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Energy use, health, and sleeping conditions in a bioclimatic university residence: lessons learned from 20 years of use

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Abstract

While recent studies have extensively explored energy consumption and conservation in students' residences, research into thermal comfort, health conditions, and sleeping comfort in these settings remains limited, especially over extended durations. In this study, we present and discuss insights gleaned over 20 years (2001–2021) on the thermal and energy behavior of Universidad Nacional de La Pampa's bioclimatic student residences in Argentina. The building, drawing on 20 years of measured and simulated data, reveals promising heating energy savings while maintaining indoor ambient comfort. Across the 2001–2021 period, heating consumption averaged 109 kWh/m^2/year, representing a 33% saving compared to conventional apartment block buildings in the same region. Our findings underscore the challenges of passive design during extreme heat, with summer temperatures exceeding comfort thresholds in buildings lacking air conditioning. A deeper analysis reveals discomfort percentages of approximately 15% (night) and 32% (nap) during sleeping periods, escalating up to 80% during heat waves. These findings echo concerns about overheated spaces in bioclimatic buildings across central Argentina, highlighting the imperative for effective summer cooling strategies. Through measurement data and simulations, this study illuminates the complex interplay between building design, environmental conditions, and occupant comfort, offering valuable insights for sustainable design and management practices.

Keywords: *long-term monitoring, students' residence, energy consumption, summer thermal comfort, sleeping comfort*

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1. Introduction

More than half of the world's population lives in cities, and that is set to increase dramatically in the coming decades [105]. Cities are the most important centers for the consumption of energy and the production of polluting greenhouse gas emissions [47], and they are also the places where solutions to climate change are devised and acted out [112]. It is well known that the operation of buildings accounts for 30% of global final energy consumption and 26% of global energy-related emissions1 (8% being direct emissions used in buildings and 18% indirect emissions from the production of electricity and heat used in buildings) [60, 87]. Total energy consumption in the building sector increased, on average, by 1% per year over the last decade and reached 133 EJ in 2022. Natural gas demand declined in 2022 following Russia's invasion of Ukraine and a mild winter, with the decline mostly noted in Europe; however, natural gas still met 23% of the energy demand in buildings worldwide [59]. Electricity now accounts for over one-third of the energy demand in the building sector: its share has steadily increased with expanding ownership of appliances and air conditioners, as well as with the electrification of heating and cooking. Global buildings energy demand will increase to almost 140 EJ in 2030 and 160 EJ in 2050, primarily because the number of households will increase from around 2.2 billion today to 3 billion by 2050, with the largest increases in Africa and the Asian Pacific. The global floor area of residential buildings will expand from around 200 billion square meters today to 310 billion in 2050 [62]. In Latin America and the Caribbean, households currently account for three-quarters of energy consumption in the building sector. Space heating and cooling account for 6–7% each, although there is significant variation among countries. In Argentina and Chile, countries with among the highest per capita heating demand in the region, space heating accounts for more than 20% (Chile) and up to 35% (Argentina) of energy consumption in the building sector. Electricity is the most significant energy source, accounting for almost 45% of the total consumption in the building sector.

Bioclimatic architecture and passive strategies are well-known techniques that offer significant benefits in reducing the energy

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consumption of buildings by optimizing the use of natural resources, incorporating design strategies that take advantage of the local climate, and improving energy efficiency [31, 32, 52, 89, 102]. Some of those passive strategies are natural ventilation and daylighting, solar orientation, and thermal mass [51, 79]. Thus, bioclimatic buildings can significantly reduce operational costs and reliance on artificial heating and cooling systems. They also contribute to the thermal comfort of occupants and the decrease of the carbon footprint through the incorporation of renewable energy sources. Studies in different climates around the world have shown that these strategies can lead to energy savings of up to 40–60% compared to conventional buildings [52, 89], while in Argentina the reductions in winter energy consumption were estimated between 50% and 80% of energy savings (Filippín and Beascochea, 2007) [39].

Minimum performance standards and building energy codes are the key policy instruments used by governments to limit buildings' pressure on the energy sector and environment while providing occupants with comfort and modern living conditions. They are increasing in scope and stringency among countries, and the use of efficient and renewable building technologies is accelerating. Yet, the sector needs more rapid changes to get on track with the Net Zero Emissions by 2050 (NZE) Scenario. This decade is crucial for implementing the measures needed to ensure that all new buildings and 20% of the existing building stock are zero-carbon-ready by 2030 [60]. In Argentina, energy standards are not compulsory, resulting in a widely unsustainable built habitat and a growing energy inefficient use [20]. Thus, for the same thermal scenario, consumption rates in Argentina double the European ones or even more than double them [49, 50]. According to IDAE [57], the average consumption of natural gas for heating in block homes in Spain, with mandatory energy-saving regulations, is 54.5 kWh/m^2/year. In Argentina, particularly in Santa Rosa City (La Pampa), where this research is made, the average consumption for heating is about 200 kWh/m^2/year [49]. The average gas consumption in Argentina ranges from 600 to 7,500 m^3/year (with an average of 1,220 m^3/year in the central zone of Argentina and 67% destined to air heating), with high dispersion in the country due to the high depending on the different climatic zones [34, 49, 64]. The Argentinean energy scenario, the possibility of reviewing building standards and codes, the growth trend of housing construction in the region, and the building labeling process, among others, require an in-depth analysis of the information regarding the characteristics of the built habitat and its energy performance. Complying with IRAM Standards in Argentina (Instituto Argentino de Normalización y Certificación) would allow for a potential reduction of the heating energy demand by close to 27%, thus saving energy and minimizing the need to use cooling systems in summer [21]. Filippín and Beascochea [38, 41] reached higher values and, in their research, were able to conclude that bioclimatic building totalized 50–80% of energy savings. However, overheating is still an unresolved problem during the summer.

Protecting occupants from cold and hot outdoor temperatures is one of the most important functions of housing. As a result, both in developed and developing countries, improving housing conditions and reducing health risks at home are two fundamental goals to achieve. Buildings that are difficult or expensive to heat contribute to an increase in deficient breathing or cardiovascular illnesses of their dwellers [12, 110]. Cold air affects the normal protective function of the respiratory tract, with increased bronchoconstriction, mucus production, and reduced mucus clearance (Department of Health, 2007). In older people, low temperatures increase blood pressure and, consequently, the risk of strokes and heart attacks. Cold, damp houses also promote mold growth, which increases the risk of respiratory infections. Also, high indoor temperatures may cause heat-related illnesses and increase cardiovascular mortality rates [90, 110]. Several indexes were proposed to measure the health conditions of indoor environments, such as the Heat Index (HI) [86], Humidex [82], and standard effective temperature SET [69]. Building overheating and resilience metrics are also numerous [45, 54]. The CIBSE (Chartered Institution of Building Services Engineers) guideline is a widely used method for measuring the risk of overheating in buildings [16].

1.1. Health and sleeping environment

Room temperature directly affects the energy performance of a building, as heating and cooling are responsible for 40% of the energy use in buildings [30]. Also, high temperatures may strongly affect sleep quality, increase wakefulness and disturbance, reduce sleep time, and affect the recovery time during the night that is needed to deal with heat during the day [72, 113]. Furthermore, heat stress during the night negatively affects people's mental capacities and threatens psychological and physical health [9, 88, 107, 111]. In addition to night sleep, naps, especially those in the afternoon, lasting approximately one hour, are usual in healthy adults and university students, who have the flexibility in work or rest schedules. There is, of course, a biological predisposition to take a short sleep during the afternoon, and most hot climate cultures have a siesta break as part of their normal daily routine [11]. In the first surveys and interview studies with more than 3,000 students, 55–60% of university students reported taking naps with a "nap zone" from 2 PM to 4 PM [25, 26, 36, 37]. More recently, Becker et al. [8] studied 7,626 students between 18 and 29 years old from six universities, and Rea et al. [94] studied nap occurrence, duration, and timing and nocturnal sleep patterns in college students. Their results indicate that, today, napping is common among college students, with studies reporting between 43% and 54% of college-age samples napping at least once per week. Sleep, therefore, is an essential element of life, which helps remove any build-up of physical and psychological fatigue throughout people's daily lives.

There are limited studies on the impact of room temperature on sleep quality in the real-life context, particularly outside laboratories [73]. The quality of sleep of young and healthy men and women under different ambient temperatures (17°C, 20°C, and 23°C) was investigated in a test chamber by Pan et al. [92]. Subjective physiological data indicated that 20°C was the most comfortable temperature when awake while 23°C was the most satisfactory temperature during sleep. A similar study for ambient temperatures of 23, 26, and 30°C confirmed that subjects felt thermally neutral at 23°C when awake but reported significantly better sleep at 26°C [72]. Another test chamber study for low ambient temperatures of (10°C, 13°C, 15°C, 18°C, and 20°C) indicated that the thermally neutral temperature for pre-sleep and post-sleep was 18.3°C, with an indoor operative temperature of 14.5–17.5°C during sleep and a bedding temperature of 30.0–30.8°C [108]. In Japan, the impact of room temperature and ventilation modes on sleep quality and energy use in the real-life context of residential bedrooms was studied [99]. The authors analyzed the comfort temperature before and after sleep, its impact on sleep quality, gender-related differences, and the impact of heating, cooling, and natural ventilation. They concluded that natural ventilation, a more energy-efficient system, had a more consistent impact on sleep quality, while heating and cooling modes sometimes had a slightly negative impact. They further concluded that opening a window during the warmer months had a positive impact on sleep quality, which is why they suggest that the correct use of natural ventilation is likely to improve sleep quality while reducing the energy use of the building. Kim et al. [71] used sleep apnea as a measure of the sleep quality of 24 women of all ages during winter, spring, and summer periods. The best sleep quality in these periods was reached at seasonally different average air temperatures: 24.4°C in spring, 22.7°C in winter, and 28.6°C in summer. Several factors are known to interfere with the normal sleep process, but no clear effects of bedroom air temperature on sleep and next-day performance have yet been demonstrated [101]. Strøm-Tejsen et al. [100] evaluated the effects of bedroom air quality on sleep and next-day performance and examined them in two field intervention experiments in single-occupancy students' dormitories.

