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The Present and Future of the Use Phase of Social Housing in Tucumán, Argentina: An LCA Perspective

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Abstract: This research focuses on assessing the environmental impact of heating and cooling systems in public housing projects, built between 2000 and 2020, in Tucuman, Argentina. It considers current and projected climate change scenarios. The study compares existing conditions with improvements suggested by IRAM 11603 for a thermo-energetic transition. Anticipating future energy consumption changes is vital for proposing sustainable retrofitting options to enhance affordability and energy efficiency, while ensuring occupants' thermal comfort. A public housing prototype in Tucumán serves as the case study. The methodology combines energy simulation and Life Cycle Assessment (LCA) to analyze current and future energy demands. The results show climate change's potential impact on housing thermal behavior and the necessity for improvements. In the base case, cooling demand exceeds 11 kWh/m^2.year, while heating demand decreases by approximately 4 kWh/m^2.year. Rehabilitation could reduce cooling demand by 57% and heating demand by 32.5%, considering future climate scenarios. Active architectural strategies are proposed for enhancing thermal performance and reducing energy consumption and carbon dioxide emissions. This study underscores the importance of analyzing future scenarios and implementing strategies for the thermo-energetic transition of existing social housing.

Keywords: energy retrofitting; carbon neutrality; climate change scenarios

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1. Introduction

Anthropogenic emissions of greenhouse gases contribute extensively to the increase in the average global temperature. One sector that contributes significantly to this problem and is of interest to this study is energy consumption in buildings, which has multiple impacts on climate change and the depletion of fossil resources [1]. Several scientific studies suggest that the thermal conditioning of a building is the main factor responsible for its energy consumption [2]. In addition, this will be further exacerbated as the gradual increase in global temperature caused by climate change is expected to impact on the energy consumption for thermal conditioning of buildings [3]. Globally, the latest report from the World Meteorological Organization confirms that in 2020, the average annual temperature exceeded normal values by 1.2 °C. According to forecasts, the estimated average temperature for the next 20 years will reach or exceed 1.5 °C of warming [4]. To this effect, if this increase is not slowed, future changes in the climate system are expected to be greater than those already observed and attributed to human activities.

Globally, residential buildings are known to consume 70% of the global final energy demand of buildings [5]. Between 1990 and 2019, global CO_2 emissions from buildings increased by 50%, global final energy demand grew by 38%, and global final electricity demand increased by 161% [3]. Under this scenario, the interest of many researchers is focused on estimating the thermal behavior that residential buildings will experience under the consequences of the temperature increase. In this regard, Mehmood et al. [6] analyze the impact of climate change on climate zones, cooling thermal demand (kWh/m^2), and indoor heat discomfort hours (DHh, hours) in buildings and evaluate this impact in different extremely hot, dry climates of South Asia through a parametric analysis for 2020, 2050, and 2080 under the A2 emissions scenario. The simulated scenario shows how the area with an extremely hot and dry climate in Pakistan may increase from 36.9% to 78.1% by 2080, increasing annual cooling requirements between 20.56 and 66.96 kWh/m^2. Guarino Turina et al. [7] propose a free-to-use tool that generates a future climate data file with the assumed RCP scenarios and a framework and elaborates the results in terms of heating and cooling requirements for air conditioning. For the application case, they analyze the results in two locations in Europe—Palermo (Italy) and Copenhagen (Denmark)—and show an increase of more than 20% in cooling requirements and similar reductions for heating in both case studies, if compared with current levels. Berardi and Jafarpur [8] investigate the effects of climate changes on the heating and cooling energy demand of buildings in Canada’s most populated urban region, i.e., the city of Toronto in Ontario. The simulation results show an average decrease of 18% to 33% for heating energy use intensity and an average increase of 15% to 126% for cooling energy use intensity by 2070. Bamdad et al. [9] analyze, using a simulation model with future climate scenarios, the performance of office buildings in two Australian cities. They reveal that, in the case of Brisbane, the energy difference between optimization under current and future climate conditions is small, but in Canberra, the cooling load increases by up to 6%.

In Argentina, 37% of the current energy consumption is attributed to the construction sector, with air conditioning being the most significant factor [5]. There remains a scarcity of studies on the impact of climate change on the energy consumption of buildings when applied to the Argentinian context. According to Flores Larsen et al. [10], energy for air heating and cooling is expected to be 23–59% lower and 360–790% higher, respectively, in 2080 than in the reference period (1961–1990). Filippin et al. [11] studied the energy consumption of 10 single-family dwellings in central Argentina over 50 years, along with different adaptation strategies for future climate conditions in 2039. The energy demand in 2010 and 2039, for both conventional and retrofitted housing, shows a decrease (22%) in winter and about a five times increase in the summer. Likewise, there is a lack of research showing the thermal behavior in a future climate scenario, in combination with the associated environmental impact in the province of Tucumán. Therefore, this research aims to answer the following questions: What is the environmental performance associated with the use phase, considering climate change in dwellings located in the metropolitan area of Tucumán, Argentina? What would be the effect of actively or passively retrofitting these dwellings?

In reference to reducing operational energy consumption and avoiding the use of non-renewable energy, the concept of architecture adapted to the climate, or bioclimatic architecture [12], is essential to address housing rehabilitation or new construction. This concept focuses on the knowledge of the climate of the location to apply passive architectural design strategies that improve the hygrothermal behavior of the interior space and therefore, reduce the demand for operational energy, which then favorably impacts the reduction of energy consumption [13]. These strategies are based on the physical principles of “capturing, accumulating and distributing heat” in winter and “protecting and dissipating heat” in summer [14]. Likewise, it is important to analyze the performance of thermo-mechanical equipment and the type of energy sources that are used; these methods are known as active strategies [5]. In this sense, the articulation of both is essential to achieve nearly zero energy and carbon buildings. In this way, a building with nearly zero energy consumption is defined as a building, new or existing, that manages to consume less than 60 kWh/m^2 of total primary energy annually, according to the Spanish Technical Code [15]. Without a doubt, controlling these intrinsic parameters of the building present triple impact benefits. On the one hand, thermal hygrothermal comfort is achieved for users, with almost zero consumption, which results in social, environmental, and economic benefits for the user. And, on the other hand, controlling these parameters allows us to reduce potential environmental impacts on the planet.

A prototype of a single-family public housing unit, with two bedrooms and a floor area of 53 m^2, is taken as a case study, since it represents more than 50% of the homes built in the last 20 years in the province, according to the database of the Provincial Housing and Urban Development Institute [IPVyDU] [16]. In the last two decades in the Metropolitan area of Tucumán, an increase of 11,236 hectares of urban land has been recorded, of which 1300 hectares belong to public works, which represents 11.6% of the urbanized surface [17]. Within that 11.6%, or 26,354, low-density social homes were built between 2003 and 2018 [16]. As stated by Malizia et al. [18], this project marks, to date, the largest public works intervention in low-density housing in the AMET. In this sense, the study of the public sector's actions in the housing field is considered relevant, both due to the volume of construction and because the state is one of the main managers of urban land [19]. The incorporation of sustainable urban policies is the responsibility of governments, and they must generate implementation and monitoring strategies [3]. At the moment, member countries are governed by the Energy Efficiency of Buildings Directive (EPBD) [20].-This aims to reduce GHG emissions and building energy consumption as much as possible. It seeks to rehabilitate less efficient buildings and improve the exchange of information regarding energy performance [21]. In this sense, the European Union (EU) is a reference in terms of sustainability and regulations applied to good construction practices. Likewise, the EU plans to establish a common language in relation to sustainable construction, including the evaluation of the impact of the entire life cycle of a building through a reference framework using basic indicators to evaluate the sustainability of residential buildings and offices under the project called Level(s) [22]. In Latin America, there is a wide variety of instruments such as laws, regulations, plans, and programs regarding sustainability. Table 1 shows some of the regulations of different Latin American countries.

