provided by different European [72], national [73] and regional tools [74] have been analysed. Fig. 3b shows the forecast to 2100 provided by the worst CC scenario (RCP-8.5), obtained with the regional tool. The median value of the outdoor temperature, expected in 2100, is around 16.2 °C, which is a moderate average outdoor temperature. For the intermediate scenario (RCP-4.5), the expected median value of the outdoor temperature, expected in 2100, is around 13.8 °C. Thus, in a region in which the heating demand has historically been far more important than the cooling demand, it is expected that, in the different CC forecasts, the heating demand will be reduced and the cooling demand will increase.

The selection of proper future weather files is a key aspect of simulating the climate resilience of buildings. As also explained in the Introduction Section, there are different methodologies and models to obtain future weather files, each with different advantages and disadvantages. In this work, weather scenarios provided by Meteonorm [11] are used, since this is a trusted source by the scientific community, and the forecasts are obtained using the downscaling methodology, which is one of the most commonly used. Meteonorm uses the RCPs of the Fifth Assessment Report (AR5) of the IPCC to provide future weather files at a local level that can be used with DB to simulate buildings in different CC scenarios. Nevertheless, as explained before, future weather scenarios may also be obtained using open source tools such as CCWorldWeatherGen [10], fed with historical weather files obtained using regional open source databases [75]. Indeed, within this work, the future weather files obtained with these two different tools were compared and it was found that the differences were negligible for the intended purpose. With this, the influence of different future weather scenarios on the demonstrator building will be analysed in order to answer RQ1 in Section 4.1. In addition, as indicated before, around two thirds of the social housing stock of the Basque Country are in areas with a similar climate to the demonstrator building, according to the Spanish classification of the CTE DB-HE [76]; thus, the results of this analysis can be extrapolated to a large number of social housing buildings.

### 3.2. *Building renovation*

The need to boost the renovation so as to meet the EU reduction targets urge to perform deep renovations in buildings [78,79]. Even though the definition of deep renovations in buildings is diverse, it usually includes the renovation of the external envelope to reduce the energy demand, the improvement of the efficiency of the energy systems, and the increase of the share of RREE, on-site or nearby [80]. In Spain, renovation aid programmes prioritize the reduction of the energy demand and, subsequently, the reduction of the NRPEC [81]. In the region of study, the Basque Country, the renovation of the external envelope has also been boosted in recent years through different aid programmes [62,82]. Consequently, in this work, the focus is on passive RMs intended to reduce energy demand. Specifically, the effect of three different RMs are analysed, which are based in previous researches conducted by the authors [83]. As explained before, due to the location of the social housing stock under study, the heating demand is currently more important than the cooling demand. Thus, two of the passive renovation actions considered in this study aim to reduce the heating demand. The first renovation measure ($RM_1$) considers a Business as Usual (BAU) approach and consists of the addition of thermal insulation from the interior of dwellings and the renovation of windows. It is considered that this RM is the minimum renovation that can be done in a building and can be performed in individual homes, because it does not need the intervention of all of the tenants. The second renovation ($RM_2$) is a passive deep renovation consisting of the addition of thermal insulation from the exterior of the opaque envelopes of the building and the improvement of ventilation. This includes the installation of External Thermal Insulation Composite Systems (ETICS) on façades, insulation slabs for roof and the first floor, the renovation of windows, and the installation of Mechanically Controlled Ventilation with Heat Recovery (MCV-HR). These two options, $RM_1$ and $RM_{2,}$ are intended to cover a wide range of possible passive renovation measures and represent common alternatives in the market to reduce heating needs. Following Table 2 provides the technical details of the RMs considered.

This work also analyses the influence of passive cooling renovation actions because, even though the heating demand is predominant in the region of study, the increase of outdoor temperatures due to global warming must also be considered. In this sense, the third renovation action ($RM_3$) is based on $RM_2$ and adds other passive actions whose aim is to reduce the expected increase in cooling demand. The new installed windows would have a low Solar Heat Gain Coefficient (SHGC), the building would be painted with white, high reflective paint, and the installed MCV would provide free-cooling in summer. Furthermore, the internal loads of the dwellings would be lowered by renovating both the lighting and the appliances. No additional solar shading is contemplated for this building because, as explained in Section 2, the demonstrator building already has good fixed shading elements. With $RM_3$, the extent to which the increase in outdoor temperatures in this region due to CC can be compensated with passive solutions will be analysed. Several studies are aware of the difficulties of properly assessing overheating in buildings [84], and that depending on the specific conditions of the region a combination of passive and active solutions would be needed [85]. Nevertheless, the scope of this study sticks to passive solutions due to the lack of data needed to perform the LCIA, as will be explained in following Section 3.4. With this, the aim is to analyse the different possible renovation scenarios, summarised in three RMs ($RM_1$, $RM_2$ and $RM_3$). To answer RQ2, the performance of these RMs is compared with the building in its current situation ($RM_0$). The results of this analysis are shown in Section 4.2.

### 3.3. User profiles

The third factor affecting the resilience of the renovation of social housing buildings, and probably the most important one, is the actual energy profile of the users in their homes. As indicated in the Introduction, previous studies performed by the authors [57,62], determined that the real heating consumption of social housing buildings of the Basque Country is considerably lower than the predicted one. In particular, in this demonstrator building, the real heating consumption is 64 % lower than the predicted one, because of the low income of tenants who cannot afford greater heating costs. This information was derived from the monitored data collected between 2019 and 2021. Consequently, the heating profile of these dwellings differs notably from the standard residential profile according to the Spanish CTE DB HE 2013 regulation [76]. In this work, the standard User Profile (UP) is denoted as $UP_0$ and the real user profile based on the collected data as $UP_1$. In this standard profile, the heating season is from October to May, whereas, in fact, tenants only use heating in the coldest months of the year, from December to March. Regarding the temperature set point, the standard profile sets 21 °C between 7:00h and 22:00h, and 17 °C the rest of the day. However, after looking at the indoor temperature measures, the real temperature set points are highly variable, with some dwellings achieving 23 °C at central times of the day, while other dwellings are at 14 °C during the night. Besides, as indicated in Section 2, no cooling system is installed in this building, whereas the standard summer profile establishes maintaining the building below 25 °C in the evenings and 27 °C on nights from May to September. Calibrated DB simulations of the demonstrator building were thus performed, with each of the previous RMs proposed, considering the real consumption of each dwelling. Then, the results of the calibrated simulations ($UP_1$) are compared with the results obtained with the standard profile ($UP_0$) to assess the influence of the real consumption on the renovation under a CC context.

In addition, the thermal comfort of users is analysed considering the real consumption, under the different CC and RM scenarios. As

**Table 2**
Details of the Renovation Measures considered in the study.

| Renovation Measure | Description | Details |
|---|---|---|
| **$RM_1$** | Business as Usual (BAU) Renovation Measure | • Addition of MW slabs of 5 cm (0.037 W/m·K) from the interior of the dwelling.<br>• Renovation of the windows with windows made of PVC frame of 1.8 W/m2·K and a glass of 1.3 W/m2·K with a SHGC of 0.7. |
| **$RM_2$** | Deep Renovation Measure | • Installation of ETICS with EPS slabs of 10 cm (0.037 W/m·K).<br>• Addition of XPS slabs of 16 cm (0.034 W/m·K) on the roof.<br>• Addition of MW slabs of 8 cm (0.040 W/m·K) below the lowest floor and in floors in contact with air.<br>• Renovation of the windows with windows made of PVC frame of 1.8 W/m2·K and a glass of 1.3 W/m2·K with a SHGC of 0.7.<br>• Installation of MCV with a HR seasonal efficiency of 85 %. |
| **$RM_3$** | Deep Renovation Measure plus cooling demand reduction actions | The same renovation actions as in $RM_2$ plus:<br>• Windows have Low Emission glass with SHGC of 0.3.<br>• Building is painted in white.<br>• The MCV allows free cooling.<br>• Renovation of electrical appliances. |

explained before, different methodologies can assess the thermal comfort in buildings. In this study, to answer RQ3, two different methodologies were followed. First, the percentage of hours of the year, in which the indoor temperature of the dwellings falls within certain temperature ranges, is calculated by analysing the hourly results of the measured temperatures and DB simulations. The temperature ranges are established according to the heating and cooling set points of the standard profile, defined in the CTE DB-HE 2019 [86], as follows: percentage of hours below 17 °C, percentage of hours between 17 and 20 °C, 20 and 23 °C and 23 and 26 °C, and percentage of hours over 26 °C. Secondly, to analyse the risk of overheating, the UNE-EN 16798 standard [35] (which modifies previous EN 15251 standard) is used, also known as the adaptive method. This is intended for buildings without mechanical cooling systems and during periods in which the running outdoor mean temperature is between 10 °C and 30 °C. The comfort temperature is calculated depending on the running outdoor mean temperature, and three different building categories are established according to the achieved comfort temperatures.

Moreover, to complete the analysis of the influence of the users' profile on the performance of the RMs and the thermal comfort; an extra scenario which simulates an increase in the energy bills of the tenants is evaluated. Previous studies [87], have found that including social aids to maintain a minimum indoor temperature of the dwellings is economically feasible and improves the efficiency of the HVAC centralised system. Thus, the current User Profile ($UP_1$), in which the heating consumption of tenants differs from the standard heating profile, is compared with an optimistic User Profile ($UP_2$), in which social aids are provided to tenants so that they can reach standard indoor conditions. With this analysis, the answer to RQ3 is completed, whose results are shown in Section 4.3.

### 3.4. Life Cycle Impact Assessment

After analysing the different CC scenarios, the renovation actions and the influence of the users' profiles, the focus is put on the assessment of the environmental impact using the LCIA. From the reviewed literature, it has been found that the majority of LCIA studies are focused on the analysis of passive renovation actions; and that there are scarce studies that consider CC together with the LCIA. In this work, environmental impact of passive RMs is analysed together with the influence of CC, which, to the authors' knowledge, represents a novelty for scientific literature. The LCIA methodology, standardized by ISO 14040 [88], evaluates the environmental impacts of a product or a process, considering the stages of its life cycle. It consists of four stages, namely the goal and scope definition, the Life Cycle Inventory development (LCI), the Life Cycle Impact Assessment (LCIA) itself, and the interpretation phase. Table 3, below, summarises the main characteristics of the phases of the LCIA performed in this work, while Fig. 4 summarises the stages of the LCIA.

The goal of the LCIA performed in this work is to compare the environmental impact of the proposed RMs (considering conventional and ecological materials) with the environmental impact of the operational use of the building. That is to say, the focus of this LCIA is not on the particular characteristics of the proposed RMs, because this would imply a more parametrized and detailed analysis of the RMs. The scope of this LCIA covers from the moment of the renovation (year 0) to 30 years in the future, which is a consistent time scenario, lower than the usual Reference Service Life (RSL) of the majority of materials used in the renovation. In this way, a Cradle to Grave analysis is performed, and the stages of the life cycle of the RMs contemplated are, namely, the Product Stage (A1-A3), the Construction Stage (A4-A5) and the Use Stage (B1-B7), as defined by ISO 14040 [88]. Nevertheless, for those materials whose RSL is equal to or lower than 30 years, a Cradle-to-Cradle analysis is contemplated, so the End of Life Stage (C1-C4) and the Recycle Stage (D) are also taken into account.