As shown, there is no consensus on the optimal ambient bedroom temperature but most of the evidence suggests a moderate temperature (20–26°C) and that a warmer or colder temperature can affect sleep negatively. Expert guidance in the United Kingdom suggests a bedroom temperature limit of 26°C or lower to prevent overheating. However, there is evidence that people sleep comfortably when temperatures range between 29°C and 31°C [84] due to the positive impact of opening windows during the warmer months. Thus, it is suggested that the correct use of natural ventilation is likely to improve sleep quality while reducing the energy use of the building.

In high- and middle-income countries, there is a great reliance on heating, ventilation, and air-conditioning systems (HVAC) to control the indoor thermal environment in bedrooms. However, these systems are expensive to buy and operate while being energy and environmentally intensive. Passive and low-energy strategies may address these challenges but the comparative effectiveness of these strategies in providing comfort in sleep environments has been little studied. In Argentina, an experimental study was conducted on the comfort conditions during sleep in three bedrooms in summer: without conventional cooling, with fan cooling, and with conventional (air conditioning) cooling [44]. Night air temperatures largely exceeded 26°C when thermal environment cooling relied only on natural ventilation and shading. The ceiling fan reduced the discomfort hours by about 44%. The bedroom with AC showed better thermal performance, with only 5% of the night hours exceeding 26°C. In this context, passive strategies that require no energy input can help reduce peak load surges in summer and during extreme temperature events [99].

1.2. Students' housing and its energy-saving interventions

One of the first studies that investigated the impact of various architectural characteristics on students' satisfaction corresponds to the 1970s [24, 106]. The purpose of this study was to find which environmental characteristics influenced students' satisfaction and which could be altered or affected by architectural design through a questionnaire given to 950 students who lived in 43 university residences on different campuses. Results indicated that students' satisfaction or dissatisfaction with a particular architectural variable did not significantly affect overall satisfaction with the total housing environment.

Today, recent studies have shown that there is an important effort in designing new residences that use more sophisticated systems, energy efficiency strategies, and automatic control, and that they pay attention to students' satisfaction. However, older facilities account for most of the housing stock on many campuses. The research of Collins [17] questioned how the age of the residence influences occupant perceptions and actions related to comfort and energy consumption. The study was conducted in two residences of the University of Oregon (USA), one built in 1963 and the other in 2006. It involved surveying 103 residents, taking thermal measurements at ten locations, and collecting utility data from the university. The results of the survey did not show a significant difference in the behavior of the residents between the oldest and newest buildings. Thermal measurements in both buildings fell inside and outside the ASHRAE Comfort Zone, which supported occupants' perceptions. The findings indicated a lack of students' awareness of energy conservation strategies.

In Kuala Lumpur, Malaysia, three residential college buildings of the University of Malaya with a focus on bioclimatic design strategies were studied [68]. The energy performance of the buildings revealed that the implementation of bioclimatic design strategies helped reduce annual energy consumption. The residential college buildings use 24–120 kWh/m²/year of electricity, with up to 90% of that electricity being conserved annually. For comparison, the authors mention that Malaysian office buildings consume about 200–250 kWh/m²/year. In Indonesia, measurements of the Sam Ratulangi University students' residence [98] were conducted to obtain information on whether the design followed Indonesian National Standard SNI 03-6389-2000 [63] on comfort and energy conservation. The scale of the thermal comfort in the room refers to the ISO-7748, and the Indonesian Standard establishes the comfortable air temperature as (25 ± 1)°C and relative humidity as (60 ± 10)%. Air temperature, wind speed, humidity, and lighting were measured simultaneously with a questionnaire on the occupants' comfort level. While originally the building was expected to meet the standards of comfort and energy conservation, measurements showed that the building does not meet the energy-efficient design criteria. The energy consumption of the rooms ranged between 34 and 157 kWh/m²/year. As a reference, conventional government office buildings in Bengkulu, Indonesia, consume about 40.9 kWh/m²/year [93].

In contrast, at Queen Mary University in London, the Richard Feilden House students' accommodation was found to align with its design intent and even exceeded the Good Practice Benchmarks CIBSE 2004 [14, 106]. High levels of insulation, thermal mass, and a proactive approach to building management have contributed to this success. The energy consumption was around 155 kWh/m²/year, 53% lower than the good-practice benchmark building CIBSE 2004 [14]. Furthermore, for benchmark comparison, Constable Terrace of the University of East Anglia was used as it has been reported to be 50% of the low yardstick for university residential buildings [27], with an annual consumption of 174 kWh/m²/year. Thus, Richard Feilden House consumed 11% less than Constable Terrace. Another successful experience was driven in Ireland, with the first students' residence built according to the Passivhaus standard in that country [55]. The buildings were monitored during 2012 and 2013. The monitoring program included building-wide energy performance and detailed energy and indoor environment parameters for 16 studio-bedrooms. The results indicated that temperature and CO_2 concentration varied greatly among users, showing the impact and variability of personal behavior. The heating demand (25 kWh/m²/year) was much lower than comparable buildings in Ireland and the building performs well as a low-energy building. To ensure the correct operation of the heating system, emphasis has to be put on the introductory briefing to new students moving into the residence.

Other aspects of students' housing are studied in the literature, such as the energy performance gap between predicted and real energy consumption [75]; the influence of aspects such as visual and thermal comfort, among others, on the quality and competitiveness of the university educational environment [56]; and the impact of the users' behavior on the maximum energy consumption [70].

In Argentina, the lack of equal opportunities to have access to education is a topic that has been central to several in-depth research works in the last few years [76]. These studies highlight that disparities in educational access are deeply rooted and manifest in various forms, from basic education to higher education [104]. In particular, data related to the Argentine higher education system reflect that considering their socio-economic background, the profile of the youth who have access to university studies does not include those coming from the less favored sectors [48]. For example, a report by the Observatory of Argentineans for Education reveals that only 12.4% of young people from the lowest income decile access university studies, compared to 46% of young people from the highest income decile [103]. This gap widens as students progress in their careers, with a higher concentration of students from higher-income sectors in advanced levels of higher education. To cope with this inequality, Argentinean universities offer students accommodation for those in need. In 1998, the National University of La Pampa (UNLPam), Argentina, promoted the design and construction of energy-efficient buildings with bioclimatic design for low-income students [40]. The adoption of appropriate bioclimatic design strategies, including envelope and façade design, solar control devices, passive daylight concepts, wind and natural ventilation, and landscaping, clearly helped to reduce the energy consumption (annual heating gas consumption is 87 kWh/m²).

As shown from this literature review, several recent studies address the issue of energy consumption and conservation in students' residences, but very little research appears to exist related to thermal comfort, health conditions, and sleeping comfort in these buildings. Furthermore, long-term analyses including several years of use are even scarcer. Such long-term analyses would help to overcome the influence of dwellers' variability on energy consumption and to obtain a complete picture of the thermal and energy behavior of the buildings in their life cycle. As stated by Vadodaria [106], student accommodation can account for up to 25% of the total energy consumption of an education campus; and therefore, it would be very useful to conduct detailed post-occupancy studies of student housing that include energy audit to fill this knowledge gap. Furthermore, a very

In this context, the objective of the present work is to present and discuss the lessons learned during 20 years (2001–2021) on the energy consumption and thermal behavior of the students' residences at Universidad Nacional de La Pampa (Argentina). The particular interest of this building is its bioclimatic design, based on capturing and accumulating solar energy, minimizing thermal losses of the envelope, and shading to reduce overheating in summer. However, the occupant's behavior has an effect on energy consumption and indoor conditions, so a long-term analysis allows to quantify the variability of such energy behavior. Besides energy consumption, aspects such as thermal comfort, sleeping conditions, and the impact of the indoor environment on health were analyzed from both measurement data information and transient thermal simulations. The paper is organized as follows: Section 2 describes the site and the studied building together with the experimental methodology and thermal model for the simulation with EnergyPlus. The analysis metrics for energy consumption, health impact (HI), and sleeping comfort are introduced. Section 3 describes the main results: energy consumption and the influence of human factors in winter; the effect of trees' growth on the indoor temperature; the evolution of the HI over the years, including an in-depth analysis of the hottest year of the period when the longest heat wave in Argentina occurred; and the sleeping conditions from both measurements in residence's bedrooms and simulations for the hottest year 2013. A present-day survey in December 2023 is also presented. Finally, Section 4 presents the main conclusions of the study and future research.

2. Materials and methods

2.1. Site and building description

2.1.1. Site description

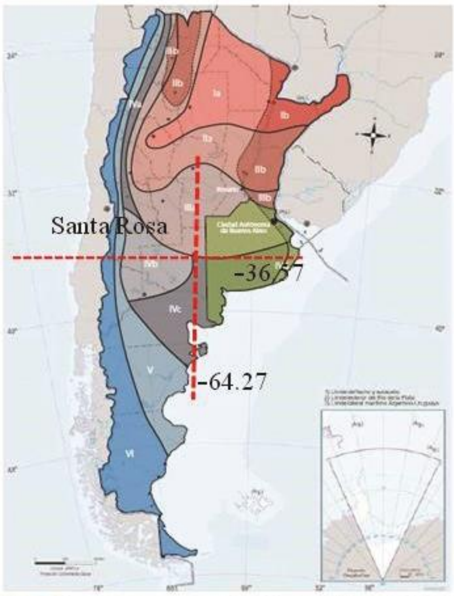
Santa Rosa (−36.57ºS, −64.27ºW, 191 m.o.s.l.) is the capital city of the province of La Pampa. Santa Rosa's climate is characterized by precipitation with monsoon conditions and a dry winter season. The climate in this zone is classified as Cfa (Köppen climate classification, [7]) and is on the border between bio-environmental warm and cold temperate climate zones according to the National IRAM Standard 11603/11. The weather data of the city is outlined in **Figure 1**.