Table 1. Regulations for sustainability in construction in Latin America.

	Regulation	Observation
Chile	Sustainable Buildings Certificate (CES)	Mandatory from 2023 [23]
Brasil	Procel Edifica Seal	Mandatory from 2012 [24]
Perú	Guide for the Sustainable Construction of Buildings in Peru	Not Mandatory [25]
Argentina	Etiquetado Energético en Argentina (PRONEV, 2018)	Not Mandatary [5]

It should be noted that all the regulations mentioned were instituted after the completion of the housing complex represented in the case study, and these regulations do not present rules regarding adaptation and resilience to the existing real estate stock in the face of a climate change scenario.

Regarding the period in which the actions under study occur, it is worth highlighting that they fall within the framework of the "decent habitat" paradigm [26], understood as the importance of guaranteeing environmental, social, and economic quality in regards to social housing, making it an affordable, healthy, and sustainable habitat. This concept encompasses the right to the establishment of a city and an ecologically balanced environment [27]. This concept emerged with the rise of "sustainable development", officially introduced in 1987 in the Brundtland Report by the World Commission on Environment and Development, and accompanied by urban and project criticism [28]. Since then, there has been a solid international consensus regarding the designing of projects that allow for cities' sustainable and affordable development. At the United Nations Conference on Housing and Sustainable Urban Development, Habitat III, held in Quito in 2016, the New Urban Agenda (NUA) was developed, which represents a common ideal to achieve a better and more sustainable future, and proposes the reconsideration of urban systems and the physical form of their spaces as a means to achieve it [29]. Argentina adheres to the principles of the NUA. It aims to move towards increasingly cleaner models of energy production and consumption, with high levels of energy efficiency and low greenhouse gas emissions (GHG). Likewise, it has an unconditional goal of reducing total GHG emissions by 18% to 37% by 2030 [28]. Tucumán is not indifferent to these international and national commitments; therefore, the case under study is immersed in this effort.

In this sense, this research will allow us to recognize whether these commitments are present or not in the guidelines and materialization of this type of housing, impacting the AMET's urban fabric. To answer those questions, an energy simulation using hourly data is performed, and the energy results are analyzed through a life cycle assessment (LCA). The use of energy and environmental impact simulation software and the possibility of evaluating future climate change scenarios makes it possible to determine situations that would be difficult or costly to analyze in other ways for the design or redesign of a building [5,10,30,31]. The originality of the paper lies in the fact that this type of research using future climate scenarios has not yet been investigated for climate and housing in Tucumán.

2. Materials and Methods

The methodology combines methods and tools, including the use of (a) a study case [32], and (b) an energy simulation, according to UNE-EN ISO 52000-1 standard [33], using the LCA methodology, according to the UNE EN ISO 14040 [34] 14044 [35], which is open and allows others to obtain data specific to the case study, thus offering more rigor to the research and reducing the risk of uncertainty. LCA is the most widespread methodology for use in environmental studies. It consists in analyzing every process that takes place in any human activity, accounting for every impact or effect that those processes might have on the environment. Among the LCA stages described in IRAM-ISO 14040, this study focuses on the B6 stage, which encompasses the operational energy use during the service life of the building. In this case, the service life of the building is estimated to be 50 years. For that reason, the most adequate functional unit for the study is the energy consumed in the case study unit over a period of 50 years. The methodological process is generated in three large phases, representing a logical and chronological itinerary that allows for obtaining from each the output for the next phase, as shown in Figure 1.

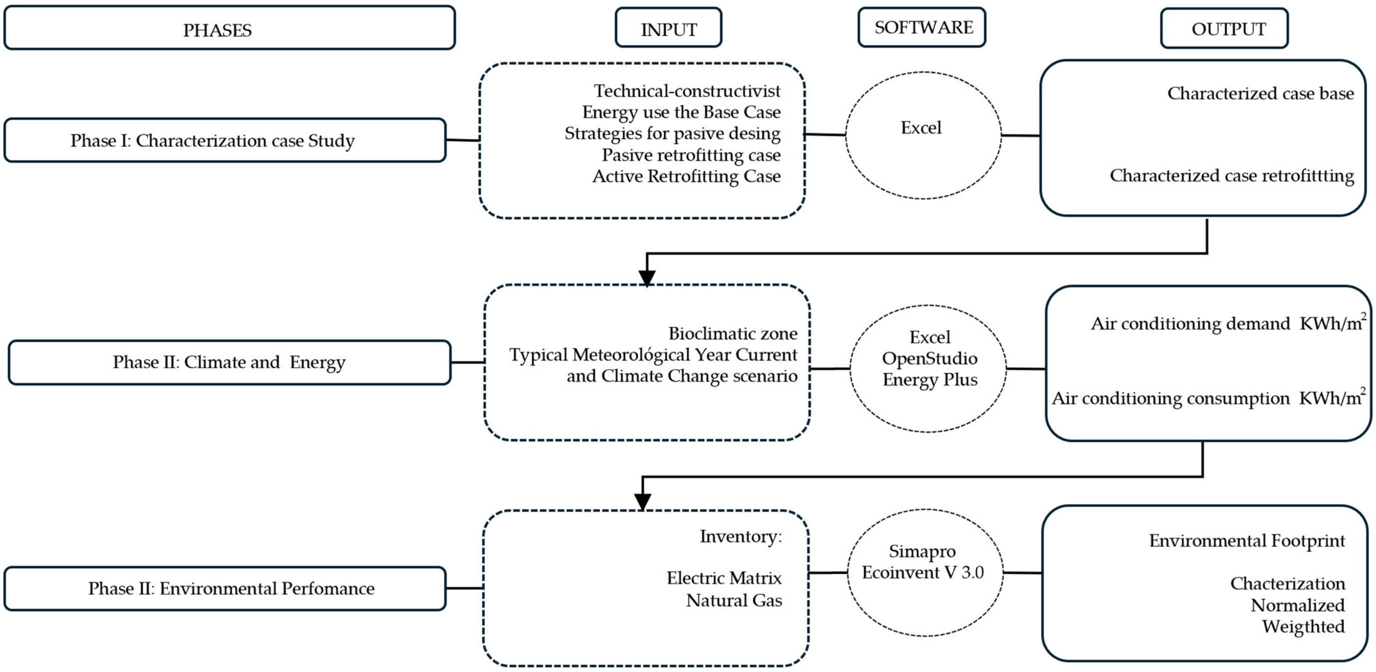


Figure 1. Methodological scheme.

In the first stage, the Characterization Case Study, the technical–constructive definition and the thermal characterization are carried out on the base case, and the equipment and energy sources used for air conditioning are specified. Likewise, the passive architectural design strategy and the active strategy for the modernization of housing are defined. All these data obtained from the different items mentioned serve as input data for the simulation process of the next phase.