The functional unit depends on the data used to assess each RM. For instance, façade insulation is usually measured in square metres of opaque façade; whereas the functional unit in window renovation is typically the number of windows replaced. Nevertheless, in this work, the LCIA results are normalised using the conditioned area of the building (see Table 1), so the results are easy to compare with other buildings. The LCI has been performed by collecting data from different Environmental Product Declarations (EPDs) of the materials of the previously described proposed RMs. In Table A2 of Appendix A, the EPD data of the considered materials is referenced. Some of the LCI data, such as the Transport of the Construction Stage (A4), have been complemented using SimaPro software [89]. Finally, in the interpretation stage, the focus is on two of the LCIA indicators: the NRPEC and the $CO_2$ emissions. To calculate the NRPEC, energy consumption must be considered. In this work, as described before, only passive aspects of the building are analysed, that is to say, the energy demand. However, to be able to calculate the energy consumption of the systems within the LCIA, the standard

**Table 3**
Characteristics of the LCIA performed in this study.

| Goal definition | Analysis of the environmental impact of the proposed renovation measures. |
|---|---|
| **Time scenario** | 30 years |
| **Scope definition** | Cradle-to-Grave analysis of the building and of products with a Reference Service Life (RSL) higher than 30 years.<br>Cradle-to-Cradle analysis of products with an RSL lower than or equal to 30 years. |
| **Stages considered** | Product Stage (A1-A3)<br>Construction Stage (A4-A5)<br>Use Stage (B1-B7)<br>End of Life Stage (C1-C4) (In Cradle-to-Cradle analysis)<br>Recycle Stage (D) (In Cradle-to-Cradle analysis) |
| **Functional unit** | Conditioned area of the building (Specific functional unit of each renovation measure detailed in Appendix A) |
| **Life Cycle Inventory (LCI)** | LCI data has been obtained according to approved EPDs (Details in Appendix A) |
| **Support software** | SimaPro. Libraries: All libraries, including Ecoinvent. Method: ReCiPe Endpoint (H) v1.13 [89]. |

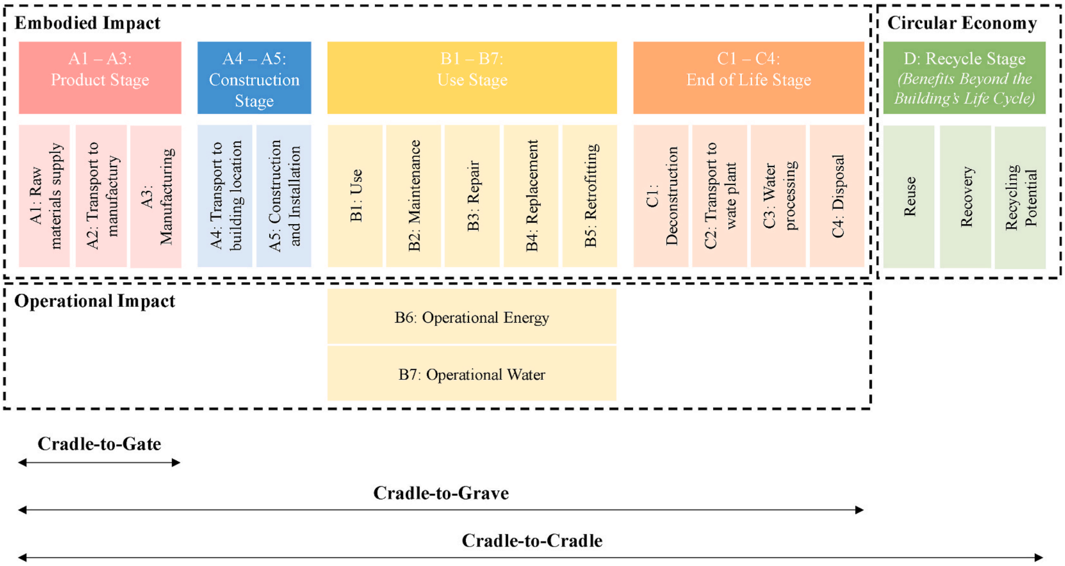


**Fig. 4.** LCIA stages based on ISO ISO 14040 [88].

efficiency indicated by the Spanish regulation [76] has been considered. Specifically, the standard performance for systems using Natural Gas (such as the boiler of the centralised system of the demonstrator building) is 92 % over the Lower Heating Value (LHV); and for systems using electricity (such as cooling systems), it is 260 %. Note as well that the NRPEC calculated using the DB simulations also considers the electricity consumption of lightning and appliances. In this sense, $RM_3$ aims to reduce the internal loads and energy consumption of this electrical equipment, as described in Section 3.2 above.

Finally, in the present study the influence of using conventional or ecological materials in the renovation of social housing buildings is also analysed. The terminology used in this work for the type of material used within the renovation, “conventional or “ecological”, is external to the ISO 14040 standard, yet this nomenclature is commonly used within the LCIA literature. For instance, for the ETICS, the use of conventional insulation such as EPS, or the use of ecological insulation, such as cork panels, is compared; and for the renovation of windows, whether they are made of PVC or wood is compared. The type of materials affects the Product Stage A1-A3 and Construction Stage A4-A5 of the LCIA. On the other hand, the Operational Energy (B6) stage will be strongly influenced by the performance of the RM, which is related to the building’s NRPEC, and by the electricity mix of the country, which will affect the $CO_2$ emissions during the operation of the building. In the RCP-2.6 scenario, it is considered that Spain achieves the target share of RREE in the electricity generation and, consequently, the emissions are reduced. In the RCP-8.5 scenario, fossil fuels would still be important for electricity generation. Thus, it is considered that the $CO_2$ conversion factors are still the same as nowadays. With this, the last RQ is answered, which evaluates whether the LCIA is an appropriate tool to assess the renovation of social housing buildings under a CC framework.

## 4. Results and discussion

### 4.1. Identification of key climate change scenarios

The analysis of the CC scenarios is the first step to properly understanding the climate resilience of the renovation of buildings. Fig. 5a, below, shows the forecasted evolution of the yearly average outdoor temperature under the considered RCP-2.6, RCP-4.5 and RCP-8.5 pathways for 2020, 2050, 2070 and 2100; considering that the historic annual average temperature in the analysed location is around 12 °C, as already indicated in Section 3.1. As depicted in Fig. 5a, it can be seen that, in 2050, the difference in the yearly average

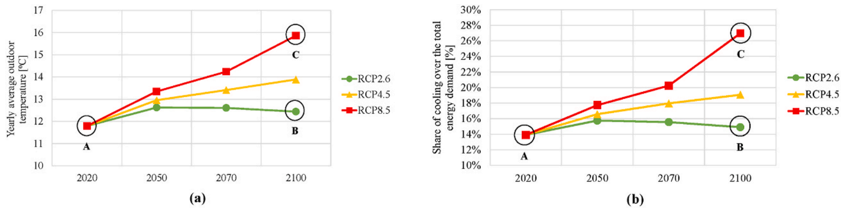


**Fig. 5.** (a) Comparison of the yearly average outdoor temperature and (b) share of cooling over the total energy demand, of the demonstrator building in its current situation (RM0), under different time scenarios (2020, 2050, 2070 and 2100) and the three Climate Change Scenarios.

outdoor temperature is reduced, being around one Celsius degree warmer for the three RCPs. On the other hand, in the following years, increasingly wider differences are obtained between the average yearly temperatures obtained with the three models. The maximum difference is observed for 2100, when the difference between RCP-2.6 and RCP-8.5 is 3.42 °C. Table 4 summarises the main climate indicators under the different RCPs and time scenarios. In this work, the present climate, which has been also obtained using the Meteonorm [11] database, is denoted as RCP00-2020. From the values indicated in Table 4 and it can be derived that, comparing the current climate (RCP00-2020) and the worst-case scenario (RCP85-2100), the trend is that the Heating Degree Days ($HDD_{15}$) will decrease and that the Cooling Degree Days ($CDD_{20}$) will increase, as expected. However, in contrast to the results found in the majority of the literature, in the region of the demonstrator building, it can be seen that, in the worst CC scenario, the decrease in the heating demand would be higher than the increase in the cooling demand. Specifically, it is expected to have 84 % less of $HDD_{15}$, and 58 % more of $CDD_{20}$. The other climate indicators shown in Table 4, the Relative Humidity (RH) and the Direct Irradiance, follow the expected trend, which is that they both slightly increase in the worst climate scenario.

In the same way as the yearly average outdoor temperature, Fig. 5b shows the share of cooling demand over the total energy demand of the building, calculated using the standard set-points indicated in Section 3.3. The cooling share increases from 14 % in the current scenario up to 27 % in the worst climate scenario, in 2100. However, this increase in the cooling share is mostly due to a decrease in the heating demand, rather than the rise in the cooling demand. To analyse this, in Fig. 6, the heating and cooling demands of the building in its current situation ($RM_0$) under different climate scenarios considered are compared. It can be seen that the CC has a greater effect on the decrease in the heating demand than the increase in the cooling demand. To be precise, the heating demand decreases by up to 42.8 % in the worst climate scenario, without renovating the building; whereas the maximum cooling increase is 30.8 %, more than ten percentage points less than the decrease in the heating demand. We have thus detected that, in the location of the demonstrator building and considering the CC projections with average yearly values, the reduction in heating demand will be far more important than a worrying increase in the cooling demand, even in the worst climate scenario. Notice that, in this section, the cooling demand is also analysed because the results shown in this section have been obtained with DB simulations considering the standard User Profile ($UP_0$).

In both Figs. 5 and 6, we have highlighted three climate scenarios; specifically, RCP00-2020 as “A”, which is the current climate scenario; RCP26-2100 as “B”, which is the most optimistic scenario in 2100; and, in contrast, RCP85-2100 as “C”, which is the most pessimistic scenario. In the subsequent sections, the focus is on these three scenarios, since any other scenario is between these three key scenarios. With this, RQ1 is answered: *How will the CC affect the renovation of social housing buildings in this specific region?* The answer is that, depending on the optimistic or pessimistic global emissions scenario, the effects will be diverse. With the optimistic scenario (RCP-2.6), the heating and cooling demand would remain similar to the present; in contrast, with the pessimistic scenario (RCP-8.5), there will be an increase in cooling demand, but a more significant decrease in heating demand. This aspect will considerably affect the different renovation actions, as explained in Section 4.2 below.