Our studied buildings are located in a low-density residential suburb of Santa Rosa city. A GoogleMap image shows the surroundings of the buildings in **Figure 1**. It is well known that the surrounding landscape can improve the microclimate conditions both in winter and summer by providing shading, evaporative cooling, a reduced ground albedo, wind channeling, building sheltering, and so on [18, 53]. Duval and Campo [29] report that air medium and minimum temperature increase with respect to the conditions beyond the plant canopy. Sailor [97] concluded that increasing the vegetation fraction up to 0.065 resulted in an estimated 3−5% decrease in summer cooling loads. Therefore, the surrounding landscape of the residences was intentionally designed to provide grass, trees, and deciduous vegetation in the building vicinity.

2.1.2. Description of the studied building

During the year 2000, energy-efficient buildings for low-income students at the UNLPam were designed and constructed. It is worth mentioning the support of a Public University in promoting this initiative to provide accommodation to low-income students coming from towns away from the capital and/or from other provinces, within the present economic context in Argentina. Residences aim to provide adequate accommodation in a favorable environment to promote good study habits. The UNLPam students can have access to a residence scholarship. Also, international students who are part of the International Mobility Program might temporarily need to use the apartments. The residents must comply with the operating guidelines contained in the Internal

Regulations for Residents Handbook. Students who receive scholarships must pay for electricity, gas, and water supply bills (UNLPam Senate Resolution No 178/2015). Usually, residents change approximately every six years. Between 2001 and 2007, there were changes in the residents of all the apartments, except the apartments on the first floor facing NE and NW.



Annual Values	Temperature	minimum average	°C	8.1
		average		15.5
		maximum average		23.4
	Relative Humidity		%	68
	Average annual solar radiation on horizontal surface		MJ/m²	16.3
Winter (IRAM 11603:2011)	Temperature	minimum average	°C	3.5
		average		9.8
		maximum average		16.0
		absolute minimum		-11.3
	Minimum design temperature			-6.0
	Relative Humidity		%	73
	Wind speed average		Km/h	10.1
	Solar radiation on horizontal surface average *		MJ/m²	8.1
Heating degree days (Tb=18°C)				1394
Summer (IRAM 11603:2011)	Temperature	minimum average	°C	15.0
		average		22.2
		maximum average		29.4
		absolute minimum		42.1
	Maximum design temperature			38.8
	Relative Humidity		%	62
	Wind speed average		Km/h	12.5
	Solar radiation on horizontal surface average *		MJ/m²	24
Cooling degree days (Tb=23°C)				449

Figure 1 • Location of the city of Santa Rosa (Province of La Pampa) in the bio-environmental classification of Argentina, GoogleMap view of the buildings, and climate data for Santa Rosa city. Source of the map: AAPE [1].

The residences are two blocks of apartments (**Figures 2** and **3**). Each double-story building block is aligned on an East-West axis and has a compact shape with 350 m² of useful floor area (useful area/apartment = 58 m²). There are six apartments (from East to West, apartments 1–3 on the ground floor; apartments 4–6 on the first floor), each one having two bedrooms and a dining room with a kitchen on the northern side, and services facing South, as shown in **Figures 2** and **3**. The solar collection area is around 18% and 14% of the apartment's useful area on the ground floor and upper floor, respectively. The apartments have a gas heater in the corridor (2,900 W), but no mechanical cooling systems. The design harmonizes the benefits of compactness and the requirements of natural daylighting, heating, and ventilation. Thus, direct solar heat gains, thermal inertia, natural ventilation, thermal insulation of the envelope, external shading, building orientation, and dwelling grouping are suggested techniques to improve thermal comfort throughout the year. **Table S1**, Supplementary materials shows the constructive details of the building (for more details on the geometry and materials, see Filippín et al. [40] 2007).

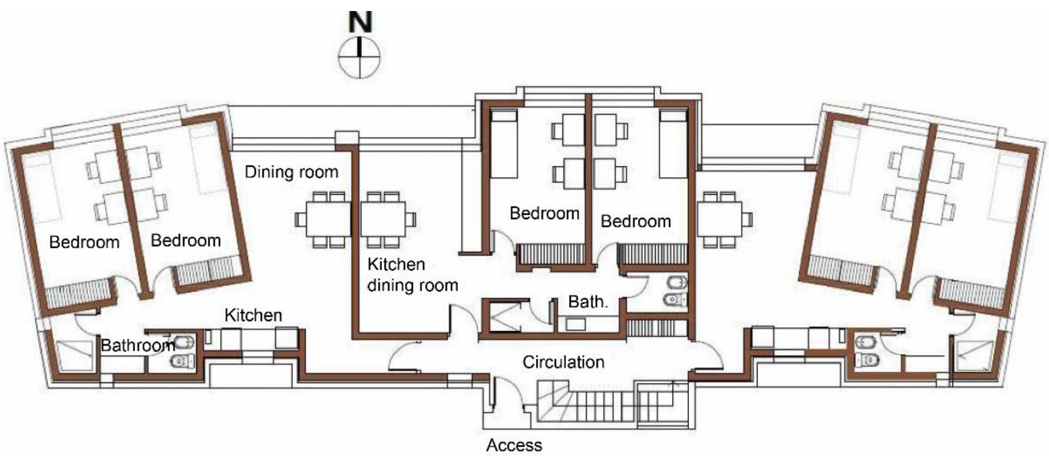


Figure 2 • Building plant.

Figure 3 • Building's facade facing north and the location of the apartments.

The external walls have three layers: an inner 180-mm brick wall to provide inner thermal mass, a 50-mm thermal insulation layer, and an external ceramic wall with concrete to protect the insulation layer (U_{wall} = 0.51 W/m²K). Roofs were insulated with a 70-mm polystyrene sheet and a light subfloor with a waterproof layer (U_{roof} = 0.46 W/m²K). The transmittance of walls and ceilings is categorized as Level B (Medium) according to the IRAM 11605 Standard (2004). This standard recommends values of 0.80 and 0.67 W/m²K for walls and ceiling, respectively, for a design outdoor temperature of −6.0°C in winter.

Hermetic aluminum frames and double glazing of windows allow the reduction of heat losses and regulate natural ventilation and daylighting (U_{window} = 3.82 W/m²K). The mitigating effect of vegetation on the microclimate was incorporated through trees and a metal pergola for deciduous plants on the north side to provide shade in summer and solar heating and natural lighting in winter. The buildings have direct solar gain through northern windows in bedrooms and dining rooms, combined with storage mass on floors and walls. The glazed areas were protected with black-out curtains and specially designed eaves to avoid overheating.

Natural ventilation was selected as the main cooling strategy because it provides a cheaper and simpler way of cooling small buildings in temperate regions where the night air temperature is lower than the comfort temperature. Thus, the heat accumulated during the day in the building mass can be dissipated. In our design, night cooling is achieved by opening the windows and allowing cross-ventilation, except in central apartments that had ventilation trough conducts. Clerestories in the roof of the staircase box improve the ventilation of the system.

2.2. Hygrothermal, energy monitoring, and occupants' surveys

2.2.1. Hygrothermal and energy monitoring

The natural gas consumption for the period 2001–2021 was obtained from the bi-monthly gas bills of the Gas Company. The students would not be the same in the whole period, as 60% of the students lived there for six years. Based on this information, the energy performance of the apartments during the period December 2000–January 2002 was analyzed in previous works [40] (Filippín and Beascochea, 2007) for all the apartments. The objective of the present research is to extend this analysis to the 20-year period 2001–2021, for which the annual gas consumption and the bi-monthly winter consumption were analyzed. To extract the fraction destined exclusively to air heating from the total gas consumption, a factor of 67% was used, as this value was found in previous studies of La Pampa's buildings [39, 49].

Six apartments in one of the blocks (Block B) were subject to detailed hygrothermal monitoring with the participation of residents, including both hygrothermal and gas consumption measures at different times of the day (May 25, 2001). The measured variables were indoor and outdoor temperature, indoor humidity, and mean radiant temperature. Humidity was measured using a thermal hygrometer, and mean radiant temperature using black spherical shell with a thermal sensor in the center of the globe. Thermal sensors were located in (a) the living area of selected apartments, (b) the staircase box, and (c) outside the building; they registered the data every ten minutes. The results of such monitoring were deeply discussed in Filippín and Beascochea (2007). Monitoring the apartments under real living conditions gave a solid base to understand the building's thermal behavior and the influence of dwellers' habits, together with the data needed to validate the building thermal model for transient simulation, as explained in the next section. Years later, another article described the post-occupancy evaluation of the building energy performance during the period 2001–2007 [39]. In 2007, a resident student developed his degree thesis in Natural Resources and Environmental Engineering and monitored the whole building between August 2007 and March 2008 [13]. The objective was to evaluate the hygrothermal conditions in the departments during winter and summer, the comfort level through the Predicted Mean Vote (PMV)-Predicted Percentage of Dissatisfied People (PPD) model and ISO 7730, and the air velocity in the kitchens when windows were open. This student was not only a resident but also promoted Dwellers Good Practices Guidelines among the other dwellers/residents. Thus, occupants were instructed about opening windows to allow night natural ventilation, closing them on hot days, using curtains to avoid direct solar gains and prevent overheating, using gas heaters in a sustainable way by turning them to pilot when they live in the apartments, etc. These instructions are important, as 33% of the occupants declared not having efficient behavior in the management and use of windows and curtains. An excessive use of gas heaters during the winter night in ground-floor apartments was found. In summer, opening windows was the main cooling strategy, which allowed reductions of the mean radiant temperature of about 2.5°C with an average air velocity of about 0.8 m/s.