In the second stage, Climate and Energy, the bioenvironmental zone where the building under study is located is determined according to the IRAM 11603 standard [36] and the Köppen–Geiger classification [37]. In addition, the current weather file is obtained from the database of the Energy Plus V9.5.0 energy simulation software, which is used in the calculation process [38]. Furthermore, this file serves as a starting point for creating a new weather file that represents the future climate scenario spanning the 10 years from 2040 to 2050, based on the predictions published by the Climate Change Knowledge Portal of the Coupled Model Intercomparison Project (CMIP), supervised by the World Climate Research Program [39]. The CMIP forms the basis of the IPCC reports. The most important climatic variables for simulation purposes are the dry bulb temperature of the outside air (°C); the relative humidity of the outside air (%); direct, diffuse, and global solar radiation (Wh/m^2); and wind speed (m/s), considering a typical meteorological year for the site. This is a statistically assembled year comprising a period of 15 to 30 years of data, where for each month, data from any year within the period is taken [40]. Then, we proceed to calculate the energy simulation for both the current case and the improved case. One of the most used software tools worldwide, EnergyPlus V9.5.0, is employed through the SketchUp Pro 2021 and OpenStudio 1.2.0 graphical interface. This software enables energy analysis through the simulation of the thermal loads of a building, taking into account its construction, associated systems, etc.

The third stage, Environmental Performance, begins by carrying out the inventory analysis of the processes involved in the life cycle stage to be evaluated. The life cycle inventory (LCI) is modeled using Simapro v9 software and the Ecoivent Database v3.8. In this case, where the operational energy of the building is analyzed, it is important to prepare the general process of the electrical matrix of Tucumán Argentina. For this purpose, Simapro software, along with the Ecoinvent V3.0 database, is used. The Argentine electrical matrix, prepared by Ref. [41] for Ecoinvents V3.0, is taken as a starting point. Additionally, the data obtained regarding the operating energy for air conditioning is uploaded to the life cycle analysis software. From there, the environmental impacts of the energy consumption of the case study are obtained through a life cycle assessment (LCA). The LCA calculation was carried out using the Environmental Footprint methodology, v3. This methodology was developed by the Joint Research Center of the European Commission, more specifically by the European Platform of Life Cycle Assessment. Documentation of this methodology, as well as its normalization and weighting process, was developed by Zampori and Pant [42]. Based on the choice of the evaluation method, the software proceeds to classify the output data obtained from the inventory and sorts them according to the impact category they affect. Furthermore, these classified values are simplified by characterization factors, resulting in what are called characterized results, according to each potential environmental impact category. Likewise, it should be noted that the evaluation method also presents the results through normalization and weighting. The values obtained for each impact category are multiplied by normalization factors to calculate and compare the magnitude of their contributions to the impact categories of the Environmental Footprint assessment method in relation to a reference unit. As a result, normalized and dimensionless values are obtained, which reflect the loads attributable to a product in relation to the reference unit. Within the method used, the normalization factors are expressed per capita based on a global value [43]. Weighting supports the interpretation and communication of analysis results. In this step, the normalized results are multiplied by a set of weighting factors (in %) that reflect the perceived relative importance of the life cycle impact categories considered [42]. It should be noted that the configuration of the software is performed to obtain the results for both the base case and the improved case under the current climate conditions, as well as under the previously mentioned future scenario.

2.1. Phase I: Case Study Characterization

This phase consists of characterizing the case study for subsequent analysis. In this sense, it merges the two main methodologies—case study and complete energy simulation of the building—since this phase prepares all the inputs for the calculation of the simulation. The data obtained are detailed below.

2.1.1. Technical–Construction Characteristics

The case study represents one of the most common housing types constructed by the Provincial Institute of Housing and Urban Development (IPVyDU) over the last 20 years. As shown in Figure 2, it is a single-family house with three free facades, covering 53 m^2 on a single floor, with two bedrooms and a bathroom on a 300 m^2 plot.

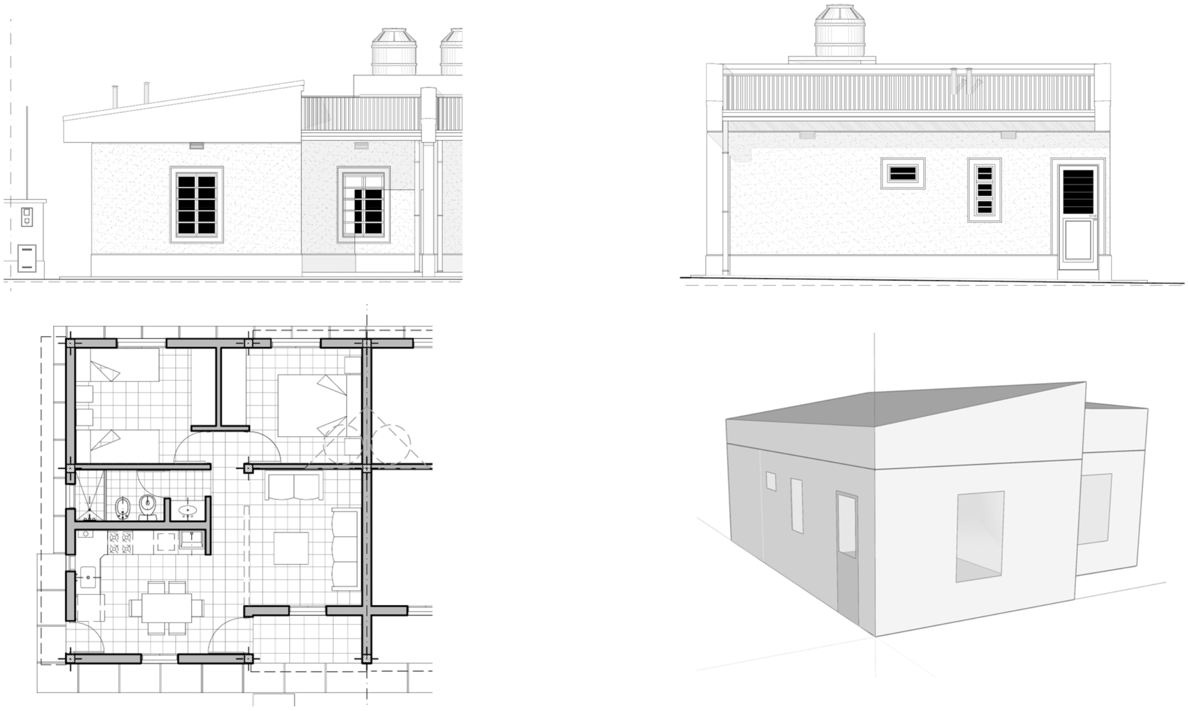
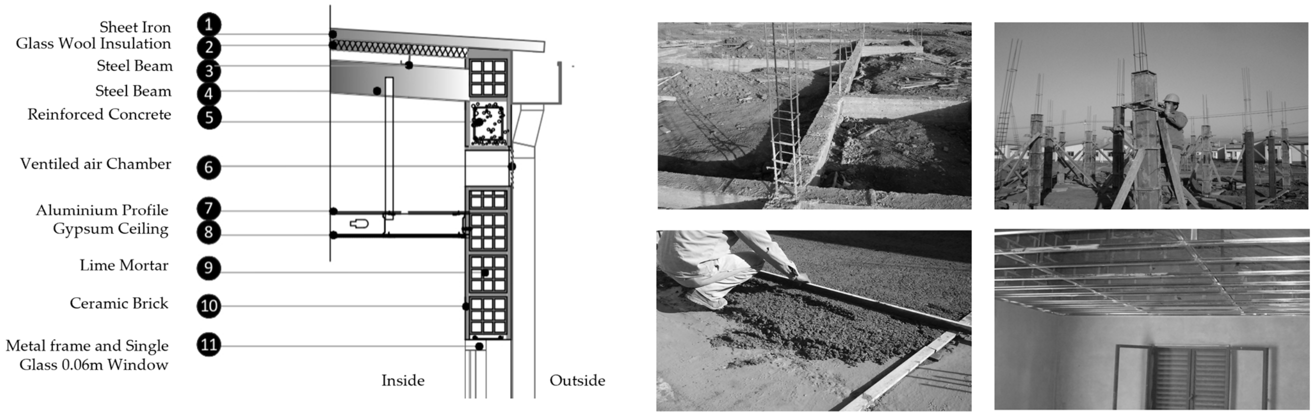


Figure 2. Overview of the house plans.