### 4.2. *Performance of the renovation measures*

Once the key CC scenarios had been identified, the effect of the proposed RMs under those climate scenarios was assessed. Fig. 7 below shows, the predicted heating demand in solid red bars and, in solid blue bars, the predicted cooling demand of the building under the proposed renovation actions. It should be remembered that, up to this point, the standard profile ($UP_0$) has been considered, so the heating and cooling demands calculated in this section are predicted demands. First, the variations in the predicted heating demand were analysed. In the current situation (RCP00-2020), the heating demand is reduced by 17.1 % with $RM_1$. Note that the minimum energy consumption reduction required by the Spanish government for grants for building renovations is 30 % [90]. On the contrary, if a deep renovation is performed ($RM_2$), the heating demand can be reduced by up to 63.3 %. Added to this, if the CC is considered, in the optimistic scenario (RCP26-2100), the heating demand decrease due to the renovation is 65.3 %, as in the previous decrease, considering the current climate. On the other hand, if the pessimistic CC scenario is considered (RCP85-2100), the heating demand can decrease by up to 82.2 %. From this, one of the main results of this study is obtained, that is, in terms of heating demand

**Table 4**

Yearly values of the main climate indicators, under the different RCPs and time scenarios considered.

| | | RCP00-2020 | RCP26-2050 | RCP26-2070 | RCP26-2100 | RCP45-2050 | RCP45-2070 | RCP45-2100 | RCP85-2050 | RCP85-2070 | RCP85-2100 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Dry bulb temperature [°C]** | **Mean** | 11.79 | 12.63 | 12.61 | 12.44 | 12.96 | 13.42 | 13.89 | 13.35 | 14.24 | 15.86 |
| | **Maximum** | 37.40 | 38.40 | 38.40 | 38.50 | 38.70 | 39.20 | 39.70 | 39.20 | 40.30 | 42.00 |
| | **Minimum** | −6.40 | −5.90 | −6.00 | −6.10 | −5.30 | −4.80 | −4.60 | −5.00 | −4.10 | −2.70 |
| **Heating Degree Days [a] ($HDD_{15}$) [°C]** | | 1818 | 1641 | 1662 | 1699 | 1573 | 1468 | 1364 | 1478 | 1299 | 988 |
| **Cooling Degree Days [b] ($CDD_{20}$) [°C]** | | 242 | 297 | 313 | 298 | 320 | 359 | 391 | 349 | 410 | 572 |
| **Relative Humidity (RH) [%]** | | 77.43 | 77.79 | 77.73 | 77.52 | 77.52 | 77.43 | 77.37 | 77.03 | 78.43 | 78.08 |
| **Direct Irradiance [kWh/$m^2$·yr]** | | 1251 | 1466 | 1427 | 1416 | 1,34 | 1377 | 1413 | 1383 | 1409 | 1518 |

[a] HDD calculated using a base temperature of 15 °C.

[b] CDD calculated using a base temperature of 20 °C.

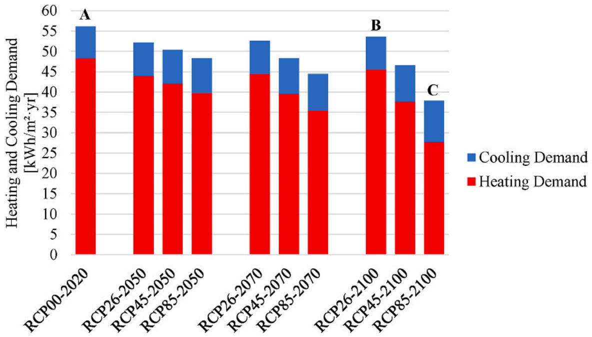
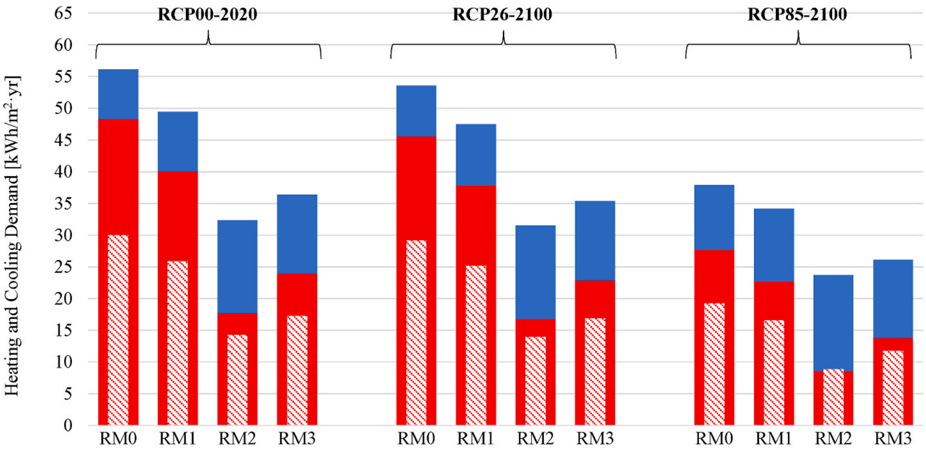


**Fig. 6.** Heating and cooling demand of the demonstrator building in its current situation ($RM_0$), under different climate scenarios, and considering the standard User Profile ($UP_0$).



| | RCP00-2020 RM0 | RCP00-2020 RM1 | RCP00-2020 RM2 | RCP00-2020 RM3 | RCP26-2100 RM0 | RCP26-2100 RM1 | RCP26-2100 RM2 | RCP26-2100 RM3 | RCP85-2100 RM0 | RCP85-2100 RM1 | RCP85-2100 RM2 | RCP85-2100 RM3 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 🟦 Predicted Cooling Demand | 7.8 | 9.4 | 14.6 | 12.4 | 8.0 | 9.6 | 14.8 | 12.5 | 10.2 | 11.5 | 15.1 | 12.3 |
| 🟥 Predicted Heating Demand | 48.3 | 40.1 | 17.7 | 24.0 | 45.6 | 37.9 | 16.8 | 22.8 | 27.7 | 22.7 | 8.6 | 13.8 |
| Cooling Demand Increase | 0 | 20.0% | 86.8% | 58.8% | 2.3% | 23.4% | 88.9% | 60.3% | 30.8% | 46.6% | 92.8% | 58.0% |
| Heating Demand Decrease | 0 | 17.1% | 63.3% | 50.4% | 5.7% | 21.7% | 65.3% | 52.8% | 42.8% | 53.0% | 82.2% | 71.5% |
| Share of Cooling | 13.9% | 19.0% | 45.2% | 34.1% | 14.9% | 20.3% | 46.8% | 35.4% | 27.0% | 33.5% | 63.6% | 47.3% |
| ▨ Real Heating Demand | 30.0 | 25.9 | 14.3 | 17.3 | 29.2 | 25.2 | 13.9 | 16.9 | 19.2 | 16.6 | 8.9 | 11.7 |

**Fig. 7.** Predicted heating and cooling demand (solid coloured bars) and real heating demand (dashed coloured bar), of the demonstrator building, under the different CC and RM scenarios considered.

reduction, the reductions obtained by the renovation are more significant than the influence of global warming.

Regarding the predicted cooling demand, it can be seen that, with $RM_2$, it can increase by up to 86.8 %, 88.9 % and 92.8 % in the current, optimistic and pessimistic scenarios, respectively. This could seem a high increase in percentage terms, but if the net value of the cooling demand is analysed, it can be seen that, in the RCP85-2100 scenario, it increases by 5.1 kWh/$m^2$·yr, from 10.2 to 15.1 kWh/$m^2$·yr. This leads to the analysis of the effect of $RM_3$, which is proposed to reduce the cooling demand. It can be seen that, in the RCP85-2100 scenario, the cooling demand of $RM_3$ is 12.3 kWh/$m^2$·yr, which represents 2.8 kWh/$m^2$·yr less than the cooling demand obtained with $RM_2$. Besides, with $RM_3$, it can be seen that a reboot of the predicted heating demand may occur. With $RM_3$, the heating demand in the RCP85-2100 scenario increases up to 13.8 kWh/$m^2$·yr when compared with the 8.6 kWh/$m^2$·yr obtained with $RM_2$, which is an increase of 5.3 kWh/$m^2$·yr. This trend is similar in the three considered CC scenarios. If passive renovation actions aimed at reducing the predicted cooling demand are performed, the effect of the reboot on the heating demand is bigger in terms of energy than the benefit of the decrease in the cooling demand. Nevertheless, the high increase of the cooling demand in percentage terms, when compared to the current situation, tells us that the risk of overheating must be studied, and this will be analysed in Section 4.3 below.

It can thus be concluded that renovation actions, such as $RM_2$, are the most suitable in buildings with similar characteristics and location to the demonstrator building. The answer to RQ2 is that, even in the worst climate scenario, the reduction in the heating demand will still be higher than the increase in the cooling demand. Besides, renovation actions focused on reducing cooling demand may have a negative effect on the efforts to reduce the heating demand. Additionally, the authors would like to stress here that they are aware of one of the limitations of this study, which is that we are working with average meteorological years. Thus, extreme weather events, such as heat waves, are not being considered; and these may considerably increase cooling demand at specific times of the year. However, these cooling peaks would be tackled not only with passive solutions, such as the ones analysed in this building, but with such active solutions as air conditioning systems, which have a fast response and cooling power.

### 4.3. *Influence of the real user profile*

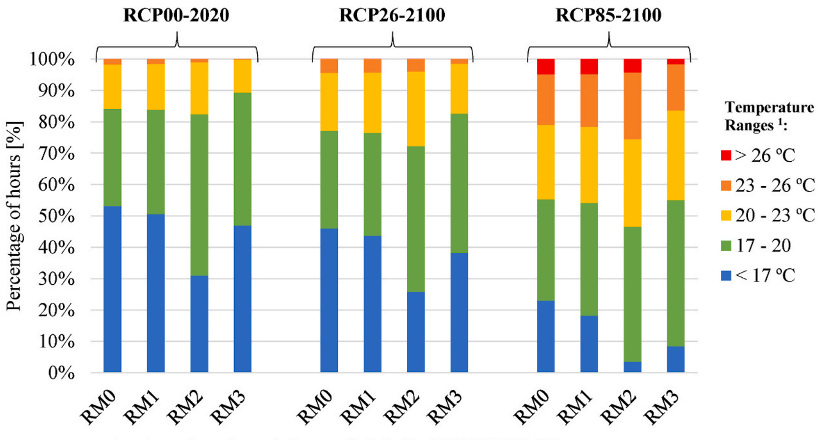
Up to this point, the influence of CC and the RMs in social housing buildings have been analysed, but considering only the standard heating and cooling profiles ($UP_0$). The results show that, in buildings with similar characteristics as the demonstrator building, renovation actions should be more focused on tackling heating demand, regardless of the climate scenario. However, as has been highlighted in this document, the real heating demand of social housing buildings differs significantly from the standard heating consumption; moreover, there is no cooling consumption in this building. This can clearly be seen in Fig. 7 below, where the real heating demand (in red dashed bars) considering the real User Profile ($UP_1$) is shown for all the cases. First, for the current climate (RCP00-2020), the real heating consumption of the current situation of the building ($RM_0$) is 37.9 % lower than the predicted heating consumption, as described in Section 3.3. It can also be seen that, if the building is deeply renovated ($RM_2$), the gap between the predicted and real heating demand is reduced, meaning that more users are able to reach standard indoor conditions without increasing their consumption. Moreover, if $RM_3$ is performed, a reboot in the heating gap occurs, which would actually worsen the effects achieved with $RM_2$.

Accordingly, if the optimistic scenario (RCP26-2100) is analysed, it can be seen that the gap between the predicted and real heating demand remain similar, as in the current climate scenario (RCP00-2020). However, if the pessimistic scenario (RCP85-2100) is analysed, the gap between the predicted and real heating consumptions is cut. Indeed, in the pessimistic scenario with $RM_2$, the real consumption exceeds the predicted heating consumption needed to achieve indoor standard conditions. With this, one could conclude that a combination of a deep renovation and the pessimistic climate scenario would actually be beneficial for the users of social housing buildings, since they would be able to achieve indoor standard conditions in winter without increasing their heating consumption.