2.2.2. Survey about thermal comfort and user behavior

Thermal comfort perception is widely variable as it is subjective and is influenced by many parameters such as environmental conditions (air temperature, humidity, wind velocity, radiant temperature) and occupant variables including physiological, psychological, cultural, and behavioral factors (metabolic rate, clothing insulation, gender, age, adaptation, skin temperature, etc.) [109]. Thus, subjects might perceive differently even if they are exposed to the same thermal environment. Besides climate chamber experiments with controlled environmental conditions, field studies allow registering the perception of thermal comfort in real-life conditions [96]. Among them, qualitative surveys and mixed methods are common methods used to gather data on individuals' thermal comfort levels and their usage patterns of heating systems [2, 78]. Qualitative open-ended questions provide qualitative insights into individual preferences and behaviors. In our case, the number of occupants was too small to conduct a survey statistically significant. This survey is, then, informative of some behavioral aspects and perceptions and it is not extrapolable. With the help of the Students' Welfare Office of the UNLPam, an online questionnaire was distributed and collected by a Google Form in December 2023 among 28 residence's occupants of the two building blocks who have lived in the building since 2016. The students were asked to categorize their subjective general perception of the thermal environment in winter and summer as very cold, cold, warm, or very warm. They were also asked about their window usage (partially opened/fully opened/closed), the schedule and preferred setting of the gas heater (maximum/minimum/pilot/off), whether they use an electric fan in summer and its schedule, and their knowledge of efficiently managing windows and curtains. The participants were informed about the purpose of the study, and their consent was obtained before participation. The surveys were not confidential, as the residents registered their apartment numbers.

2.3. Thermal simulation with EnergyPlus

Simulations of the building's thermal behavior were carried out using EnergyPlus V23.1.0 [35]. The software can simulate both single- and multi-year weather files. The thermal model of the building consists of 20 convex thermal zones (each apartment has three thermal zones, **Figure 4**). The geometry details of each thermal zone are summarized in **Table S1**, Supplementary materials. The opening between the kitchen and the corridor was simulated through *Air wall* materials, which allow heat and air exchange between zones. The occupancy schedules corresponded to two students per apartment. No additional internal gains were defined. A constant value of 2 air changes per hour was adopted for air infiltrations, following the convention established by the Argentine Institute for Standardization and Certification [66]. The constructive data were obtained from building plans and materials [39, 40]. The thermal properties of walls and roofs were summarized in **Table S2**, Supplementary materials. Inside and outside convective algorithms were set with the default models, that is, the TARP algorithm for inside surfaces and the DOE-2 algorithm for outside ones (more details in the EnergyPlus Manual, DOE [28]). Since 2007, trees and plants have fully grown so they are included as site shading objects with a varying transmittance schedule (1 in the period April–September, 0.2 in the rest of the year when trees have full foliage). For the annual heat load calculation, the *IdealHeatLoads* object in EnergyPlus was used, with a heating period from April to September and a constant thermostat set to 22.3°C. This thermostat value corresponds to the average temperature measured in the six apartments during 2001 [39].

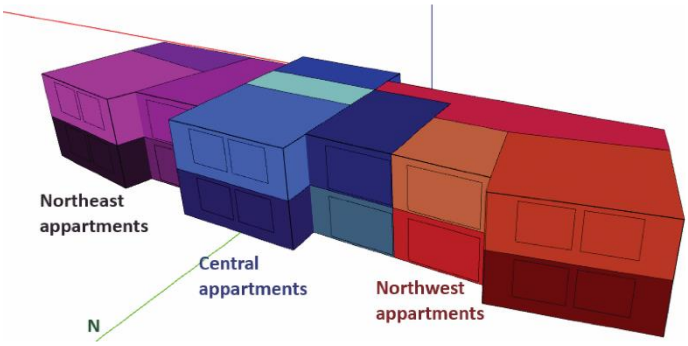


Figure 4 • Thermal zones of the building (three zones per apartment).

The observed hourly climatic data (air temperature and relative humidity, air pressure, wind velocity, and direction) in the period 2001–2021 were obtained from the National Meteorological Service. The solar irradiance on a horizontal surface was measured on the building roof during the measurement campaign in 2001 [40]. For the other years of the period 2007–2021, hourly solar irradiance data were downloaded from the database of NASA POWER [83]. The meteorological parameters of this database are based upon the GMAO MERRA-2 assimilation model (spatial resolution of 0.5° lat × 0.625° long, about 50 km in the latitudinal direction). In this research, EPW format files were downloaded, which is the file format of the meteorological data in EnergyPlus software. A previous verification was made for Santa Rosa by comparing NASA POWER data with hourly on-site registers provided by the National Meteorological Service of Argentina (Station 876230) and a good correlation (R^2 = 0.94) was found [45].

The thermal model was validated in previous research with the measured data of hourly air temperature registered in the six apartments for the whole year 2001 (Filippín *et al.*, 2009). This validated model was used to simulate the building behavior in the period 2001–2021. To validate the thermal model, we compared the simulated and measured hourly data of the indoor air temperature of the six apartments. We divided the period in two, one in winter with heating (July–August) and another in summer without heating (November–December). The accuracy of the simulation results was checked according to the ASHRAE Guideline 14 of the American Society of Heating, Refrigerating, and Air-conditioning Engineers, which recommends for hourly calibration that the normalized mean bias error (NMBE, Eq. (1)) should be less than 10% and the coefficient of variation of the root-mean-square error (CV_{RMSE}, Eq. (2)) should be less than 30%:

$$\mathrm{NMBE} = \frac{\sum_{i=1}^{n}(t_{mi} - t_{si})}{(n-1)\overline{t_m}} \quad (1) \tag{1}$$

$$\mathrm{CV_{RMSE}} = \frac{1}{\overline{t_m}} \sqrt{\frac{1}{(n-1)} \sum_{i=1}^{n} (t_m - t_s)^2} \quad (2) \tag{2}$$

where t_{mi} and t_{si} are the measured and simulated temperatures at hour i, respectively; n is the time steps of the data; and $\overline{t_m}$ is the sample mean of the measured temperature. The NMBE values obtained for each apartment varied between 6.2% and 9.7% and the CV_{RMSE} between 20.1% and 27.6%. The highest values were obtained in winter because of the variability in the use of the gas heater among dwellers.

2.4. Metrics

The following metrics were used to study the building's thermal behavior and the impact of the warm thermal environment on health: the energy consumption in winter obtained from the gas bills, the annual HI (obtained from multi-annual thermal simulations), and the PMV/PPD during the sleep hours (night and nap) in summer (obtained from both measurements and thermal simulations). Additionally, the effect of the vegetation cover on the indoor temperature of the apartments was estimated by comparing the measured indoor temperatures during the summer period December 1–21 of 2001 (neither vegetation nor trees) and 2007 (fully grown trees and vegetation).

2.4.1. Winter energy consumption

In this work, the winter energy consumption obtained from the gas bills from 2001 to 2021 was analyzed by the usual statistical indicators: average consumption, standard deviation, and coefficient of variability, CV (%). The CV is a standardized measure of dispersion of a probability distribution or frequency distribution and it is expressed as a percentage. In practice, CV usually ranges between 0% and 100%; however, values higher than 100% could occur in some cases and make evident an extremely high dispersion of data and the need to detect the sources of this variability, usually errors in the data acquisition or post-processing [81]. In energy consumption of a sample of houses, high CV values are usually found due to the morphological differences between dwellings (geometry, shape, orientation, materials, etc.) and due to different behavioral patterns between owners (related to users' preferences and attitudes).

2.4.2. HI for summer health conditions

Air temperature is not the only variable determining heat perception. It depends on several environmental (air temperature and humidity, wind velocity, mean radiant temperature) and human response (activity, clothing level, age, etc.) variables. Various models are available based on human heat balance considerations, although the results are relatively similar [4, 10]. While several different "apparent" or "equivalent" temperatures have been proposed, we focus on the HI because it is widely used around the world as it is a good descriptor of the heat perception variable. HI is expressed as an apparent temperature calculated through an equation [95], derived by multiple regression analysis, that combines air temperature T and relative humidity RH. In SI units, HI is estimated as:

$$\begin{aligned} \mathrm{HI} = & -8.785 + 1.61139411\,T + 2.338549\,\mathrm{RH} - 0.14611605\,(\mathrm{TR\,H}) \\ & -(1.2308094\times10^{-2})T^2 - (1.6424828\times10^{-2}) + (2.211732\times10^{-3})T^2\mathrm{RH} \\ & + \left(7.2546\times10^{-4}\right)\mathrm{TR\,H}^2 - \left(3.582\times10^{-6}\right)T^2\,\mathrm{RH}^2 \end{aligned} \quad (3)$$

The Rothfusz regression is appropriate when conditions of temperature and humidity permit a HI value higher than 26.7°C (except the values at 32.2°C and 45%/70% relative humidity vary unrounded by less than ±0.5°C, respectively). If HI < 26.7°C, a simpler formula is used, which for SI units is expressed as:

$$\mathrm{HI} = 1.1\,T + 0.0261\,\mathrm{RH} - 3.94 \quad (4)$$

Equations (3) and (4) were used to calculate the HI in each apartment.