The construction type is referred to as traditional in this region of the country, constructed using a wet construction system, except for the roof, which is made of metal beams and plates [44]. Its structure consists of reinforced concrete columns, while the vertical closures are made of hollow ceramic bricks. The windows are made of single-pane glass, without a thermal break, and the doors are made of metal; see Figure 3.



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

Figure 3. Construction type: (**a**) constructive detail and (**b**) construction technology.

2.1.2. Thermal Characteristics

Regarding the main characteristics that allow for determining the thermo-energy behavior of the unit, the case under study presents a relationship between the volume and surface area of 0.77, and its percentage of openings is 16.8%. As shown in Table 2, the base case presents high U-values (W/m^2 K) within its envelope. Its exterior wall has no thermal insulation, the windows are made of single glass, and the frame does not have a thermal break. The metal doors do not have thermal insulation. The roof has thermal insulation, which is standard glass wool, with a thickness of 0.05 m. To obtain these U-values (W/m^2 °K), each layer and the material that make up the analyzed constructive elements are specified in the Energy Plus energy simulation software, along with the detailed values of thermal conductivity, specific weight, and thermal capacity that correspond to the IRAM 11601 standard [45]. For this type of envelope characteristic, a low level of tightness is considered, and therefore, an infiltration of two air changes per hour (ACH) is assumed [46,47]. Two thermal zones are considered—the daily sector corresponding to the kitchen-dining and living area and the nocturnal sector corresponding to the bedrooms. Likewise, four people are taken as the number of occupants, with an activity level of 108 W/person of metabolism [46]. The energy consumption for air conditioning is determined according to the Olgyay bioclimatic chart [12] defined for the sector, which is expressed with a temperature of 26 °C in summer, with acceptable relative humidity values between 20 and 52%, and a temperature of 20 °C in winter, with acceptable relative humidity values between 20 and 80%, reaching fair average values of 23 °C for the whole year [48]. In addition, heating and cooling schedules are configured for both thermal zones. Temperature control is programmed from 8:00 a.m to 10:00 p.m every day for the daily zone, both in winter and summer. The temperature control is determined from 10:00 pm to 8:00 am for the nocturnal thermal zone.

Table 2. Building envelope base case.

Area	U-Value (W/m^2 K)	Surface Area (m^2)
W1—Exterior wall	1.43	44.65
R1—Roof	0.63	48.14
F1—Ground Floor—Ceramic	2.29	48.14
S1—Window	5.2	5.09
D1—Door	5.88	3.11

2.1.3. Energy Uses for the Base Case

The house is assumed to use electric energy for cooling, and a split-type air conditioner with a COP of 2.4 is considered. In this type of housing, it is very common for heating to be generated through a natural gas appliance. Therefore, an additional amount of net energy is consumed for heating. This is because the heating device—a balanced draft heater—consumes 65% more energy compared to that demanded by the building to achieve adequate temperatures in winter [5]. In addition, there is 25% more energy loss in the transmission of energy through the distribution network. The house does not possess renewable energy sources [49].

2.1.4. Architectural Strategies for Passive Design

Based on the above, and according to IRAM 11603, the sector under study is defined as bioclimatic zone IIb and thus, the general recommendations of this standard for the design of the building in this zone are expressed below. The following are the general recommendations of this standard for building design in this zone: (a) light colors on exterior walls and ceilings; (b) high thermal insulation on ceilings and walls facing east and west; (c) surfaces protected from solar radiation; (d) allowance for cross ventilation of the house, although, in this zone, winter is of limited importance.

2.1.5. Passive Retrofitting Case

Based on the characteristics of the building in the case study, it is proposed to evaluate an improvement of the envelope to achieve thermal and hygrometric comfort in its interior space. To this end, it is proposed to incorporate External Thermal Insulation Systems (ETIS) in the vertical enclosures, incorporating 0.10 m thick glass wool with a density of 30 kg/m^3. In the roof, it is also proposed to increase the thermal insulation using glass wool with a thickness of 0.10 m. In addition, the windows will be replaced with double hermetic glass, PVC frames with a thermal bridge break, and metal frame doors with a solid wood layer with a thickness of 0.04 m. As for the total envelope, the flooring element is exempt from changes because, being in constant use, it is difficult to carry out interventions. Table 3 shows the new U-values (W/m^2 K) obtained through the proposal of passive retrofitting.

Table 3. Building envelope retrofitting case.

Area	U-Value (W/m^2 K)	Surface Area (m^2)
W2—Exterior wall	0.46	44.65
R2—Roof	0.32	48.14
F2—Ground Floor—Ceramic	2.29	48.14
S2—Window	2.8	5.09
D2—Door	1.5	3.11

2.1.6. Active Retrofitting Case

For the case rehabilitated through active strategies, first, it is proposed to supply all energy demands through electricity. In this sense, for the cooling/heating and the domestic hot water system, the aim is to achieve the energy efficiency of appliances using an integrated system with an ideal average performance score of 4, according to supplier reference values [50,51].

2.2. Phase II: Energy and Climate

In this phase, the climate of the location is analyzed, using both the current typical meteorological year, along with a future climate change scenario and the adaptation to this situation by obtaining the operational energy consumption of air conditioning in kWh/m^2.year. This is achieved through the complete energy simulation of the base case building and its improvement alternative.

2.2.1. Bioclimatic Zone of the Sector under Study

The bioclimatic zone in which this type of social housing is located is defined as bioclimatic zone IIb, according to the IRAM 11603 standard [52,53]. This zone is characterized by a warm-temperate climate, with thermal amplitudes greater than 14 °C. The summer season has average temperatures between 20 °C and 26 °C, with mean maximum temperatures greater than 30 °C [54]. The winter is not very cold and presents mean temperature values between 8 °C and 12 °C, and minimum values rarely fall below 0 °C. Generally, winters in this zone are relatively mild [55]. According to the Köppen–Geiger classification, is defined as humid subtropical Cwa, with dry winters and warm summers [56–58].

2.2.2. Typical Meteorological Year

A climate file compatible with the Energy Plus software is used for the simulation. The file contains the values of the climatic variables characterizing the typical meteorological year for San Miguel de Tucumán. This type of file is acquired from the repository of free climatic data for simulating the thermal performance of buildings [59]. For the case of Tucumán, the values of some of the climatic variables were recorded by the weather service of the Benjamín Matienzo airport for the period between 2014 to 2018, while others, such as solar radiation, were collected through satellite data [2]. In the case of the current climate, it is essential to highlight that, for typical summer days, maximum temperature values are observed with peaks between 35 to 41 °C, which, on average, is close to the design temperature of 38.8 °C proposed by the standard. However, at 30 °C, the data from this study differ from what the standard determines as the average maximum temperature, set at 29.3 °C for summer. In the case of winter, similarities with the standard values are observed, both in the data obtained for winter and the thermal amplitude between day and night; see Figure 4.