Up to this point, the results indicate that the reduction in the heating consumption is more important than the increase in the cooling demand. Nevertheless, to be sure about the effects of the proposed RMs under a CC framework, the indoor conditions of the dwellings must also be analysed. The gap between the standard user ($UP_0$) and the real User Profile ($UP_1$) can directly influence the thermal comfort of the dwellings because, as described before, the real users are not able to meet the standard set points. To analyse this aspect, Fig. 8 shows the percentage of hours in the year in which the indoor temperature of the dwellings falls within specified temperature ranges. It can be seen that, in the current situation and climate scenario (RM0_RCP00-2020), the indoor temperature of the dwellings remains below 17 °C for more than 50 % of the hours in the year, which is a worrying situation. If the building is renovated to reduce heating demand with $RM_2$, this situation will improve, and around 70 % of the hours of the year the indoor temperature of the dwellings will be above 17 °C.

If the CC scenarios are now considered, the first aspect to notice is that the thermal comfort between the current and optimistic scenarios is slightly different, in contrast to the results of the performance of the RMs shown in the previous section. This is because of the difference in HDD and CDD, as shown in Table 4. Now, paying attention to the pessimistic scenario, two aspects can be highlighted. First, it can be seen that the percentage of hours with indoor temperatures below 17 °C would be drastically reduced. Thus, again, one could state that global warming would be beneficial for social housing building users, at least in regions with similar weather to that analysed in this work. The second aspect to be highlighted is that the percentage of hours with indoor temperatures higher than 26 °C is low, below 4 % in the worst cases; this means that the risk of overheating in buildings with similar characteristics to the demonstrator building is relatively low. This reinforces the idea that, in this type of building, renovation actions should prioritize the reduction of heating demand, no matter the CC scenario.

Finally, in order to provide a more comprehensive analysis of the thermal comfort of the dwellings, and focusing on the risk of



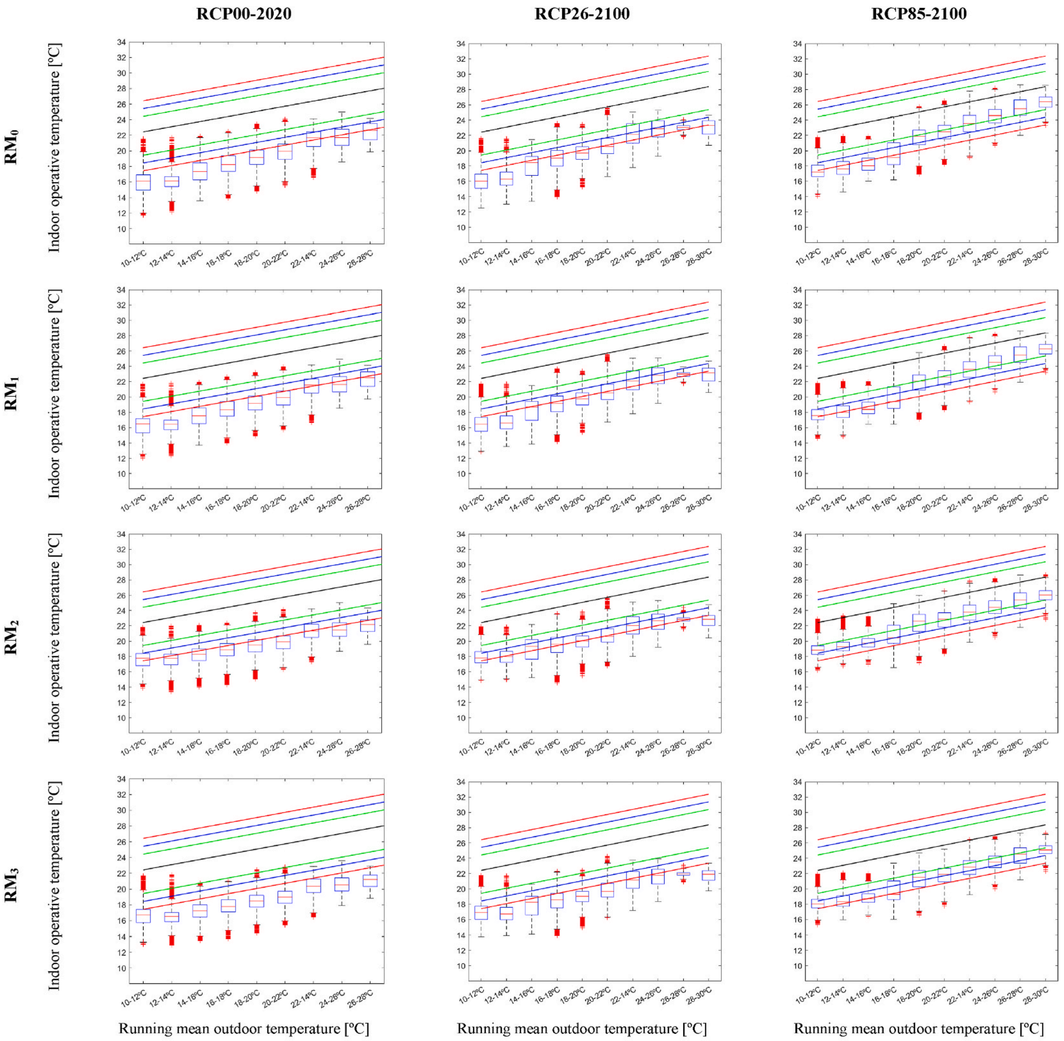
¹ Temperature ranges selected according to the standard user profile defined in CTE DB-HE 2019 [86].

**Fig. 8.** Percentage of hours of the year in which the indoor temperature of the dwellings falls within specified temperature ranges, under the different CC and RM scenarios analysed, and the real User Profile ($UP_1$).

[1] Temperature ranges selected according to the standard user profile defined in CTE DB-HE 2019 [86].

overheating during the summer period, the UNE-EN 16798 [35] standard has been used. The results are shown in Fig. 9 for the different CC and RMs scenarios considered. The boxplots represent the dispersion of the hourly indoor operative temperature of the dwellings, calculated using the DB simulations, depending on the running average outdoor temperature. The black line indicates the comfort temperature calculated using the UNE-EN 16798 standard [35]. Moreover, the green, blue and red lines represent the comfort ranges for Building Categories I, II and III, respectively. As depicted in Fig. 9, it can be seen that, in the current climate scenario (RCP00-2020), the indoor operative temperature remains below the comfort temperatures of a Category III building and the majority of the hours remain below the lower limits. Only with deep renovations (such as $RM_2$) would a Category III building be progressively reached for these real users. Now, if the building is analysed in its current situation (RM0), it can be seen that, in the worst CC scenario (RCP85-2050), the operative temperatures would significantly improve thermal comfort, especially for warmer outdoor temperatures. This is consistent with the results shown in Fig. 8 above. In this figure, with the $RM_2$ and the RCP85-2050 scenario, the percentage of hours below 17 °C is drastically reduced. Furthermore, the comfort analysis using the UNE-EN 16798 [35] standard confirms that the risk of overheating in this location is non-existent, no matter the degree of renovation or the CC scenario. In none of the scenarios analysed does the indoor operative temperature exceed the upper limit of Category I.

An important conclusion that can be derived from the comfort analysis, which is that, in terms of the improvement in the indoor



**Legend:**

**Boxplots:** hourly indoor operative temperature of the dwellings.

— Comfort temperature according to UNE-EN 16798 [35].

— Comfort temperature limits for building type I according to UNE-EN 16798 [35].

— Comfort temperature limits for building type II according to UNE-EN 16798 [35].

— Comfort temperature limits for building type III according to UNE-EN 16798 [35].

**Fig. 9.** Boxplots of the indoor operative temperatures under different RM and CS, compared with the comfort regions according to UNE-EN 16798 [35].

temperature distribution, the climate scenario is more significant than the renovation action. In contrast, in Section 4.2 above, we observed that a deep renovation could significantly tackle the heating demand. However, with the results of this subsection, it can be seen that the indoor conditions of the tenants are further improved by global warming rather than renovation actions. Obviously, one cannot rely on CC to improve the indoor conditions of the tenants. Thus, other actions such as deeper renovations, including more efficient HVAC systems, are needed. Another possibility is to provide tenants with financial aid so as they can increase their heating consumption and improve indoor conditions. In this sense, in Section 4.4 below, an extra scenario is analysed in which financial aid is provided to tenants ($UP_2$), so they can to get closer to the standard consumption. To sum up, the answer to RQ3 is that the indoor conditions of social housing buildings would remain poor even with deep passive renovations. Consequently, deeper renovations or other complementary actions, such as providing financial aid to increase heating consumption, are also needed.

### 4.4. *Life-cycle impact assessment*

Until now, the analysis performed has been static in the three key CC scenarios; specifically, the current scenario (RCP00-2020), and the future optimistic and pessimistic scenarios (RCP26-2100 and RCP85-2100), respectively. The present LCIA allows a dynamic analysis of the environmental impact of the renovation of buildings to be performed, in the different future climate scenarios, while also considering the influence of the proposed User Profiles ($UP_1$ and $UP_2$). In this section, the focus is on $RM_2$, since Section 4.2 identified that this set of renovation actions was the most effective for the demonstrator building. Fig. 10a below shows the cumulative NRPEC of the building in different scenarios. The black line represents the building without renovation ($RM_0$) in the pessimistic RCP-8.5 scenario; while the green line also represents $RM_0$, but considering the optimistic RCP-2.6 scenario. It can be seen that the difference between the optimistic and pessimistic CC scenarios is negligible in 2050; these scenarios even overlap, according to the small differences in climate scenarios in the short term, as explained in Section 4.1.

Fig. 10a also shows another two scenarios for a further understanding of the renovation action $RM_2$. In red, the results of the pessimistic RCP-8.5, considering $UP_1$ (solid line) and $UP_2$ (dashed line) are analysed; while the results of the optimistic RCP-2.6, also considering $UP_1$ and $UP_2$, are shown in blue. Remember that the RCP-2.6 scenario considers that the global targets of $CO_2$ emissions reduction are being achieved; thus, the share of RREE of the electricity grid is progressively improved. With this, it can be seen that the starting point of both lines differ because of the renovation, as considered in 2020 in this study. There would be an increase of the NRPEC due to the renovation itself, specifically of 228 kWh/m$^2$·yr. At the end of the considered life cycle, in 2050, it can be seen that the cumulative NRPEC is compensated for when compared to the building without renovation. The NRPEC reduction is higher when considering the optimistic scenario RCP-2.6, due to the improvements in the electricity grid. Specifically, in 30 years, the reduction in the cumulative NRPEC is 30 % and 19 %, when comparing the building without renovation with the optimistic and pessimistic scenarios, respectively. In addition, the initial increase in NRPEC due to the renovation is recovered in approximately 8 years. Now, if the cumulative NRPEC considering the $UP_2$ is analysed, we can see that there is a slight increase in 2050, due to a higher consumption in order to achieve indoor standard conditions. However, this increase is negligible, and there is still a significant reduction of the NRPEC; which means that providing financial aid to improve the indoor conditions of the tenants is energy efficient in a long-term scenario. Fig. 10b shows the same results as in Fig. 10a, but for the cumulative $CO_2$ emissions in 30 years. The trend of all the analysed scenarios is similar and the initial $CO_2$ emissions due to the renovation are compensated for in approximately six years.