It is worth noting that more recent reviews suggest that this existing HI is well-defined for most combinations of high temperature and humidity experienced on the Earth in the preindustrial climate. However, global warming is increasingly generating conditions for which the HI is undefined. Therefore, an extension of the original HI was proposed by Lu and Romps [77] using the same physiological model as in the original work to ensure backward compatibility. In the conditions of Santa Rosa city, the temperature and humidity of the analyzed period are not so extreme; thus, the Rothfusz Eqs. (3) and (4) are valid.

The resulting HI values are categorized according to the possible heat disorders in people as shown in **Table 1** [85].

Table 1 • Categories of possible heat disorders according to the HI values

HI (°C)	Category	Possible heat disorders
26.7–32.2	Caution	Possible fatigue with prolonged exposure and/or physical activity.
32.2–40.6	Extreme caution	Possible sunstroke, muscle cramps, and/or heat exhaustion with prolonged exposure and/or physical activity.
40.6–54.4	Danger	Sunstroke, muscle cramps, and/or heat exhaustion likely. Heatstroke is possible with prolonged exposure and/or physical activity
> 54.4	Extreme danger	Heatstroke likely

In our study, the hourly HI was calculated for the 20 thermal zones in the building, for each year of the studied period, by thermal simulation with EnergyPlus. The hourly values were categorized as *Safe, Caution, Extreme Caution, Danger*, and *Extreme Danger* (**Table 1**) and the number of hours in each category was automatically calculated and reported in the *Annual Thermal Resilience Summary* of EnergyPlus. A script in Python was developed to extract these data and generate the comparative graphs. The results are shown in box plots graphs, which are useful as they provide a visual summary of the data enabling researchers to quickly identify mean values, the dispersion of the data set, and signs of skewness. Box plots visually show the distribution of numerical data and skewness by displaying the data quartiles (top and bottom of the boxes) and maximum/minimum values (at the end of the whiskers). The box lengths indicate how the data are dispersed between each sample: the longer the box, the more dispersed the data.

2.4.3. PMV/PPD during sleep in bedrooms

The model of Lan et al. [74] for sleeping was used in this work. This model calculates the PMV and PPD during sleeping, considering some aspects related to the mattress, the body position, and the reduced metabolic rate, among others. The following assumptions were made: a modified metabolic rate (0.7 met or 40 W/m² corresponding to an immobile person during the whole period of sleep), the body in a supine position (with 0.39 of it in contact with the mattress), vapor evaporation from the body in contact with a bed reduced to 20% compared to when not in contact with the bed, no regulatory sweating during sleep, a mattress thermal conductivity of 0.048 W/m²-K, and mean radiant temperature similar to air temperature. Thus, PMV and PPD can be calculated as [74]:

$$\mathrm{PMV}_{\mathrm{sleep}} = 0.0998\left\{40 - \frac{13.41 - 1.519p_a - 0.13T_a}{A_D} - \left[1.875\left(5.52 - p_a\right) + \frac{0.61\left(34.6 - T_a\right)}{0.155I_{\mathrm{clo}} + 1/\left(f_{\mathrm{clo}}h\right)} + 0.0187\left(\frac{35.4 - T_a}{d}\right)\right]\right\} \quad (5)$$

$$\mathrm{PPD} = 100 - 95\exp\left(-0.03353\,\mathrm{PMV}^4 - 0.2179\,\mathrm{PMV}^2\right) \quad (6)$$

where A_D (m²) is the area of the human body (1.7 m²), I_{clo} (clo) is the clothing insulation of the sleep covering (including the sleepwear and bedding, from Lin *et al.*, 2008), f_{clo} is the covering area factor (ratio of the clothed body), d is the mattress height (0.20 m), T_a and p_a are the ambient air temperature (°C) and water vapor pressure (kPa), respectively. The total heat transfer h is calculated as the sum $h_r + h_c$, where the radiative heat transfer coefficient h_r (W/m²-K) is assumed as 3.235 (W/m²-K) and the convective heat transfer coefficient h_c (W/m²-K) at the body surface depends on air velocity and is calculated as:

$$h_c = \begin{cases} 2.7 + 8.7v^{0.67} & \text{for} \quad 0.15 < v < 1.5 \\ 5.1 & \text{for} \quad 0 \le v \le 0.15 \end{cases} \quad (7)$$

Finally, the comfort zone for sleeping is defined as Category III of Standard ISO 7730 and CEN 15251 for existing buildings (Xu and Lian (2023)). Thus, the indoor environment is considered in thermal comfort when $-0.7 < \mathrm{PMV}_{\mathrm{Sleep}} < 0.7$ and PPD < 15%.

Equations (5) and (6) were incorporated in a Python script that calculates PMV and PPD hourly values and characterizes the thermal sensation of the bedrooms' occupants. In our work, we consider night rest between 11 PM and 7 AM, and nap rest between 2 and 4 PM. Air temperature and relative humidity were obtained either from measurements during 2007 or from thermal simulation with EnergyPlus (for the year 2013). Water vapor pressure was calculated from the air temperature through known thermodynamic equations (i.e., $p_a = 0.133322\exp\left[20.386 - 5132/\left(T_a + 273.15\right)\right]$). The clothing insulation I_{clo} was considered typical summer coverings (0.6 clo short-sleeved t-shirt, pants, and blanket, Lan et al. [74]) and 2.2 clo in winter (full-sleeved sleepwear + winter blanket), and f_{clo} considering a covering of body surface area of 59.1% (bottom part of the body) in summer and 94.1% in winter, according to Lin and Deng (2008). The air velocity was considered as 0.1 m/s—when there are no fans in the bedroom—or 0.6 m/s—maximum air velocity of fans, when available, to avoid discomfort—according to Lan et al. [74].

3. Results

3.1. Retrospective and compendium of measured energy consumption and human factors during winter

Monitoring the apartments in real living conditions provided a solid basis for understanding the thermal behavior of the building and the influence of the inhabitants' habits. The main results indicated that the building had a good performance in winter, with temperatures between 18°C and 26°C and an annual average gas consumption of 144 kWh/m²/year, a figure that is about 37% lower than in conventional houses in the same climate [43]. In La Pampa, around 67% of the annual gas consumption is destined for air heating [39, 49]; so, the energy consumption for air heating of the studied building is about 96 kWh/m²/year. The highest consumption of gas for heating occurred during the most severe winter months (July–August), with bi-monthly values between 18 and 44 kWh/m² per apartment. This consumption was greater in the apartments on the ground floor as compared with the apartments on the upper floor. It is also necessary to remark on the influence on the consumption of human-dependent factors. For example, independently of outdoor temperature, 26% of measured indoor temperature in the apartment on the ground floor facing northeast exceeded 24°C, with the highest gas consumption during July–August. When asked, the occupants of this apartment explained that a heater was regularly working all over the night. A survey in 2008 indicated that 50% of all residents turned the heater to pilot at night. In total, 33.3% and 16.7% left the heater on at high and low temperatures, respectively [13]. Therefore, the difference in gas consumption among apartments could not be fully explained by design-dependent factors, but by the individual behavior of dwellers that differ in their habits of heating the indoor environment.

The gas bills of the 20-year period 2001–2021 of the six apartments were analyzed. **Figure 5** and **Tables 2–4** show the total annual consumption for each apartment and the associated statistical parameters (average value, inter-annual standard deviation, and coefficient of variability). An average heating energy consumption of about 109 kWh/m²/year (with a variability of about 18%) was estimated as 67% of the average annual gas consumption. The inter-annual coefficient of variation for the period 2001–2021 ranges between 20% and 32% (**Table 2**). The highest energy consumption is observed on the ground floor. It is worth mentioning that since 2015, an increase in annual natural gas consumption of about 25% has been observed in some apartments (**Figure 5**), probably due to the change in the groups of students, some maintenance issues, or some construction pathologies. **Figure 5b** shows the energy consumption in the coldest bi-month (July–August) and the outdoor conditions represented by the heating degree days (HDD) (Base = 18°C), defined as the summation of the number of degrees Celsius that the mean daily air temperature falls below 18°C over the period July–August. Thus, 2007 was the coldest winter in the period and caused a peak in heating energy consumption. However, the maximum energy consumption in 2020 (135 kWh/m²/year) is not related to cooler outdoor conditions but to the COVID pandemic, when students must be at home for the whole year. As shown, the relationship between HDD and heating energy consumption is not as strong as expected: in fact, the linear regression showed an R^2-value of 0.143, a value that indicates that there is not a good fit between both variables. This could be explained by the high variability in energy consumption between apartments with different dwellers' habits, the impact of the pandemics (2020 and 2021), and the renovation of students who were not the same throughout the whole period. It is possible that the increase in gas bills in the last years due to the elimination of subsidies could also have had an impact on consumption. This high variability was also in coincidence with the behavior previously studied in Filippin et al. [39, 40].