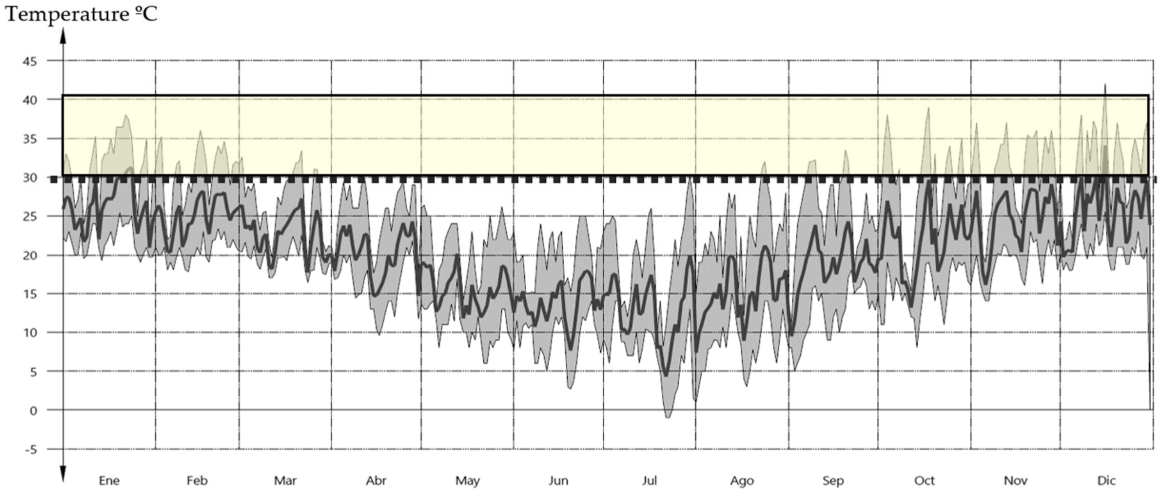


Figure 4. Average annual temperatures of the current typical meteorological year.

2.2.3. Typical Meteorological Year with Climate Change Scenario

To develop a future climate scenario, a new typical meteorological year is prepared to coincide with the estimated temperature increase, according to predictions published for Tucumán, Argentina, on the Climate Change Knowledge Portal of the Coupled Model Intercomparison Project (CMIP), supervised by the World Climate Research Program. The CMIP forms the basis of the IPCC reports. In this regard, within the Shared Socioeconomic Pathways (SSPs), the so-called SSP2-4.5—Middle of the Road—is taken, which considers that challenges persist in reducing vulnerability to social and environmental changes and encompasses the Representative Concentration Pathway (RCP) RCP 4.5, which limits the temperature increase to 2 degrees [60,61]; see Figure 5.

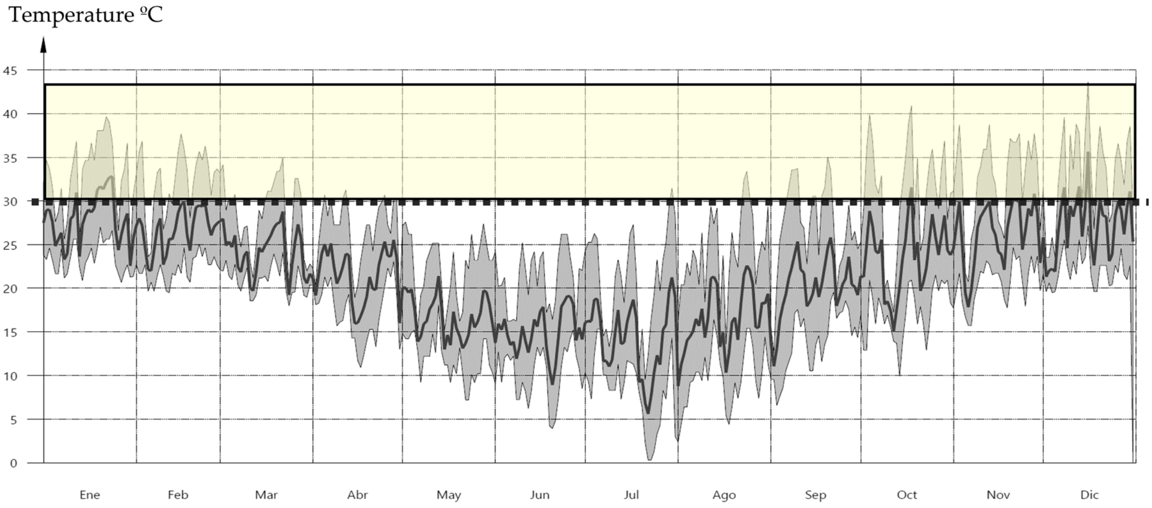


Figure 5. Average annual temperatures of the future typical meteorological year.

In the climate with a future scenario, it is observed that the condition in summer worsens, in which there will be peaks of temperatures between 40 °C to 45 °C, and in winter, it will not reach temperatures below 0 °C. Furthermore, it is evident that the thermal amplitude between daytime and nighttime hours increases slightly in the summer and winter seasons. To this end, it is apparent that in both situations, the months with temperatures above 30 °C occur from September to March. As for the months with temperatures below 10 °C, May, June, July, August, and part of September are observed in both climates. It is essential to highlight that this route entails risks and consequences of climate change at an intermediate level, beyond what some experts project temperatures to be towards the end of the century throughout the national territory, highlighting the case of northwest Argentina, with an increase of more than 3 °C for a high concentration scenario (RCP8.5) [52].

2.3. Phase III: Environmental Performance

Through this process, it is possible to evaluate the relevance of potential environmental impacts. In the first instance, the type of electrical matrix in Tucumán is identified and quantified with the use of the results obtained in the LCI. Subsequently, an analysis of the impacts is carried out through the characterization, normalization, and weighting of the results.

Inventory

Electrical generation in Tucumán can be classified according to its primary purpose: (1) generation associated with transmission and distribution networks and (2) self-producers of electrical energy, as set out in Table 4. It should be noted that due to the uncertainty regarding the change in the energy matrix in Argentina, making temporary extrapolations regarding the incorporation of renewable energies in the matrix is not considered [62]. Therefore, for the environmental impacts calculated in this work, only the most unfavorable case, the present one, is used.

Table 4. Tucumán electrical matrix.

Central	Generation Type	Number of Machines	Nominal Power (MW)	High Voltage (MWh)	%
El Cadillal	Hydro	2	14	21,704	0.36
Escaba	Hydro	3	24	84,889	1.41
Pueblo Viejo	Hydro	2	19	54,339	0.90
CT Tucumán	Natural Gas, combined cycle	2	288	1,885,711	31.22
CTSM de Tucumán	Natural Gas, combined cycle	4	547	3,403,087	56.35
CT Pluspetrol Norte	Natural Gas, conventional cycle	2	246	263,278	4.36
Independencia	Natural Gas, conventional cycle	3	110	313,505	5.19
Sarmiento	Natural Gas, conventional cycle	1	10	-	-
Amaicha	Oil	4	2	4371	0.07
Tafí del Valle	Oil	10	5	8766	0.15
		Total	1265	6,039,650	100
Transformation and Distribution			Percentual losses		References
Distribution of low voltage electricity			6.6%		[20,54]
Transformation from medium to low			6.2%		[55]
Distribution of medium voltage electricity			0.84%		[56]
Transformation from high to medium			1.34%		[57]
Distribution of high voltage			6.2%		[58]

Compared to the data presented, ten power plants associated with the transmission and distribution networks are shown, of which there are ten plants. Among these, three of these, which are small hydroelectric plants, produce energy of renewable origin, including Cadillal, with an installed capacity of 12.6 MW, Escaba, with a capacity of 24 MW, and Pueblo Viejo, with a capacity of 15 MW, with a gross generation of 160,932 MWh of electricity [59]. These are also included in the 6.9% of renewable energy in the country before the start of the RenovAr projects [48]. The remaining seven plants are thermal, located in El Bracho, SM de Tucumán, Tafí del Valle, and Amaicha del Valle, with a value of 6,026,513 MWh of gross electricity generation. These constitute 4.9% of the percentage share in the country's gross electricity generation. The self-producers of electricity are mainly turbo steam thermal plants that use bagasse and natural gas as fuel and are typical of the agricultural sugar industry. To this end, the impact of electricity generation using natural gas is evident, equaling 87.55% of the combined cycle and 9.55% of the conventional cycle, which adds up to 97.1% of the total, revealing the dependence that this type of energy presents when compared to that of non-renewable sources. Hydroelectric plants of renewable origin represent 2.6% of the total generated, and finally, self-producers currently represent 0.156% of the province's total electrical production. Furthermore, according to the official sources [54,56–58], the percentages of energy loss considered due to the transformation and distribution of electrical energy amount to a total of 21%.