Additionally, the LCIA also allows for the analysis of the influence of using conventional or ecological materials within the renovation process. Again, the goal of this LCIA is not to assess in detail the impact of the RM itself, but to compare the environmental impact of the renovation against the impact of the operational use of the building. Fig. 11 shows the cumulative environmental indicators (NRPEC in Fig. 11a, and $CO_2$ emissions in Fig. 11b) in 30 years, comparing the different cases analysed. The grey and black bars indicate the impact of the Use Stage of the building in its current situation ($RM_0$). Then, the different cases considering the renovation of the building with $RM_2$ are analysed depending on different variables. Firstly, the type of material used within the renovation, namely, conventional materials (dark colours), and ecological materials (light colours). Secondly, the impact due to the Renovation Stage (dashed bars) and the Use Stage (solid bars). Lastly, the CC scenario, specifically, RCP26 (grey and blue bars) and RCP85 (black and red bars). In addition, two of the User Profiles considered are compared, the Real User Profile ($UP_1$) and the Optimistic User Profile ($UP_2$). Remember that, in Table A2 of Appendix A, the detailed LCI and EPD data of all the RMs are shown.

From Fig. 11, it can be seen that the weight of the environmental indicators, both NRPEC and $CO_2$ emissions, due to the Renovation Stage is significantly lower than the impact of the Use Stage. Fig. 11a and b also show a detail of the Renovation Stage, to understand

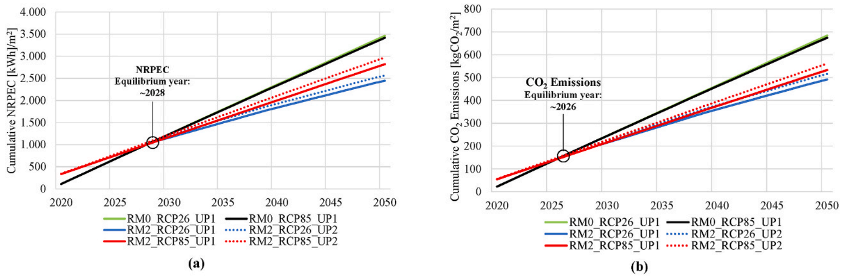


**Fig. 10.** **(a)** Cumulative NRPEC and **(b)** Cumulative CO2 Emissions of the demonstrator building under different RMs, CC and UPs.

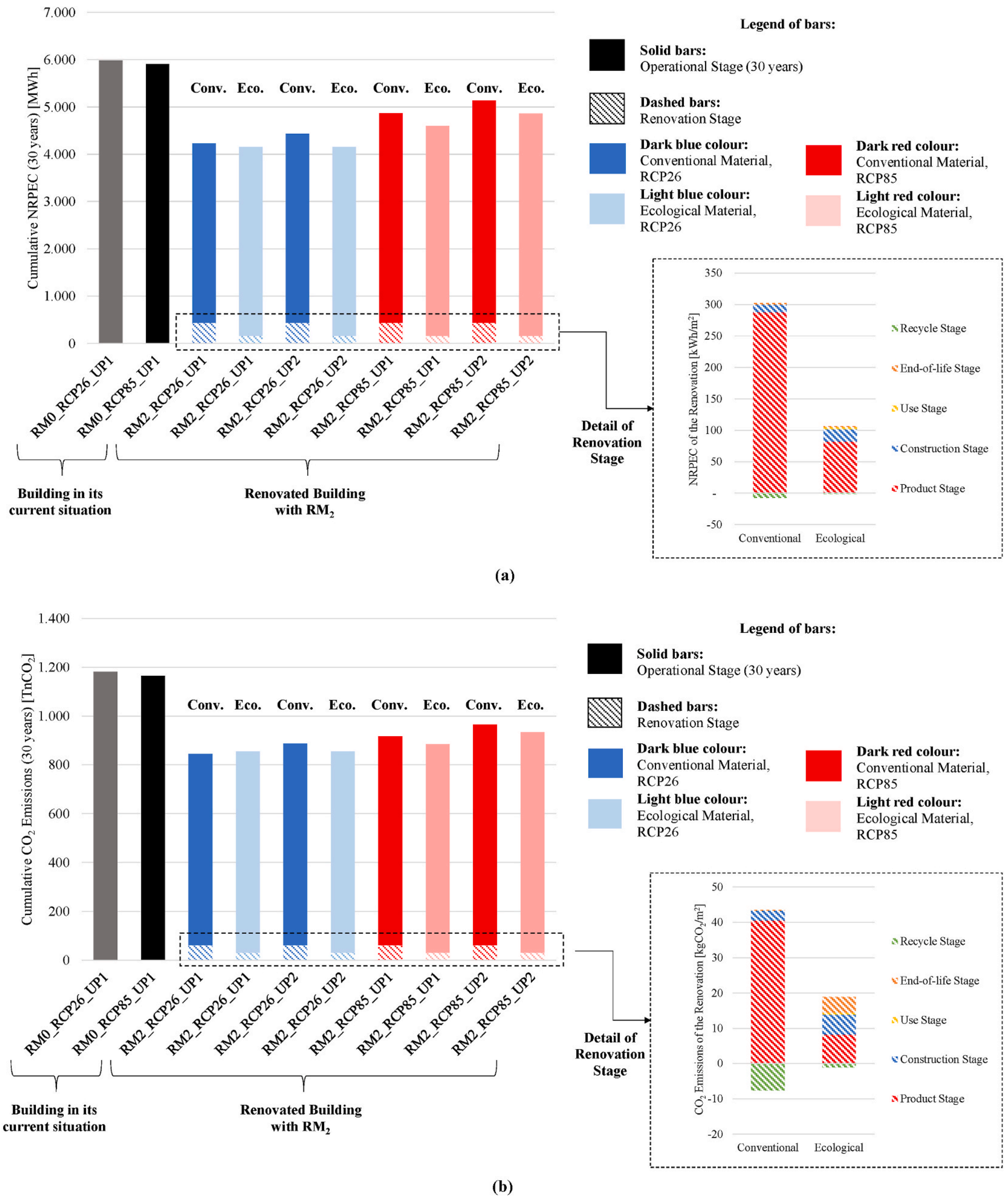


**Fig. 11.** **(a)** Cumulative NRPEC and **(b)** Cumulative CO2 Emissions of the demonstrator building under different RM, CS and UP.

the weight of each indicator of the renovation (A1-A5, C1-C4 and D). The value of the environmental indicators of the ecological renovation actions, as expected, is lower than the indicators when using conventional materials. However, when putting this difference into context with the whole considered building life cycle, the difference between using ecological materials or not is comparatively low. To analyse the specific figures, Table 5 summarises the main indicators of the LCIA. The weight of the Renovation Stage over the total cumulative NRPEC ranges between 3.3 % and 10.3 %, depending on the CC and UP scenarios considered. Similarly, the weight of the cumulative $CO_2$ emissions ranges between 3.3 % and 7.4 %. Moreover, if ecological materials are used, the reduction in the cumulative NRPEC ranges between 5.3 % and 6.5 %, and the reduction in the cumulative $CO_2$ emissions ranges between 3.2 % and 3.7 %. Notice that the share between the environmental impact of the Renovation Stage and the Operation Stage can increase if the time scenario is extended up to 2100. Consequently, in answering RQ4, one may think that the use of ecological materials in the renovation of social housing buildings is not justified and that the LCIA is not a suitable tool to assess these renovations. However, in the authors' opinion, no matter how small the contribution to reducing NRPEC and $CO_2$ emissions may be, such contributions are necessary to achieve the energy transition goals. Furthermore, these differences between using conventional and ecological materials can be

**Table 5**
Main results of the LCIA of the renovation of the demonstrator building, under different CCS and UP, comparing between conventional (Conv) and ecological (Eco.) materials.

| | Renovation Scenario | RM0 | | RM2 | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | CC Scenario | RCP26 | | RCP26 | | | | RCP85 | | | |
| | User Profile | UP1 | | UP1 | | UP2 | | UP1 | | UP2 | |
| | **Type of Material** | **-** | **-** | **Conv.** | **Eco.** | **Conv.** | **Eco.** | **Conv.** | **Eco.** | **Conv.** | **Eco.** |
| **Cumulative NRPEC Consumption [MWh/m$^2$]** | **Renovation Stage** | – | – | 251 | 93 | 251 | 93 | 251 | 93 | 251 | 93 |
| | **Use Stage (30 yr)** | 3463 | 3417 | 2194 | 2194 | 2313 | 2313 | 2567 | 2567 | 2721 | 2721 |
| | **Weight of Renovation Stage** | – | – | 10.3 % | 4.1 % | 9.8 % | 3.9 % | 8.9 % | 3.5 % | 8.5 % | 3.3 % |
| | **Ecological Reduction** | – | – | – | 6.5 % | – | 6.2 % | – | 5.6 % | – | 5.3 % |
| **Cumulative $CO_2$ Emissions [TnCO$_2$/m$^2$]** | **Renovation Stage** | – | – | 36 | 18 | 36 | 18 | 36 | 18 | 36 | 18 |
| | **Use Stage (30 yr)** | 684 | 674 | 453 | 453 | 477 | 477 | 495 | 495 | 523 | 523 |
| | **Weight of Renovation Stage** | – | – | 7.4 % | 3.8 % | 7.0 % | 3.6 % | 6.8 % | 3.5 % | 6.4 % | 3.3 % |
| | **Ecological Reduction** | – | – | – | 3.7 % | – | 3.5 % | – | 3.4 % | – | 3.2 % |

amplified if the renovation of HVAC systems is also included in the LCIA.

## 5. Conclusions

This work performs a comprehensive analysis of the climate resilience of the social housing stock of the Basque Country, under different Climate Change (CC) scenarios and Renovation Measures (RMs). The Life Cycle Impact Assessment (LCIA) is also used to analyse the environmental impact of the renovation. All these aspects are analysed in detail under the influence of the monitored real consumption of social housing buildings, which have been proved to differ significantly from the predicted consumption of standard residential buildings. To do this, a demonstrator building is used, which is representative of a high percentage of the social housing stock of the Basque Country. This building has been monitored for the past few years, so the actual consumption and the real indoor conditions can be thoroughly derived. With this information, calibrated simulations using Design Builder have been performed to assess the influence and environmental impact of CC and user profiles on the renovation of social housing buildings.

The analysis is structured to answer four Research Questions (RQ). RQ1 analyses the influence of the CC in the specific region of the analysed building stock. The analysis of the Representative Concentration Pathways (RCPs), particularly RCP-2.6, RCP-4.5 and RCP-8.5, in different time scenarios (from 2020 to 2100) indicates that the decrease in heating demand will exceed the increase in cooling demand in this region. Specifically, in the worst climate scenario and without any building renovation, the heating demand decreases by up to 42.8 %, whereas the cooling demand increases by 30.8 % when the standard set-points are considered. Indeed, to notice significant changes between the analysed RCPs, the time scenario must be extended to 2100. Thus, in contrast with most of the literature regarding the climate resilience of buildings, the climate forecasts of the analysed region indicate that renovation actions should still be focused on tackling heating demand, while looking into the cooling demand in a complementary manner.

In this sense, RQ2 analyses the effect of specific renovation actions on the social housing stock under a CC context. Two Renovation Measure sets ($RM_1$ and $RM_2$) dedicated to reducing heating demand are analysed. $RM_3$, on the other hand, adds actions to reduce a possible increase in the cooling demand. The results corroborate the outcomes of the previous point, indicating that RMs aiming to reduce heating demand are more energy efficient, even in the worst climate scenario (RCP85-2100). Indeed, if actions to reduce cooling demand are performed ($RM_3$), an unwanted rebound in heating demand occurs, counteracting the effect achieved with the deep renovation. From the analysis of the RMs under the different CC scenarios, it can also be concluded that renovation actions have more influence on the heating demand than CC itself; which means that, even for the expected warmest climate scenario, renovations to reduce heating needs will be necessary. That is to say, the heating demand reduction of $RM_2$ without global warming is 63.3 %, and if the worst CC scenario is considered, the reduction increases up to 82.2 %.