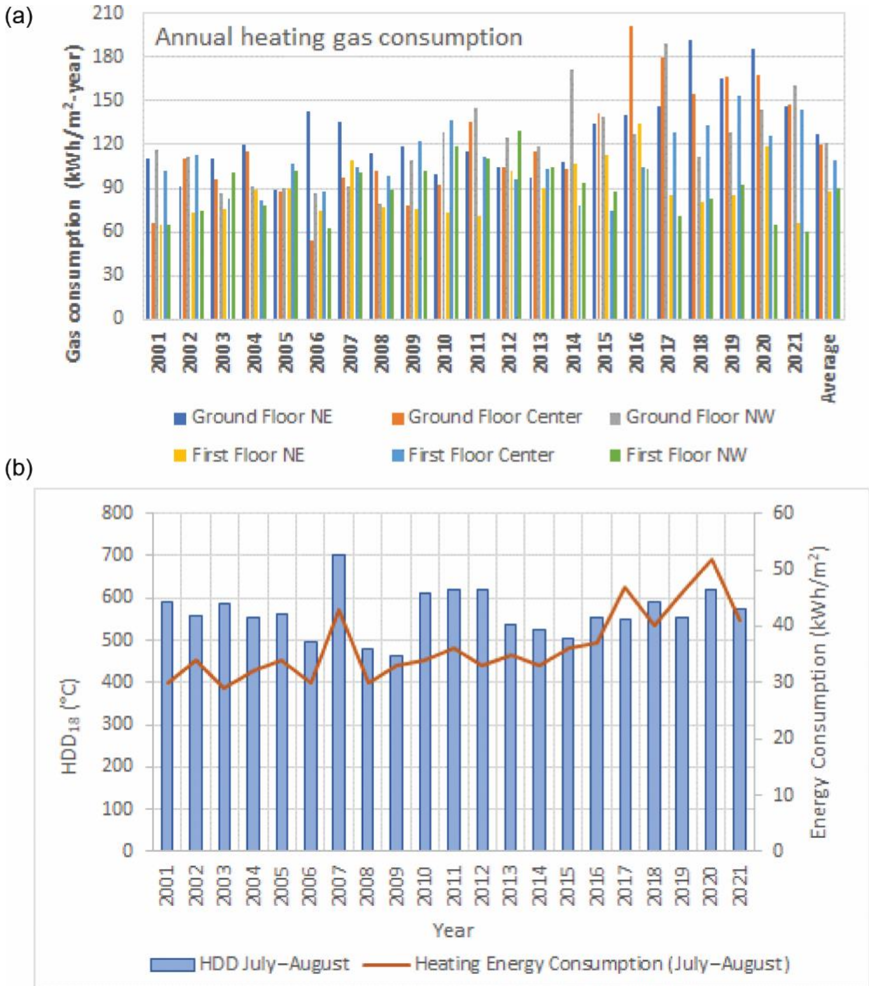


Figure 5 • (a): Annual natural gas consumption destined to heating (kWh/m²/year) for each apartment, calculated from the distribution company bills (1 m³ of gas = 9.8 kWh, 67% of total consumption destined to air heating), during the period 2001–2021. (b): Heating degree days (HDD) below 18°C and heating energy consumption for July–August averaged for the six apartments, in the period 2001–2021.

Table 2 • Total annual natural gas consumption (kWh/year) averaged in the period 2001–2021, and annual consumption destined to air heating (kWh/m²/year) calculated from the distribution company bills as 67% of the total consumption. Standard deviation and coefficient of variability (%) between apartments, during the period 2001–2021, are also shown

Apartment	**Average consumption**		**Standard deviation (kWh/year)**	**Inter-annual coefficient of variability (%)**
	Total (kWh/year)	**Heating 67% (kWh/m²/year)**		
Ground floor NE	10,992	127	2,499	23
Ground floor center	10,377	120	3,359	32
Ground floor NW	10,517	121	2,565	24
First floor NE	7,638	88	1,648	22

First floor center	9,447	109	1,930	20
First floor NW	7,811	90	1,684	22
Average		**109**		

Table 3 • Annual heating energy consumption in kWh/m²/year

	Ground floor			First floor					
	NE	Center	NW	NE	Center	NW	Average	SD	CV (%)
2001	110	66	116	65	102	65	88	24.7	28
2002	91	110	111	73	113	75	96	18.6	19
2003	110	96	86	76	83	101	92	12.9	14
2004	120	115	91	89	82	78	96	17.5	18
2005	88	88	90	91	107	102	94	8.2	9
2006	142	54	86	75	87	62	85	31.2	37
2007	136	98	91	109	105	101	107	15.7	15
2008	114	102	80	76	99	89	93	14.2	15
2009	118	78	110	76	123	101	101	20.0	20
2010	100	92	128	73	137	119	108	24.1	22
2011	115	135	145	71	112	111	115	25.7	22
2012	105	105	125	102	96	130	110	13.7	12
2013	97	116	118	90	103	105	105	10.9	10
2014	108	103	171	107	78	94	110	31.9	29
2015	134	141	139	113	74	87	115	28.4	25
2016	140	201	128	135	105	103	135	35.6	26
2017	146	180	190	85	128	71	133	48.6	36
2018	192	154	112	80	134	82	126	43.3	34
2019	166	167	128	85	153	92	132	36.2	27
2020	186	168	144	119	126	65	135	42.6	32
2021	146	147	161	66	144	60	121	45.3	38
Average	127	120	121	88	109	90	**109**		
SD	29	39	30	19	22	19		**7.6**	
CV (%)	23	32	24	22	20	22			**18**

SD, standard deviation; CV, coefficient of variability (%).

Table 4 • Bi-monthly (July–August) heating energy consumption (kWh/m²)

	Ground floor			First floor					
	NE	Center	NW	NE	Center	NW	Average	SD	CV (%)
2001	40	22	44	18	33	21	30	10.7	36
2002	32	46	35	24	36	28	34	7.8	23
2003	38	33	27	25	15	36	29	8.3	29
2004	35	41	37	30	28	24	32	6.1	19
2005	28	36	29	35	40	35	34	4.7	14
2006	52	18	30	27	32	22	30	11.7	39
2007	50	36	38	45	53	36	43	7.4	17
2008	38	28	27	27	29	32	30	4.3	14
2009	38	26	36	22	36	38	33	7.0	21

2010	28	35	49	25	32	34	34	8.2	24
2011	35	37	52	23	40	26	36	10.3	29
2012	41	35	47	36	30	11	33	12.6	38
2013	32	33	42	39	29	35	35	5.0	14
2014	33	37	53	41	14	22	33	13.8	42
2015	29	49	49	41	25	26	36	11.3	31
2016	42	54	37	38	26	24	37	10.9	29
2017	59	68	69	10	60	18	47	26.2	55
2018	55	58	23	28	43	32	40	14.4	36
2019	53	64	48	27	55	29	46	14.7	32
2020	64	56	55	55	51	31	52	10.8	21
2021	46	53	48	25	52	21	41	14.1	34
Average	41	41	42	31	36	28	**36**		
SD	11	14	11	10	13	7		**6.1**	
CV (%)	26	33	27	33	35	26			**17**

SD, standard deviation; CV, coefficient of variability (%).

Tables 3 and **4** show the annual and bi-monthly heating energy consumption in kWh/m²/year, per apartment, in the period of 20 years. The annual average consumption is 109 kWh/m²/year per apartment. In 2001, when indoor measurements were taken and good indoor thermal conditions were found in winter, the average consumption was about 88 kWh/m²/year per apartment. Thus, as higher consumptions were registered in other years of the period, it is possible to infer that the indoor thermal conditions were adequate in all the periods 2001 and 2021. Regarding the bi-monthly gas consumption for heating in July–August (**Table 4**), the results show an average consumption between 2001 and 2021 of 37 kWh/m²/year (CV = 17%). It is worth mentioning that 2007 had a more severe winter (HDD_{Base} = 18°C and during July was around 10% higher than in 2001) with a marked increase of about 32% in the volume consumed by the residential sector in the region [33]. The value for the whole period 2001–2021 corresponds to a saving of 33% compared to other conventional apartment block buildings facing north in the same region [42, 43].

Tables 3 and **4** also show that apartments on the first floor consume about 22% less energy for heating in a year than those on the ground floor. The year with the highest consumption (for both, annual and winter periods) corresponds to 2020, due to the COVID-19 pandemic that obliged students to rest at home. In this year, the building's average bi-monthly consumption was 52 kWh/m²/year in 2020, which corresponds to a value 42% higher than the average 2001–2021 (36 kWh/m²/year).

In the EU, the energy consumption for heating per square meter and per dwelling has decreased since 2000, thanks to the implementation of stricter building codes, combined with financial incentives to promote the thermal retrofitting of existing dwellings and the adoption of more efficient heating systems [3]. For example, the heating consumption is about 52 kWh/m²/year in Spain and 125 kWh/m²/year in the United Kingdom. In our case study, without mandatory regulations regarding the energy efficiency of buildings, and with a limited availability of economic resources to design and build the apartments described in the case study, the value of 109 kWh/m²/year was promising. The IEA report [58] considers that technology and design are at the heart of a sustainable economy in the construction sector and that high-performance building construction and energy renovations may reduce the sector's energy use by almost 30% by 2050.

3.2. Retrospective evaluation during summer

3.2.1. The Heat Index (2007–2021)

Figure 6 shows the evolution of hours with HI > 26.7°C throughout the period 2007–2021. The lowest values always correspond to the ground floor while the highest were recorded on the upper floor, particularly in the NW orientation. In general, the medians range between 14% and 24%; thus, none of the apartments showed HI values in non-safe conditions lower than 10%. It is interesting to note that 2007 was the most benign year in terms of presenting the lowest HI levels, yet the overheating percentages ranged between 8% and 21% for the different areas of the building.

The year 2013 presented the highest dispersion (boxplot length) and range (distance between maximum and minimum values): the apartments' zones presented a high number of hours in non-safe conditions, between 15% and 35% (i.e., between 1,315 and 3,065 hours per year). The year 2013 is particularly interesting because of the heat wave that occurred from December 11, 2013, to January 2, 2014, in the northern and central areas of the country, as well as in northern Patagonia. It was the longest heatwave experienced in Argentina since records began in 1906, affecting at least 52 cities throughout the country. The highest temperature (45.5°C) was recorded in Chamical (La Rioja). Santa Rosa reached 40.4°C on December 23. The long persistence of this heat wave (22 days) made the event exceptional, breaking several records in terms of the greatest number of consecutive days with minimum and maximum temperatures above the average in several meteorological stations in the region. It was the first heat wave with a level of danger to health that was categorized as extreme (red alert). The National Meteorological Service and the Ministry of Health warned the population about the risks to avoid and the basic care to follow by the population in the face of intense heat.