3. Results

This section presents the results of the thermal simulation of the base case and the improved case and expresses the values of energy demand and consumption for air conditioning in the current and future climate. It also shows the results of the life cycle assessment and the environmental impact associated with the energy consumption for both cases. The lifespan of the building under analysis is assumed to be 50 years.

3.1. Thermal Simulation

The energy demand results required to achieve the indicated hygrothermal comfort level in the simulation show that the base case requires 15 kWh/m^2.year for cooling in the current climate and 26.06 kWh/m^2.year for the future climate. For heating, 17.24 kWh/m^2.year and 13.08 kWh/m^2.year are obtained, respectively. In the case of retrofitting, envelope improvement allows for obtaining 5.53 kWh/m^2.year in the current climate and 11 kWh/m^2.year in the future climate. As for the energy demand for heating, the rehabilitated house requires 12.02 kWh/m^2.year in the current climate and 8.77 kWh/m^2.year in the future climate. A summary of the results obtained is shown in Table 5.

Table 5. Energy demand.

		Current Climate 2020–2040		Future Climate 2040–2070	
Case	**Unit**	**Cooling**	**Heating**	**Cooling**	**Heating**
Base	KWh/m^2.year	15.00	17.24	26.06	13.08
Retrofitting	KWh/m^2.year	5.53	12.02	11	8.77

Based on the above, the summary of the values obtained in the simulation with the introduction of thermomechanical appliances is presented in Table 6. In the base case, electricity is considered for cooling and natural gas for heating. In contrast, in the case of passive and active retrofitting, electric energy is proposed for air conditioning. For the base case, a value of 6.23 kWh/m^2.year is obtained for cooling in the current climate and 10.86 kWh/m^2.year in the future climate. In the heating situation, 28.44 kWh/m^2.year is required in the current situation and 21.58 kWh/m^2.year in the future. In the case of retrofitting, a value of 1.38 kWh/m^2.year is achieved for cooling in the current situation and 2.03 kWh/m^2.year in the future situation, and for heating, 3.01 kWh/m^2.year is obtained in the current situation and 2.19 kWh/m^2.year in the future situation. It should be noted that these values are necessary for loading into the Simapro software. The most relevant result is the decrease in net energy required for heating between the base case and the case with passive and active retrofitting.

Table 6. Energy consumption.

		Current Climate 2020–2040		Future Climate 2040–2070	
Case	**Unit**	**Cooling**	**Heating**	**Cooling**	**Heating**
Base	KWh/m^2.year	6.23	28.44	10.86	21.58
Retrofitting	KWh/m^2.year	1.38	3.01	2.03	2.19

Using these results for net energy consumed for cooling and heating in the current and future climate, the value of annual primary energy associated with air conditioning can be considered. The results are compared with the reference values proposed by the Spanish Technical Code [15], which sets the primary energy limit for housing at a value of 60 kwh/m^2. The values achieved for the case study are shown below in Table 7. It should be noted that the energy vectors used are obtained from the database of the Ministry of Energy of Argentina [63]. The electric energy vector is 3.6, and the natural gas vector is 1.25.

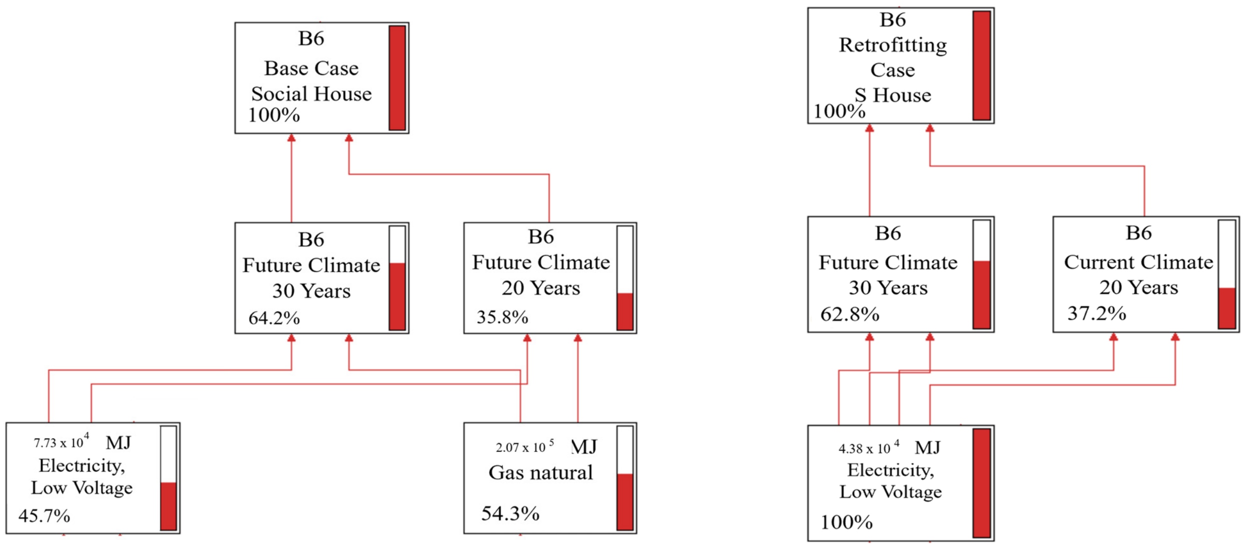
Table 7. Primary energy.

		Current Climate 2020–2040		Future Climate 2040–2070	
Case	**Unit**	**Cooling**	**Heating**	**Cooling**	**Heating**
Base	KWh/m^2.year	22.43	35.55	39.09	27.00
Retrofitting	KWh/m^2.year	5.00	10.86	7.30	7.88

In the base case in the current climate, the primary energy values for air conditioning are 57.98 KWh/m^2.year and in the future climate, they are 66.09 KWh/m^2.year. These values show that the case study in its current situation does not comply with what is recommended by the standards for nearly zero energy buildings, since it is only within the proposed limits when considering air conditioning alone. In the case of rehabilitation, the primary energy values reach 15.86 KWh/m^2.year under the current climate and 15.18 KWh/m^2.year under the future climate. These values are acceptable since, it they imply that the air conditioning would present only 25% of the value established as a limit, considering that the other services of the home must be included.