However, analysing the resilience of the renovation of social housing buildings should not be done considering only the consumption of standard users. It has been proven that real consumption is significantly lower than the predicted standard users' consumption, due mainly to an overrepresentation of tenants with low incomes. Implementing this perspective, if the optimistic RCP-2.6 scenario is considered, in 2100 the real heating demand would still be lower than predicted, even if a deep renovation is performed. In contrast, if the pessimistic RCP-8.5 scenario is met, the real heating consumption would exceed the predicted heating demand. Nevertheless, global warming should not be considered as the solution to making the predicted and real consumption of social housing buildings equal. Other actions must be considered, apart from passive measures, such as improving the efficiency of the heating and cooling facilities, or including renewable energy systems, or economic measures such as providing the tenants with financial aid to increase their consumption capacity.

The real consumption of social housing buildings not only affects the performance of the renovations, but also the indoor conditions in these dwellings. The influence of CC and the real user profile on the hourly indoor temperatures of the dwellings have been analysed. The starting point is worrying, since the indoor temperature of the dwellings currently remains below 17 °C, more than 50 % of the year. If the heating demand of the building is reduced with $RM_2$, the percentage of hours in the year below 17 °C can be reduced to 24 % and 4 % for the optimistic RCP-2.6 and pessimistic RCP-8.5 scenarios, respectively. Thus, in contrast to the previous findings, it seems that, regarding the indoor conditions of the dwellings, the influence of CC is stronger than the influence of the RM. Indeed, it has once more been determined that global warming could be beneficial for this type of user in low-income situations. With this, RQ3 is answered, as it asked what the influence of the real consumption of social housing buildings on their renovation under a CC context is.

Finally, to complete the study and answer RQ4, the LCIA is used to analyse the environmental impact of the renovations if conventional or ecological materials are used. As expected, the environmental impact of renovations using ecological materials is lower. The Non–Renewable Primary Energy Consumption (NRPEC) and the $CO_2$ emissions can be reduced by up to 3.7 % and 6.5 %, depending on whether ecological materials are used or not. Nevertheless, the influence of the Renovation Stage is negligible when compared with the influence of the Use Stage of the building during its life cycle. Specifically, the Renovation Stage can account for up to 10.3 % of the cumulative NRPEC and up to 7.4 % of the cumulative $CO_2$ emissions of the building, no matter the CC scenario considered. Nevertheless, in the authors' opinion, regardless of whether the weight of the Renovation Stage is low, using ecological materials can contribute to achieving $CO_2$ emissions reduction targets.

As has been identified before, more actions in addition to the renovation of the building are suggested to improve the indoor conditions of these tenants. In this sense, since the LCIA also allows dynamic analysis to be done, a user profile scenario has been simulated in which social, financial aid is provided to the tenants so they can achieve standard indoor conditions. Furthermore, within the optimistic scenario RCP-2.6, it is considered that, as $CO_2$ emissions reduction targets are achieved, the mix of the electricity generation improves. It has been proved that, if financial aid is provided to the tenants to increase their energy consumption, they are able to reach indoor standard conditions; while the long-term environmental impact of the increase in the energy consumption is not significant when compared to the whole building life cycle. The results show a double benefit: if economic aid is provided and the building is renovated, there will still be a positive environmental impact while also improving the tenants' conditions.

With this, the four RQs set in this work, which aimed to analyse the influence of real consumption towards the renovation of social housing buildings under a CC framework, have been answered. Within this research, future lines of work have been identified that could help address some of the limitations of this study, such as the use of forecasted Typical Meteorological Years (TMY), which do not consider extreme weather events, such as heat waves, that would considerably increase cooling needs at certain times over the years. Even though the thermal comfort analysis performed with UNE-EN 16798 indicates no overheating risk for the studied case, future studies should focus on analysing the cooling demand in heat waves and regions in which the cooling demand is predominant, even in the pessimistic scenario. Concerning the latter, those expected peaks in cooling loads are more likely to be tackled with active systems, such as air conditioning, rather than using passive solutions, which are the ones analysed in this study. In this sense, another future line of research is to incorporate active systems into the LCIA analysis, but there is still a considerable lack of availability of Environmental Product Declarations (EPDs) needed to perform the analysis.

## CRediT authorship contribution statement

**Pablo Hernandez-Cruz:** Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ivan Flores-Abascal:** Writing – review & editing, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Juan María Hidalgo-Betanzos:** Writing – review & editing, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Manuela Almeida:** Writing – review & editing, Methodology, Investigation, Funding acquisition, Conceptualization. **Aitor Erkoreka-Gonzalez:** Writing – review & editing, Methodology, Funding acquisition, Conceptualization.

## Conflicts of interest

The authors declare no conflict of interest.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Appendix A

**Table A 1**

Summary of the analysed cases in this work, according to the Climate Change (CC) scenario, Renovation Measure (RM), type of material and User Profile (UP), and indication of the Results and Discussion Section (4.x) in which each case is analysed.

| RM | UP | RCP00-2020 | RCP26-2050 | RCP26-2070 | RCP26-2100 | RCP45-2050 | RCP45-2070 | RCP45-2100 | RCP85-2050 | RCP85-2070 | RCP85-2100 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | UP$_0$ | 4.1, 4.2,4.3 | 4.1, 4.2 | 4.1, 4.2 | 4.1, 4.2,4.3 | 4.1, 4.2 | 4.1, 4.2 | 4.1, 4.2 | 4.1, 4.2 | 4.1, 4.2 | 4.1, 4.2,4.3 |
| | UP$_1$ | 4.3, 4.4 | | | 4.3, 4.4 | | | | | | 4.3, 4.4 |
| | UP$_2$ | | | | | | | | | | |
| 1_conv | UP$_0$ | 4.2 | | | 4.2 | | | | | | 4.2 |
| | UP$_1$ | 4.3 | | | 4.3 | | | | | | 4.3 |
| | UP$_2$ | 4.3 | | | 4.3 | | | | | | 4.3 |
| 2_conv | UP$_0$ | 4.2 | | | 4.2 | | | | | | 4.2 |
| | UP$_1$ | 4.3, 4.4 | | | 4.3, 4.4 | | | | | | 4.3, 4.4 |
| | UP$_2$ | 4.3, 4.4 | | | 4.3, 4.4 | | | | | | 4.3, 4.4 |
| 2_eco | UP$_0$ | | | | | | | | | | |
| | UP$_1$ | 4.4 | | | 4.4 | | | | | | 4.4 |
| | UP$_2$ | 4.4 | | | 4.4 | | | | | | 4.4 |
| 3_conv | UP$_0$ | 4.2 | | | 4.2 | | | | | | 4.2 |
| | UP$_1$ | 4.3 | | | 4.3 | | | | | | 4.3 |
| | UP$_2$ | 4.3 | | | 4.3 | | | | | | 4.3 |

**Climate Change (CC) scenarios casuistry:**

- RCP00-2020: Current climate scenario.
- RCP26-2050, RCP26-2070 and RCP26-2100: Future climate scenario obtained with Meteonorm [11], considering Representative Concentration Pathway 2.6 (RCP-2.6) established by Ref. [6], in 2050, 2070 and 2100 time scenarios.
- RCP45-2050, RCP45-2070 and RCP45-2100: Future climate scenario obtained with Meteonorm [11], considering Representative Concentration Pathway 4.5 (RCP-4.5) established by Ref. [6], in 2050, 2070 and 2100 time scenarios.
- RCP85-2050, RCP85-2070 and RCP85-2100: Future climate scenario obtained with Meteonorm [11], considering Representative Concentration Pathway 8.5 (RCP-8.5) established by Ref. [6], in 2050, 2070 and 2100 time scenarios.

**Renovation Measures (RM) scenarios casuistry:**

- RM$_0$: Current situation of the building.
- RM$_1$: Business as Usual (BAU) renovation measure. Details in Table 2.
- RM$_2$: Deep renovation measure. Details in Table 2.
- RM$_3$: Deep renovation measure plus cooling demand reduction actions. Details in Table 2.

**Material used in the RMs:**

- Conv.: Conventional materials, such as EPS or MW for insulation or PVC for windows. Details of LCIA data in Table A 2.
- Eco.: Ecological materials, such as cork for insulation or wood for windows. Details of LCIA data in Table A 2.

**Users' Profiles (UP) scenarios casuistry:**

- UP$_0$: Standard user profile according to Spanish CTE DB HE 2013 regulation [76].
- UP$_1$: Real user profile, according to real consumption collected data.
- UP$_2$: Optimistic user profile, considering financial aids to achieve standard conditions.

**Table A 2**

LCI data of the conventional and ecological materials considered to analyse the environmental impact of the proposed renovation.

| | Product | EPD Functional Unit (fu) | Reference Service Life (RSL) [years] | LCIA Indicator (per fu) | A1-A2-A3 Product stage | Construction Stage | | Use Stage | | | | | | | End-of-Life Stage | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | A4 Transport to customer | A5 Construction installation | B1 Use | B2 Maintenance | B3 Repair | B4 Replacement | B5 Refurbishment | B6 Operational energy use | B7 Operational water use | C1 Demolition | C2 Transport to waste processing | C3 Waste processing | C4 Disposal | D Recycle Stage |
| **Conventional Materials** | **MW ETICS** [1] | $m^2$ of opaque envelope | 50 | GWP [kg $CO_2$] | 16 | 4 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | NC[8] | NC | NC | NC |
| | | | | NRPEC [MJ] | 350 | 61 | 21 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | NC | NC | NC | NC |
| | **XPS Slab Insulation** [2] | $m^2$ of slabs | 50 | GWP [kg $CO_2$] | 2.92 | 0.092 | 0.0737 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | NC | NC | NC | NC |
| | | | | NRPEC [MJ] | 63.5 | 1.42 | 0.0541 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | NC | NC | NC | NC |
| | **Aluminium Windows** [3] | $m^2$ of windows | 30 | GWP [kg $CO_2$] | 147 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.62 | 0.507 | 0.0238 | −37.3 |
| | | | | NRPEC [MJ] | 3950 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 15.7 | 17.6 | 6.96 | −900 |
| **Ecological Materials** | **Cork ETICS** [4] | $m^2$ of opaque envelope | 50 | GWP [kg $CO_2$] | −0.61 | 0.0574 | 3.51 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | NC | NC | NC | NC |
| | | | | NRPEC [MJ] | 98.6 | 0.767 | 48.8 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | NC | NC | NC | NC |
| | **MW Slab Insulation** [5] | $m^2$ of slabs | 50 | GWP [kg $CO_2$] | 0.91 | 0.41 | 0.15 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | NC | NC | NC | NC |
| | | | | NRPEC [MJ] | 10 | 5.6 | 0.49 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | NC | NC | NC | NC |
| | **Wood Windows** [6] | Number of windows | 30 | GWP [kg $CO_2$] | 38.52 | 1.98 | 2.75 | 0 | 2.7 | 0 | 0 | 0 | 0 | 0 | 0 | 0.46 | 0.04 | 21.36 | −5.2 |
| | | | | NRPEC [MJ] | 855.02 | 31.78 | 0.57 | 0 | 63.88 | 0 | 0 | 0 | 0 | 0 | 0 | 7.45 | 5.14 | 14.14 | −246.2 |

**7NC:** Not considered due to the definition of the cradle-to-grave LCIA.

[1] **Conventional MW ETICS:** ISOVER ETICS System (EPD S-P-02252) [91].