Figure 7 shows a more detailed analysis of what happened in 2013, when the ground floor apartments presented 1,470 hours per year, on average, with HI > 26.7°C (17% of the year), while for the floor high this value was 2,710 hours per year, on average, with HI > 26.7°C (31% of the year). It should be remembered that the apartments do not have air conditioning to deal with the extreme heat. Due to this, a more exhaustive analysis of the interior conditions in the bedrooms during December 2013, when the heat wave occurred, was included. As shown in **Figure 7**, HI was in safe conditions during the last hours of the night, while in the rest of the day, the HI values were categorized as "Caution" and "Extreme Caution" (possible sunstroke, muscle cramps, and/or heat exhaustion with prolonged exposure). The worst situation, again, in the upper floor apartment, indicates that HI values can exceed 33°C, and during 70% of the hours, the residents were exposed to indoor conditions that are potentially damaging to their health.

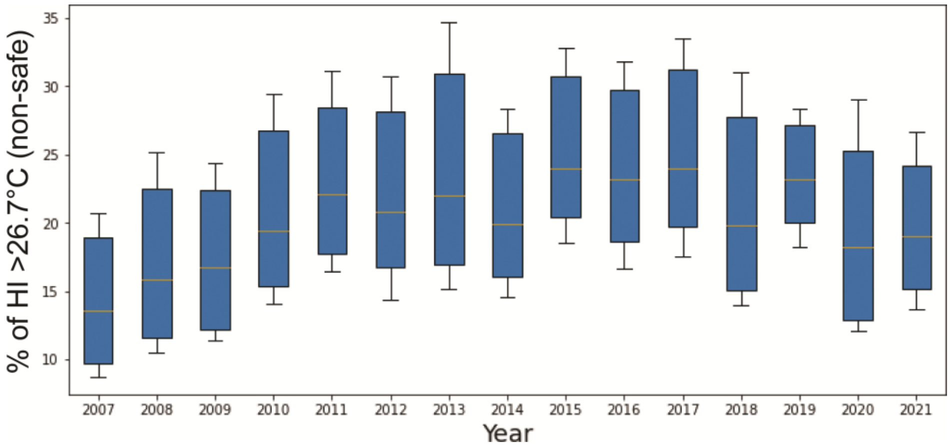


Figure 6 • Percentage of hours in each year (8,760 hours) when the indoor conditions are not safe (Caution, Extreme Caution, Danger, Extreme Danger). The boxplot shows the data quartiles (top and bottom of the rectangle), median (orange line in the rectangle), and maximum/minimum values (at the end of the whiskers). HI, Heat Index.

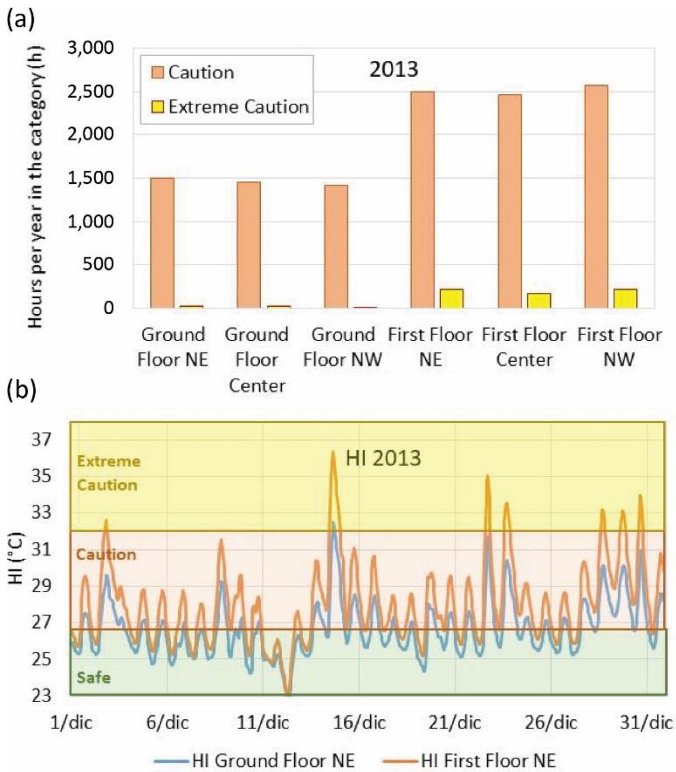


Figure 7• (a): number of hours in the categories Caution and Extreme Caution for the year 2013, when a prolonged heat wave occurred. (b): hourly distribution of HI during December 2013, for the NE apartments. HI, Heat Index.

It is worth mentioning that these high temperatures favor the life cycle of the Aedes aegypti mosquitoes, with an optimal temperature range for their development between 25°C and 30°C [19, 22, 80]. Aedes aegypti is the primary vector of the viruses of dengue, yellow fever, chikungunya, and Zika. It has been postulated that, due to the increased temperature produced by climate change, the mosquito has appeared in places where it was not common, allowing the viruses to spread uncontrolled in different regions [46]. Very recently, the first analysis to look for a relationship between dengue with heatwaves was presented including the risk of dengue infection with temperature by subgrouping studies according to Köppen-Geiger climatic zones [23]. Thus, the high indoor temperatures and HI values in summer could collaborate, in the future, with the expansion and growth of the mosquito.

In conclusion, in the period 2007–2021, the HI in non-safe conditions ranged on average between 8% and 34%, with a median of 20% hours for the entire period and considering the entire building. In the case of the worst meteorological conditions such as those that occurred in 2013, the apartments had non-safe conditions of between 17% (ground floor) and 31% (first floor). Considering that overheating should not exceed 10% of the hours of the year [16], it is concluded that the building presents significant overheating in all its rooms, which was exacerbated by the gradual and constant increase in summer temperatures. During hot weather and heat waves, the apartments' conditions for health were categorized as "Caution" and "Extreme Caution", indicating a potential health risk.

3.2.2. Measured sleeping conditions in summer (December 2007)

Based on the Lan et al. [74] model, the PMV_{Sleep} and PDD_{Sleep} metrics were estimated during both night sleep and naps for December 2007. **Figure 8** shows results with PMV values between 0 and 2 (i.e., the environment is perceived as "slightly warm"). The averages of PMV_{Sleep} on the night and nap periods are 0.7 and 1.1 (slightly warm), respectively, which correspond to PPD_{Sleep} values of about 15% (night) and 31% (nap).

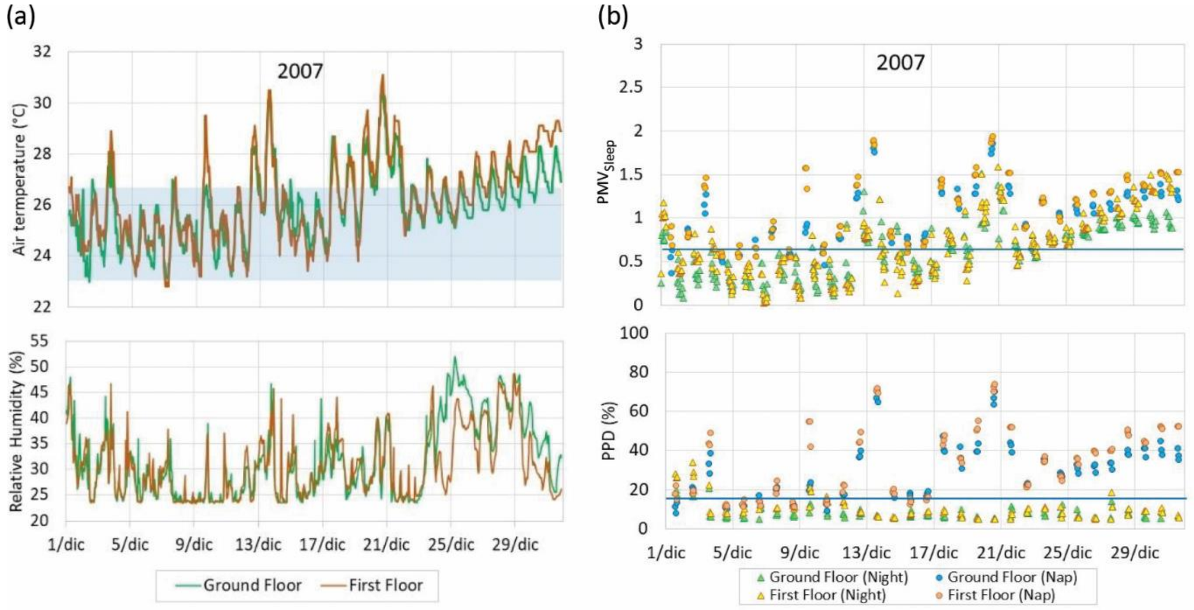


Figure 8 • Thermal monitoring of central apartments (at the ground floor and first floor) during December 2007 (a), and PMV/PPD estimation during sleep (night and nap) (b). References: light blue box: 23–27°C Level A for night temperatures of Scheme 2 IRAM 11659-1:2004.

During nights, the temperature conditions are, mostly, within the limits of the summer comfort zone of 23–27°C recommended by the Argentinean IRAM Standard 11659-1:2004 [67] for activities that require little physical fatigue. However, during naps, the temperatures would not be within such limits. An inspection of PMV_{Sleep} values evidences that during naps the environment is perceived as slightly warm while during nights it is perceived between neutral (first part of December) and slightly warm (second part of December). The neutral temperature for sleeping was estimated as 22.8°C, in accordance with Pan et al. [92] who found a value of 23°C as the most satisfactory temperature during sleep. On average, the residents perceive as uncomfortable 80% of the hours during naps and 44% during nights.