3.2. Life Cycle Assessment

In the base case scenario, which utilizes electricity and natural gas, higher energy consumption is observed for the years of service life considered for the future climate scenario, representing a consumption of 62.3% compared to 35.8% for the current climate. Additionally, the total natural gas consumption for the building's entire service life is 2.07 × 10^5 MJ, representing 54.3% of the total environmental impact of building conditioning. In contrast, electricity consumption is 7.73 × 10^4 MJ, representing 45.7% of the total environmental impact. In the case of passive and active retrofitting, higher consumption is also evident in the future climate scenario. Still, only electric energy is used, with a total consumption value of 4.38 × 10^4 MJ. Figure 6 shows the percentage distribution of environmental impacts in each stage. The environmental impacts were evaluated using the Environmental Footprint method. The results of the characterization are divided into 18 different impact categories; see Table 8.



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

Figure 6. Contribution of each module to the total environmental impact Stage B6. (**a**) Base case; (**b**) retrofitting.

Table 8. Environmental Footprint characterization comparison.

Impacts Category	Unit	Base	Retrofitting
Climate change	kg CO_2 eq	2.67×10^{4}	6.62×10^{3}
Climate change—Fossil	kg CO_2 eq	2.64×10^{-3}	5.91×10^{-4}
Climate change—Biogenic	kg CO_2 eq	1.30×10^{2}	4.40×10^{1}
Climate change—Land use and LU change	kg CO_2 eq	2.64×10^{1}	7.70×10^{0}
Ozone depletion	kg CFC11 eq	8.07×10^{-5}	1.84×10^{-5}
Ionizing radiation	kBq U-235 eq	4.94×10^{-5}	1.62×10^{-5}

Photochemical ozone formation	kg NMVOC eq	1.46×10^{-6}	1.82×10^{-7}
Particulate matter	disease inc.	2.94×10^{-1}	8.80
Human toxicity, non-cancer	CTUh	3.08×10^{-2}	1.35×10^{-2}
Human toxicity, non-cancer—organics	CTUh	5.48	1.83 E+00
Human toxicity, non-cancer—inorganics	CTUh	5.91×10^{1}	1.99×10^{1}
Human toxicity, non-cancer—metals	CTUh	1.27×10^{5}	3.63×10^{4}
Human toxicity, cancer	CTUh	-6.06×10^{2}	-2.53×10^{2}
Human toxicity, cancer—organics	CTUh	1.55×10^{3}	6.69×10^{2}
Human toxicity, cancer—inorganics	CTUh	4.16×10^{5}	1.08×10^{5}
Human toxicity, cancer—metals	CTUh	5.30×10^{-5}	1.68×10^{-5}
Acidification	mol H+ eq	2.67×10^{4}	6.60×10^{3}
Eutrophication, freshwater	kg P eq	1.69×10^{1}	6.20
Eutrophication, marine	kg N eq	1.96×10^{1}	7.62
Eutrophication, terrestrial	mol N eq	4.79×10^{-6}	7.61×10^{-7}
Ecotoxicity, freshwater	CTUe	1.47×10^{-5}	3.94×10^{-6}
Ecotoxicity, freshwater—organics	CTUe	3.42×10^{-5}	1.22×10^{-5}
Ecotoxicity, freshwater—inorganics	CTUe	9.71×10^{-7}	2.69×10^{-8}
Ecotoxicity, freshwater—metals	CTUe	2.40×10^{-15}	4.45×10^{-16}
Land use	Pt	4.93×10^{-7}	1.55×10^{-7}
Water use	m^3 deprive.	6.56×10^{2}	2.10×10^{2}
Resource use, fossils	MJ	6.33×10^{4}	1.70×10^{4}
Resource use, minerals and metals	kg Sb eq	6.27×10^{4}	1.91×10^{4}

Since the characterization results are given in different units, the impact categories are not directly comparable. Therefore, the normalization process is essential for providing a comparative baseline among the various environmental impacts. In the case of the weighting process, it can be a helpful tool to give more emphasis to the impact categories that require special attention at the current moment. This is the case for climate change potential, which, given the current global climate crisis, should be regarded with special attention. The normalized results show high impacts related to the "Resource use, fossils" category related to energy generation, climate change, and ecotoxicity in both scenarios. However, the retrofitted case presents a significant decrease in the three categories mentioned above. The use of fossil resources shows a decrease in the order of 74%, the climate change category shows a decrease of 75.7%, and ecotoxicity shows a decrease around 71%; see Figure 7.

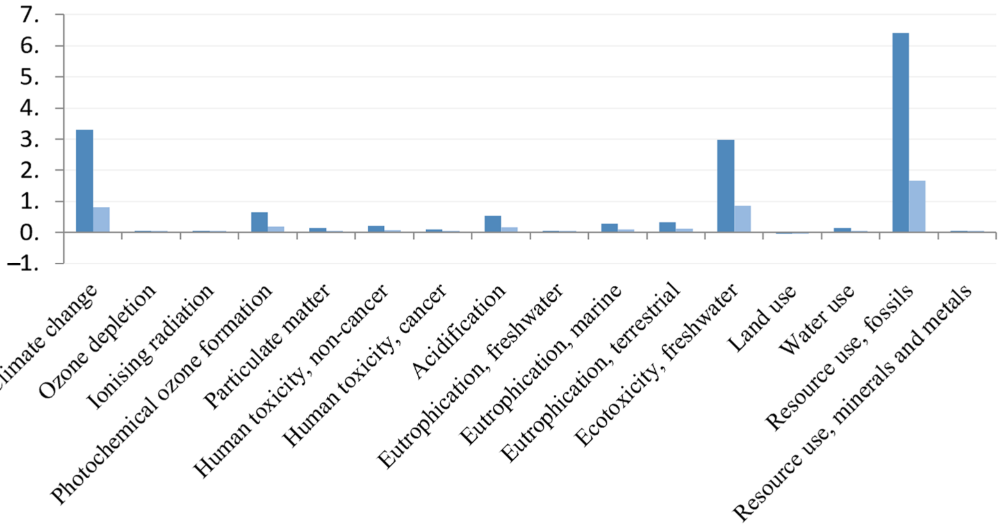


Figure 7. Normalized EF comparative results.

After weighting the normalized results, it became apparent that the climate change potential and the category "Resource use, fossils" became more significant. Moreover, similar to the normalization results, significant differences were observed between the impact associated with energy consumption for air conditioning in the base case compared to the retrofitted case; see Figure 8.

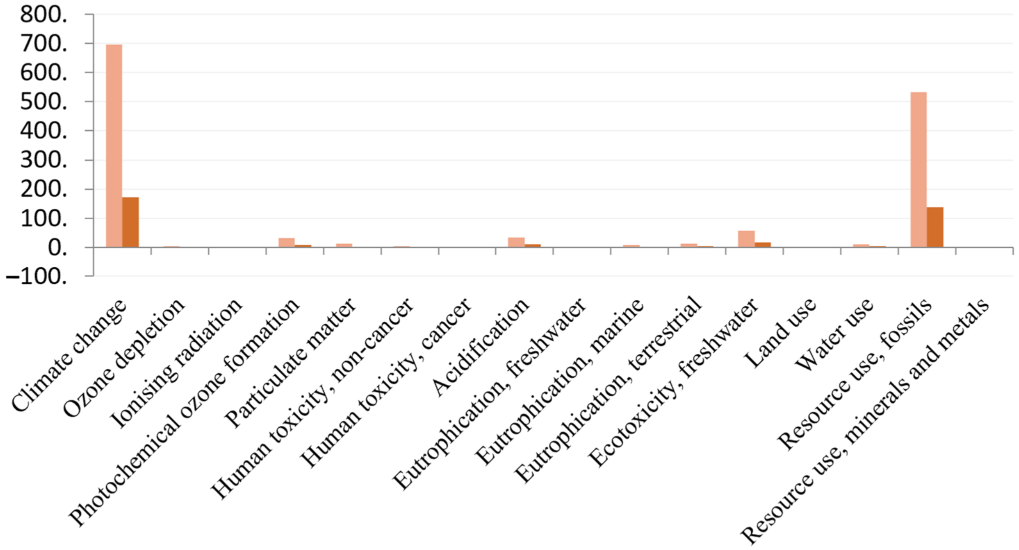


Figure 8. Weighted EF comparative results.