[2] **Conventional XPS Slab Insulation:** SOPREMA XPS Insulation Slab (DAPcons NTe.003) [92].

[3] **Conventional Aluminium Windows:** CORTIZO Aluminium Window (DAPcons 100.026) [93].

[4] **Ecological Cork ETICS:** WEBER THERMA NATURA ETICS System (DAP 943-25718-001) [94].

[5] **Ecological MW Slab Insulation:** ROCKWOOL MW Slab Insulation (EPD-RW_11–2020_RW-LAT-ES_ES-0001) [95].

[6] **Conventional Wood Windows:** Elitfönster Original Trä Wood Window (EPD S-P-05382) [96].

## Data availability

The authors do not have permission to share data.

## References

[1] NASA, Evidence on climate change [Online]. Available: https://science.nasa.gov/climate-change/evidence/. (Accessed 7 June 2024).
[2] IPCC, "The Intergovernmental Panel on Climate Change. " [Online]. Available: https://www.ipcc.ch/.
[3] IPCC, "Sixth Assessment Report - Synthesis Report," 203AD.
[4] European Commission, "Long-term renovation strategies." [Online]. Available: . https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficient-buildings/long-term-renovation-strategies_en.
[5] WCRP, World climate research programme [Online]. Available: https://www.wcrp-climate.org/. (Accessed 7 June 2024).
[6] IPCC, Cambio Climático 2021: Bases Físicas, 2021.
[7] K. Riahi, et al., The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: an overview, Global Environ. Change 42 (2016) 153–168, https://doi.org/10.1016/j.gloenvcha.2016.05.009.
[8] C.N. Nielsen, J. Kolarik, Utilization of climate files predicting future weather in dynamic building performance simulation – a review, J. Phys. Conf. Ser. 2069 (2021) 12070, https://doi.org/10.1088/1742-6596/2069/1/012070.
[9] T.E. Palmer, et al., Performance-based sub-selection of CMIP6 models for impact assessments in Europe, Earth Syst. Dynam. 14 (2023) 457–483, https://doi.org/10.5194/esd-14-457-2023.
[10] M.F. Jentsch, P.A.B. James, L. Bourikas, A.B.S. Bahaj, Transforming existing weather data for worldwide locations to enable energy and building performance simulation under future climates, Renew. Energy 55 (2013) 514–524, https://doi.org/10.1016/j.renene.2012.12.049.
[11] Meteotest, Meteonorm [Online]. Available: https://meteonorm.com/en/meteonorm-version-8. (Accessed 9 May 2024).
[12] A. N. A. L. (Arup) and A. A. LLC, Weathershift [Online]. Available: https://weathershift.com/. (Accessed 7 June 2024).
[13] E. Rodrigues, M.S. Fernandes, D. Carvalho, Future weather generator for building performance research: an open-source morphing tool and an application, Build. Environ. 233 (2023) 110104, https://doi.org/10.1016/j.buildenv.2023.110104.
[14] A. Robert, M. Kummert, Designing net-zero energy buildings for the future climate, not for the past, Build. Environ. 55 (2012) 150–158, https://doi.org/10.1016/j.buildenv.2011.12.014.
[15] R. Escandón, C.M. Calama-González, A. Alonso, R. Suárez, Á.L. León-Rodríguez, How do different methods for generating future weather data affect building performance simulations? A comparative analysis of southern Europe, Buildings 13 (9) (2023), https://doi.org/10.3390/buildings13092385.
[16] J.B. Dias, G. Carrilho Da Graça, P.M.M. Soares, Comparison of methodologies for generation of future weather data for building thermal energy simulation, Energy Build. 206 (2020) 109556, https://doi.org/10.1016/j.enbuild.2019.109556.
[17] I. Andrić, et al., Modeling the long-term effect of climate change on building heat demand: case study on a district level, Energy Build. 126 (Aug. 2016) 77–93, https://doi.org/10.1016/J.ENBUILD.2016.04.082.
[18] L. Troup, M.J. Eckelman, D. Fannon, Simulating future energy consumption in office buildings using an ensemble of morphed climate data, Appl. Energy 255 (2019), https://doi.org/10.1016/j.apenergy.2019.113821.
[19] I. Andrić, A. Pina, P. Ferrão, J. Fournier, B. Lacarrière, O. Le Corre, The impact of climate change on building heat demand in different climate types, Energy Build. 149 (Aug. 2017) 225–234, https://doi.org/10.1016/J.ENBUILD.2017.05.047.
[20] V.M. Nik, J. Arfvidsson, Using typical and extreme weather files for impact assessment of climate change on buildings, Energy Proc. 132 (2017) 616–621, https://doi.org/10.1016/j.egypro.2017.09.686.
[21] I. Andrić, O. Le Corre, B. Lacarrière, P. Ferrão, S.G. Al-Ghamdi, Initial approximation of the implications for architecture due to climate change, Adv. Build. Energy Res. 15 (3) (2021) 337–367, https://doi.org/10.1080/17512549.2018.1562980.
[22] Buildings Performance Institute Europe (BPIE), The Renovation Wave Strategy & Action Plan: Designed for Success or Doomed to Fail? A Review and Gap Analysis of the Renovation Wave, 2021.
[23] C. Maduta, D. D'agostino, S. Tsemekidi-Tzeiranaki, L. Castellazzi, G. Melica, P. Bertoldi, Towards climate neutrality within the European union: assessment of the energy performance of buildings directive implementation in member states, Energy Build. 301 (2023) 113716, https://doi.org/10.1016/j.enbuild.2023.113716.
[24] M.P. Tootkaboni, I. Ballarini, V. Corrado, Analysing the future energy performance of residential buildings in the most populated Italian climatic zone: a study of climate change impacts, Energy Rep. 7 (2021) 8548–8560, https://doi.org/10.1016/j.egyr.2021.04.012.
[25] C. Baglivo, Dynamic evaluation of the effects of climate change on the energy renovation of a school in a mediterranean climate, Sustainability (Switzerland) 13 (11) (2021), https://doi.org/10.3390/su13116375.
[26] C. Filippín, F. Ricard, S. Flores Larsen, M. Santamouris, Retrospective analysis of the energy consumption of single-family dwellings in central Argentina. Retrofitting and adaptation to the climate change, Renew. Energy 101 (2017) 1226–1241, https://doi.org/10.1016/j.renene.2016.09.064.
[27] A.R. Rempel, J. Danis, A.W. Rempel, M. Fowler, S. Mishra, Improving the passive survivability of residential buildings during extreme heat events in the Pacific Northwest, Appl. Energy 321 (June) (2022) 119323, https://doi.org/10.1016/j.apenergy.2022.119323.
[28] D. Rukmal Liyanage, K. Hewage, S. Asad Hussain, F. Razi, R. Sadiq, Climate adaptation of existing buildings: a critical review on planning energy retrofit strategies for future climate, Renew. Sustain. Energy Rev. 199 (2024), https://doi.org/10.1016/j.rser.2024.114476.
[29] U.Y. Ayikoe Tettey, L. Gustavsson, Energy savings and overheating risk of deep energy renovation of a multi-storey residential building in a cold climate under climate change, Energy 202 (Jul) (2020), https://doi.org/10.1016/J.ENERGY.2020.117578.
[30] R.F. De Masi, A. Gigante, S. Ruggiero, G.P. Vanoli, Impact of weather data and climate change projections in the refurbishment design of residential buildings in cooling dominated climate, Appl. Energy 303 (Dec) (2021), https://doi.org/10.1016/J.APENERGY.2021.117584.
[31] R. Suárez, R. Escandón, R. López-Pérez, Á. Luis León-Rodríguez, T. Klein, S. Silvester, Impact of climate change: environmental assessment of passive solutions in a single-family home in southern Spain, Sustainability (2018), https://doi.org/10.3390/su10082914.
[32] B. Arballo, E. Kuchen, Y.A. Naranjo, A.A. Frank, Evaluación de modelos de confort térmico para interiores, in: VIII CRETA - Congreso Regional de Tecnología de la Arquitectura, 2016.
[33] M. Marco, A. Ramezani, A. Buoite Stella, A. Pezzi, Climate change and building renovation: effects on energy consumption and internal comfort in a social housing building in northern Italy, Sustainability (Switzerland) 15 (7) (2023), https://doi.org/10.3390/su15075931.
[34] F. P.O., Assessment of man's thermal comfort in practice, Br. J. Ind. Med. 30 (1973) 313–324.
[35] Aenor, UNE-EN 16798-1, 2020.
[36] K. Błazejczyk, et al., An introduction to the Universal thermal climate index (UTCI), Geogr. Pol. 86 (1) (2013) 5–10, https://doi.org/10.7163/GPol.2013.1.
[37] A. Vilches, A. Garcia-martinez, B. Sanchez-monta, Life Cycle Assessment (LCA) of Building Refurbishment: A Literature Review, vol. 135, 2017, pp. 286–301, https://doi.org/10.1016/j.enbuild.2016.11.042.
[38] A. Sharma, A. Saxena, M. Sethi, V. Shree, Varun, "Life cycle assessment of buildings: a review,", Renew. Sustain. Energy Rev. 15 (1) (2011) 871–875, https://doi.org/10.1016/j.rser.2010.09.008.
[39] A. Faiz, A. Rashid, S. Yusoff, A review of life cycle assessment method for building industry, Renew. Sustain. Energy Rev. 45 (2015) 244–248, https://doi.org/10.1016/j.rser.2015.01.043.
[40] M.M. Khasreen, P.F.G. Banfill, G.F. Menzies, Life-Cycle Assessment and the Environmental Impact of Buildings: A Review, Sustainability (2009) 674–701, https://doi.org/10.3390/su1030674, no. i, pp.

[41] M. Leichter, C. Piccardo, Assessing Life Cycle Sustainability of Building Renovation and Reconstruction: A Comprehensive Review of Case Studies and Methods, Elsevier Ltd., Aug. 15, 2024, https://doi.org/10.1016/j.buildenv.2024.111817.

[42] M. Almeida, R. Mateus, M. Ferreira, A. Rodrigues, Life-cycle costs and impacts on energy-related building renovation assessments, Int. J. Sustain. Build. Technol. Urban Dev. 7 (3–4) (2016) 206–213, https://doi.org/10.1080/2093761X.2017.1302837.

[43] R. Mateus, S.M. Silva, M.G. de Almeida, Environmental and cost life cycle analysis of the impact of using solar systems in energy renovation of Southern European single-family buildings, Renew. Energy 137 (2019) 82–92, https://doi.org/10.1016/j.renene.2018.04.036.

[44] S.M. Silva, R. Mateus, L. Marques, M. Ramos, M. Almeida, Contribution of the solar systems to the nZEB and ZEB design concept in Portugal – energy, economics and environmental life cycle analysis, Sol. Energy Mater. Sol. Cell. 156 (2016) 59–74, https://doi.org/10.1016/j.solmat.2016.04.053, 2016.

[45] H. Amini Toosi, M. Lavagna, F. Leonforte, C. Del Pero, N. Aste, Life Cycle Sustainability Assessment in Building Energy Retrofitting; A Review, Elsevier Ltd., Sep. 01, 2020, https://doi.org/10.1016/j.scs.2020.102248.

[46] A. González, C. Sendra, A. Herena, M. Rosquillas, D. Vaz, Methodology to assess the circularity in building construction and refurbishment activities, Resour., Conserv. Recycl. Adv. 12 (Dec. 2021), https://doi.org/10.1016/j.rcradv.2021.200051.

[47] X. Oregi Isasi, et al., Sofias - software for life-cycle assessment and environmental rating of buildings, Inf. Construcción 68 (542) (2016), https://doi.org/10.3989/ic.15.055.

[48] Y. Decorte, N. Van Den Bossche, M. Steeman, Guidelines for defining the reference study period and system boundaries in comparative LCA of building renovation and reconstruction, Int. J. Life Cycle Assess. 28 (2) (Feb. 2023) 111–130, https://doi.org/10.1007/s11367-022-02114-0.

[49] H. Nydahl, S. Andersson, A.P. Åstrand, T. Olofsson, Extended building life cycle cost assessment with the inclusion of monetary evaluation of climate risk and opportunities, Sustain. Cities Soc. 76 (Jan) (2022), https://doi.org/10.1016/j.scs.2021.103451.

[50] D. Carolina Gámez-García, J. Manuel Gómez-Soberón, R. Corral-Higuera, H. Saldaña-Márquez, M. Consolación Gómez-Soberón, S. Paola Arredondo-Rea, A cradle to handover life cycle assessment of external walls: choice of materials and prognosis of elements, Sustainability (Switzerland) 10 (2018), https://doi.org/10.3390/su10082748.

[51] European Commission, "Delivering the European Green Deal." Accessed: Apr. 29, 2024. [Online]. Available: . https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/delivering-european-green-deal_en#renovating-buildings-for-greener-lifestyles.

[52] C. Whitehead, Social housing models: past and future, Crit. Hous. Anal. 4 (1) (2017) 11–20, https://doi.org/10.13060/23362839.2017.4.1.320.

[53] K. Scanlon, C. Whitehead, M. Fernández Arrigoitia, Social Housing in Europe, 2014.

[54] M. Braga, P. Palvarini, Social Housing in the EU - Report for European Parliament's Committee on Employment and Social Affairs, European Parliament, 2013.

[55] D. Teli, T. Dimitriou, P.A.B. James, A.S. Bahaj, L. Ellison, A. Waggott, Fuel poverty-induced 'prebound effect' in achieving the anticipated carbon savings from social housing retrofit, Build. Serv. Eng. Res. Tecnol. 37 (2) (2016) 176–193, https://doi.org/10.1177/0143624415621028.

[56] I. Antepara, L. Papada, J.P. Gouveia, N. Katsoulakos, D. Kaliampakos, Improving energy poverty measurement in southern European regions through equivalization of modeled energy costs, Sustainability 12 (14) (2020) 1–21, https://doi.org/10.3390/su12145721.

[57] P. Hernandez-Cruz, C. Giraldo-Soto, C. Escudero-Revilla, J. María Hidalgo-Betanzos, I. Flores-Abascal, Energy efficiency and energy performance gap in centralized social housing buildings of the Basque Country, Energy Build. 298 (2023) 113534, https://doi.org/10.1016/j.enbuild.2023.113534.

[58] S. Perez-Bezos, O. Guerra-Santin, O. Grijalba, R. Javier Hernandez-Minguillon, Occupants' behavioural diversity regarding the indoor environment in social housing. Case study in Northern Spain, J. Build. Eng. 77 (2023) 2352–7102, https://doi.org/10.1016/j.jobe.2023.107290.

[59] S. Perez-Bezos, A. Figueroa-Lopez, M. Etxebarria-Mallea, X. Oregi, R. Javier Hernandez-Minguillon, Assessment of social housing energy and thermal performance in relation to occupants' behaviour and COVID-19 influence-A case study in the Basque country, Spain, Sustainability 14 (2022), https://doi.org/10.3390/su14095594.

[60] R. Escandón, R. Suárez, J.J. Sendra, Field assessment of thermal comfort conditions and energy performance of social housing: the case of hot summers in the Mediterranean climate, Energy Pol. 128 (2019) 377–392, https://doi.org/10.1016/j.enpol.2019.01.009.

[61] S. Perez-bezos, O. Grijalba, R. Javier Hernandez-Minguillon, Evaluation of thermal comfort perception in social housing context, Environ. Climat. Technol. 27 (1) (2023) 289–298, https://doi.org/10.2478/rtuect-2023-0022.

[62] Alokabide, Plan de Ciencia, Tecnología e Innovación - PLAN ZERO PLANA, 2020.

[63] Alokabide, "Alokabizi." [Online]. Available: https://www.alokabide.euskadi.eus/alokabizi/es/.

[64] Alokabide, "Alokabide S.A." Accessed : June. 7, 2024. [Online]. Available: https://www.alokabide.euskadi.eus/inicio/.

[65] European Commission, Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the Energy Performance of Buildings (Recast) [EN], 2010, p. 23.

[66] "Design Builder." Accessed: Jan. 10, 2024. [Online]. Available: https://designbuilder.co.uk/.

[67] AEMET, Mapas climáticos de España (1981-2010) y ETo. https://www.aemet.es/es/conocermas/recursos_en_linea/publicaciones_y_estudios/publicaciones/detalles/MapasclimaticosdeEspana19812010, 1996-2016.

[68] Euskalmet, "Atlas climático del País Vasco ," https://opendata.euskadi.eus/catalogo/-/informes-estudios/atlas-climatico-del-pais-vasco/.

[69] F. E. C. E. A. (FECEA), Universidad del País Vasco/Euskal Herriko Unibertsitatea, La Rochelle Université, Technological & Innovative Platform for Environmental Efficiency -Tipee, Universidade do Minho, and O. del T. y U. Gobierno de Cantabria. Consejería de Obras Públicas, "ARCAS - Interreg Sudoe." Accessed: March. 30, 2023. [Online]. Available: http://www.arcassudoe.eu/about/?lang=en.

[70] ARCAS Consortium, " Climate and air quality map ARCAS," https://fecea-viewer.predictia.es/.

[71] A.C. Bernabé, B.L. Mariño, R.R. Fresneda, J.V.M. García, Evolución de los climas de Köppen en España en el periodo 1951-2020, 2022.

[72] IPCC, IPCC WGI interactive atlas: regional information (advanced) [Online]. Available: https://interactive-atlas.ipcc.ch/. (Accessed 7 June 2024).

[73] AEMET, Visor de Escenarios de Cambio Climático [Online]. Available: https://adaptecca.es/. (Accessed 7 June 2024).

[74] Ihobe, Escenario Climáticos en Euskadi y Series de Datos [Online]. Available: http://escenariosklima.ihobe.eus/home. (Accessed 7 June 2024).

[75] Euskalmet, Public weather station - open data [Online]. Available: https://www.euskalmet.euskadi.eus/observacion/datos-de-estaciones/#. (Accessed 4 May 2023).

[76] Ministerio de Fomento, " CTE-HE. Código Técnico de la Edificación. Documento Basico HE Ahorro de energia," June, p. vol. 68, 2017.

[77] Instituto Geográfico Nacional (IGN), Visualizador del Atlas Didáctico del IGN [Online]. Available: https://www.ign.es/web/ign/portal/qsm-cnig. (Accessed 7 June 2024).

[78] Buildings Performance Institute Europe (BPIE), The Renovation Wave Strategy & Action Plan: Designed for Success or Doomed to Fail? A Review and Gap Analysis of the Renovation Wave, 2021.

[79] C. Maduta, D. D'agostino, S. Tsemekidi-Tzeiranaki, L. Castellazzi, G. Melica, P. Bertoldi, Towards climate neutrality within the European union: assessment of the energy performance of buildings directive implementation in member states, Energy Build. 301 (2023) 113716, https://doi.org/10.1016/j.enbuild.2023.113716.

[80] Buildings Performance Institute Europe (BPIE), Deep renovation: shifting from exception to standard practice in EU policy [Online]. Available: https://www.bpie.eu/publication/deep-renovation-shifting-from-exception-to-standard-practice-in-eu-policy/, 2021.

[81] M. y A. U. Ministerio de Transportes, Programa de ayudas para la rehabilitación integral de edificios residenciales y viviendas [Online]. Available: https://www.transportes.gob.es/ministerio/proyectos-singulares/prtr/vivienda-y-agenda-urbana/programa-de-ayudas-para-la-rehabilitacion-integral-de-edificios-residenciales-y-viviendas. (Accessed 17 April 2024).

[82] Gobiernos Vasco and Etxebide, " Medidas financieras en materia de rehabilitación accesibilidad y eficiencia energética," https://www.etxebide.euskadi.eus/etxe-medidas-financieras-rehabilitacion/webetxe00-content/es/.

[83] P. Hernandez-Cruz, J. María Hidalgo-Betanzos, I. Flores-Abascal, A. Erkoreka-Gonzalez, J. Fernandez-Luzuriaga, The effect of considering the real consumption on the assessment of the renovation of social housing buildings, Energy Build. 319 (May) (2024) 114535, https://doi.org/10.1016/j.enbuild.2024.114535.

[84] S. Attia, et al., Overheating calculation methods, criteria, and indicators in European regulation for residential buildings, Energy Build. 292 (May) (2023) 113170, https://doi.org/10.1016/j.enbuild.2023.113170.

[85] P. Engelmann, D. Kalz, G. Salvalai, Cooling concepts for non-residential buildings: a comparison of cooling concepts in different climate zones, Energy Build. 82 (Aug. 2014) 447–456, https://doi.org/10.1016/j.enbuild.2014.07.011.
[86] Ministerio de Fomento (Espana), CTE DB-HE 2019 Documento Basico HE Ahorro de Energia 2019. 2019, pp. 1-129. [Online]. Available: http://www.arquitectura-tecnica.com/hit/Hit2016-2/DBHE.pdf.
[87] P. Hernandez-Cruz, I. Uriarte, J.M. Hidalgo-Betanzos, Í. Antepara, I. Flores-Abascal, A novel strategy to guarantee a minimum indoor temperature in social housing buildings, J. Build. Eng. 76 (February) (2023) 107230, https://doi.org/10.1016/j.jobe.2023.107230.
[88] Aenor, UNE-EN ISO 14040:2006/A1 (2022).
[89] PRé Sustainability B.V., “ SimaPro.” Accessed: June. 12, 2024. [Online]. Available: https://simapro.com/.
[90] M. y A. U. Ministerio de Transportes, Programa de ayudas para la rehabilitación integral de edificios residenciales y viviendas [Online]. Available: https://www.transportes.gob.es/ministerio/proyectos-singulares/prtr/vivienda-y-agenda-urbana/programa-de-ayudas-para-la-rehabilitacion-integral-de-edificios-residenciales-y-viviendas. (Accessed 17 April 2024).
[91] S.L. Saint-Gobain Isover Ibérica, ISOVER ETICS System (EPD S-P-02252), 2021.
[92] S.L.U. Soprema Iberia, SOPREMA XPS Insulation Slab, DAPcons NTe.003, 2021.
[93] CORTIZO, CORTIZO Aluminium Window (DAPcons 100.026), 2020.
[94] W. Saint-Gobain, WEBER THERM NATURA (DAP 943-25718-001), 2016.
[95] A./S. Rockwool International, ROCKWOOL MW Slab Insulation, EPD-RW_11-2020_RW-LAT-ES_ES-0001), 2020.
[96] A.B. Elitfönster, Elitfönster Original Trä Wood Window (EPD S-P-05382), 2022.