The change of energy source—from natural gas to electricity—produces positive results, despite the need to improve the existing electrical grid in the province. This change in energy source reduces the energy consumption for heating by nine times. Furthermore, to effectively achieve decarbonization of the energy consumption of these homes, it is recommended to include the self-generation of energy through photovoltaic panels located on the roof. In this sense, if five panels of 2 m^2 each are applied, with north orientation and an inclination of 30°, it is possible to obtain an average value of 2.4 kWp, generating 3657.2 kWh annually [63]. These values indicate that the generation of renewable energy exceeds the energy needed for climate control, making it possible to meet other consumption needs—such as lighting and hot water—and even feed power back to the grid.

4. Discussion

The results obtained regarding the required energy demand show that the original home presents a low adaptation to the current climate. The situation is even more alarming with the climate change scenario from 2040, where there is a 73% increase in energy demand to supply summer needs, with a value of 26.06 kWh/m^2 per year. Although demand decreases by 23.6% in winter, both results highlight the impact of the future climate scenario for the bioclimate of the region, with longer and more rainy summers and shorter and drier winter periods [60]. These results demonstrate the urgent need to initiate actions that reverse the current scenario and, even more urgently, the future scenario.

In the case of the proposed retrofitting for the dwelling, a demand of 5.53 kWh/m^2 per year is obtained for air conditioning, representing a 63.15% reduction in energy demand compared to the base case in the current climate. Also, there is a 30% reduction in the demand for heating in the current climate. In the future climate scenario, the values of KWh/m^2 per year for air conditioning increase compared to those of the current climate, with a demand of 11 kWh/m^2 per year, which represents a 50% increase, but there is a 57.7% reduction compared to the base case in the future climate. In the case of heating, the demand is 8.77 KWh/m^2 per year for the future climate scenario, representing a 27%

reduction compared to the existing demand in the current climate. Therefore, if we compare the demand for heating between the base and rehabilitated case in the future climate, it is reduced by 33%. While these results are encouraging, allowing for improved hygrothermal comfort for the user and reduced energy demand, active dwelling retrofitting is necessary, since the dwellings currently uses inefficient thermo-mechanical devices and non-renewable energies.

Based on the results concerning the energy consumption of the current housing, both in the present and future climate, the most significant consumption is for heating, which requires 65% more energy than cooling to achieve the desired temperature in the environment, plus an additional 25% for losses in energy distribution and transportation. Therefore, the proposed retrofitting includes replacing the current devices with more efficient and electric models.

Decarbonizing the existing real estate in the metropolitan area of Tucumán is necessary. It must include improvements to each home and a comprehensive strategy that improves the energy matrix by increasing the use of renewable energy sources, promoting self-generation of energy, improving the efficiency of electromechanical devices, and reducing subsidies to energy sources such as natural gas. This means resolving the problem of ensuring long-term sufficiency and efficiency. As expressed in the 6th IPCC report [3], the decarbonization of buildings is constrained by multiple barriers and obstacles, as well as a limited flow of finance (robust evidence, high agreement). The lack of institutional capacity, especially in developing countries, as well as appropriate governance structures, slows down the decarbonization of the global building stock.

In addition to the environmental impacts, it is crucial to consider the other two pillars of sustainability. The built environment, especially housing, has ramifications for society and the economy. Regarding society, energy performance influences how well people live inside the building, as it will impact their thermal comfort and their overall quality of life. In the case of economic sustainability, choosing materials and constructions for a building affects maintenance costs. It can even influence the local or regional economy, depending on the size of the project [64]. The social impacts are typically studied through a Social Life Cycle Assessment (S-LCA). This methodology has grown over the last decade [65]. In the case of the economy, these typesof studies are conducted using the Life Cycle Cost methodology.

Life Cycle Sustainability Assessment (LCSA) is a methodology that encompasses these three aspects of sustainability by combining LCA, S-LCA, and LCC [66]. In future studies, these housing developments in Tucuman will be studied holistically in terms of their sustainable performance.

5. Conclusions

Several conclusions can be drawn from this work.

First, the results show a high cooling demand, which is evidence of the low hygrothermal performance of the base case envelope, since a demand of more than 11 kWh/m^2.year is expected for cooling and a decrease of about 4 kWh/m^2.year is predicted for heating. In other words, an energy demand for cooling increases considerably in the future climate scenario, by about 73% compared to that for today's climate.

Secondly, the inefficiency of the air conditioning systems installed in these dwellings and the use of natural gas for heating further increases energy consumption and accordingly, the environmental impacts, with values in the most relevant categories according to the normalization of the results of 2.67×10^4 kg CO_2 eq associated with climate change, 6.33×10^4 MJ with the use of fossil resources, and 1.47×10^{-5} CTUe regarding the ecotoxicity of fresh water.

Third, the proposed passive and active retrofitting are very encouraging. A 57% reduction in cooling demand and a 32.5% reduction in heating demand is possible for the future climate. The improvements coming from the thermal conditioning of the envelope and the proposed changes in the electrical consumption equipment allow for the achievement of a rational use of energy. To this effect, a significant reduction in the most relevant categories of environmental impacts is shown, since the climate change values are 6.62×10^3 kg CO_2 eq, 1.70×10^4 MJ for fossil resource use, and 3.94×10^{-6} CTUe for the ecotoxicity of fresh water.

Fourth, the method used is feasible for use in evaluating other prototypes in this province, as well as elsewhere. The combination of the energy simulation software with future climate scenarios and the associated environmental impacts achieves a holistic outcome of the problem. This approach allows the pre-visualization of the optimal building improvement proposal, without incurring high economic or environmental costs.

Among the main contributions of this work, we can highlight the originality shown in the object of study itself. To date, social housing in the metropolitan area of Tucumán has not been studied in terms of its environmental impacts. The need to alleviate housing emergencies must be combined with responding to the climate emergency itself. Therefore, carrying out this type of study manages to contribute in two different and related aspects. On the one hand, it shows precise environmental impact data adapted to the Argentine context that can be useful for professionals in the public and housing sectors in the national context. On the other hand, it highlights the need to study and combine the aforementioned aspects of social and environmental sustainability in this type of housing project. In the Latin American context, projects are often carried out without adequate reflection on their life cycle. Through this study we seek to change that dynamic.

And finally, it is relevant to study the actions of the public sector in the housing arena, the rehabilitation public housing construction would be one of the fundamental strategies to be implemented within a master plan that includes other important changes. Among them, the restriction of the use of gas appliances and the decarbonization of the electrical matrix are crucial to reduce the carbon footprint resulting from this type of housing. The incorporation of sustainable urban policies is the responsibility of governments, which must develop implementation and monitoring strategies. This is essential to promote a healthy, balanced environment, conducive to human development, in which productive activities meet present needs without compromising future generations, as established in the 1994 Reform of the Argentine National Constitution. As explained in the Discussion section, all of these aspects could be studied by conducting an LCSA, which allows for integrating the social, the economic, and the environmental impacts in a single methodology.

As future lines of research, it is proposed to advance the evaluation of the construction typologies of the remaining of the homes built over the last 20 years. In this way, data that facilitates decision making by leaders is provided to reduce the impact of a large portion of the existing real estate stock.

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