These results would agree with the HI calculated in the previous section: for December, on average, 20% of the hours in the apartment on the ground floor and 33% in the first floor, and the HI value was >26.7°C ("Caution", possible fatigue with prolonged exposure). Particularly, during the hottest days, HI was in the "Caution" category all over the night, when the PMV_{Sleep} was >1 (environment perceived as "slightly warm"). Again, the highest percentage of records above 26.7°C is observed on the upper floor of the building.

3.2.3. Sleeping conditions in the hottest year (December 2013)

Figure 9 shows the hourly values of PMV_{Sleep} for the year 2013, considered the most extreme of the period due to the heat wave of December 2013. It is observed that in the cold months (May–July), 98% of the PMV values fall within the Category III comfort zone of the ISO Standard, while in the warm months December–March the comfort hours are reduced to 12% (upstairs) and 27% (ground floor) of the hours. A more detailed analysis of December (**Figure 10**) in the sleeping hours of the nap (2 PM–4 PM) and night (11 PM–7 AM) shows that the worst conditions appear on the first floor, with values of PMV_{Sleep} reaching 2.7 (warm) during naps and up to 2 (slightly warm) during nights. In general, bedrooms are uncomfortable during the sleeping hours.

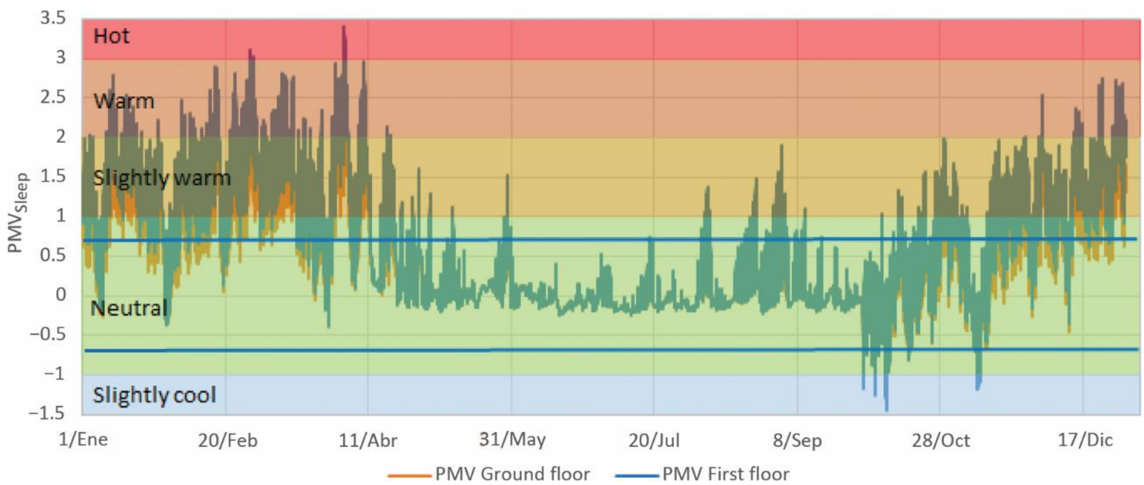


Figure 9 • Hourly PMV_{Sleep} for the year 2013 in the ground- and first-floor bedrooms. Horizontal lines in blue correspond to the limits of ±0.7 in PMV of Category III of standards ISO 7730 and CEN 15251.

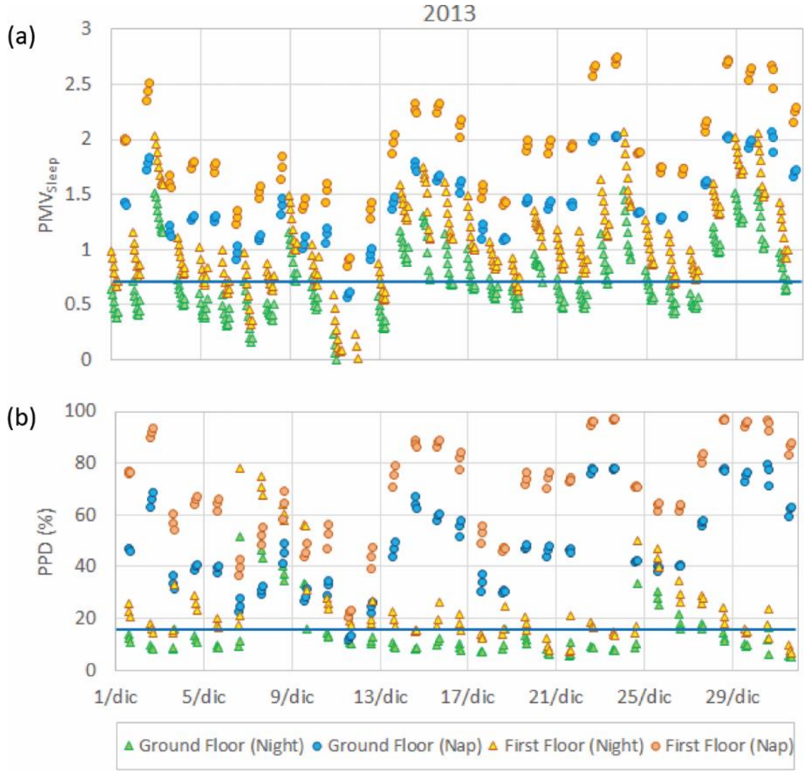


Figure 10 • Predicted Mean Vote (PMV) (a) and Predicted Percentage of Dissatisfied People PPD (b) for naps (2 PM–4 PM) and night (11 PM–7 AM) in the ground and first-floor bedrooms, for December 2013. Horizontal lines in blue correspond to the limits of ±0.7 in PMV (and 15% in PPD) of Category III of standards ISO 7730 and CEN 15251.

3.2.4. The measured effect of the tree shading on the building's indoor temperature

Figure 12 and **Table S3,** Supplementary materials shows the difference in average temperatures measured between inside and outside for the period December 1–21, for the years 2001 (without trees) and 2007 (with trees, see **Figure 11**). Outdoor air temperature was higher in 2007 (average temperatures of 21.3°C and 23.9°C in 2001 and 2007, respectively, see **Table S3,** Supplementary materials). To compare both periods, instead of absolute temperature values, the differences between indoor and outdoor temperatures were considered. **Figure 12** shows positive values, thus indicating that the average interior temperature is higher than the exterior temperature. This effect is more pronounced on the upper floor due to the greater heat gains due to exposure of the envelope. With the growth of the trees in 2007 (**Figure 11**), a clear decrease in these differences is observed, indicating that the shading produced by them contributed to reducing the average indoor temperature of the building by 1.7°C.

Figure 11 • The residences in 2001 (without trees) and with full coverage of trees (2008).

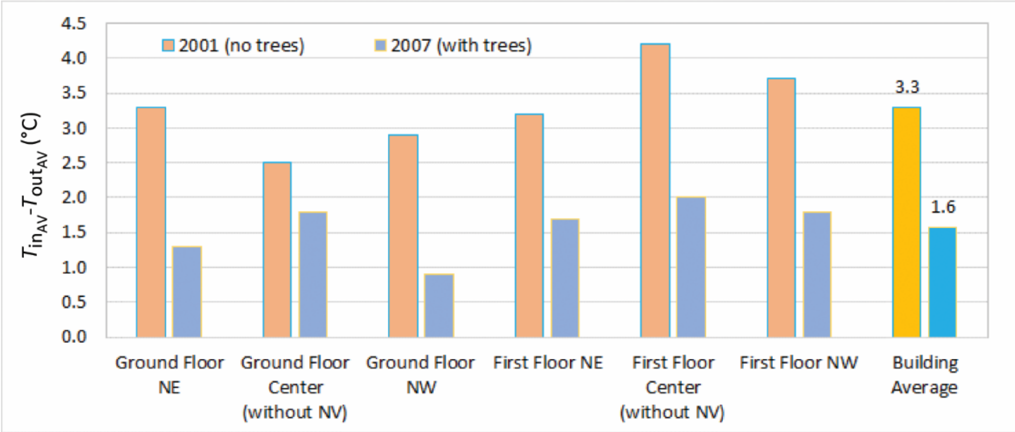


Figure 12 • Differences in average air temperature between the interior and exterior of the apartments, for the period December 1–21, for the years 2001 (without trees) and 2007 (with trees). The beneficial effect of trees is observed, which allows the temperature difference to be reduced, on average, 1.7°C. Full data are available in **Table S3**, Supplementary material.

It is also interesting to note that the central apartment on the first floor, without natural cross ventilation, is the one with the worst heat conditions, with the greatest temperature differences. The occupants confirmed that they have kept the windows closed during the night and early morning, preventing fresh air from entering to refresh the interior environment, due to an allergy problem among the inhabitants [39]. In contrast, the occupants of the NW apartment on the ground floor followed certain use habits that guaranteed the success of the bioclimatic design strategies implemented (opening curtains to maximize direct solar gain, rational use of the gas heater, opening windows to ventilate during adequate times). These different behaviors impact the indoor environment, as discussed in Filippín et al. [39].

Figure 13 shows the results for the average maximum and minimum temperatures of the period. As expected, the difference between the maximum interior and exterior temperatures increases noticeably when the trees are grown, because the interior temperature peaks decrease by shading the glass areas. Thus, in 2001 the maximum temperature inside was just 0.8°C lower than the maximum outside temperature, while in 2007 this value was 3.2°C. In the case of the minimum temperatures, although they are always above the outdoor average (9°C in 2001 and 7.5°C in 2007), it can be concluded that the presence of trees allows a slight improvement in the minimum indoor temperature. However, poor night ventilation is evident in all apartments, evidenced by the high differences between indoor and outdoor minimum temperatures.

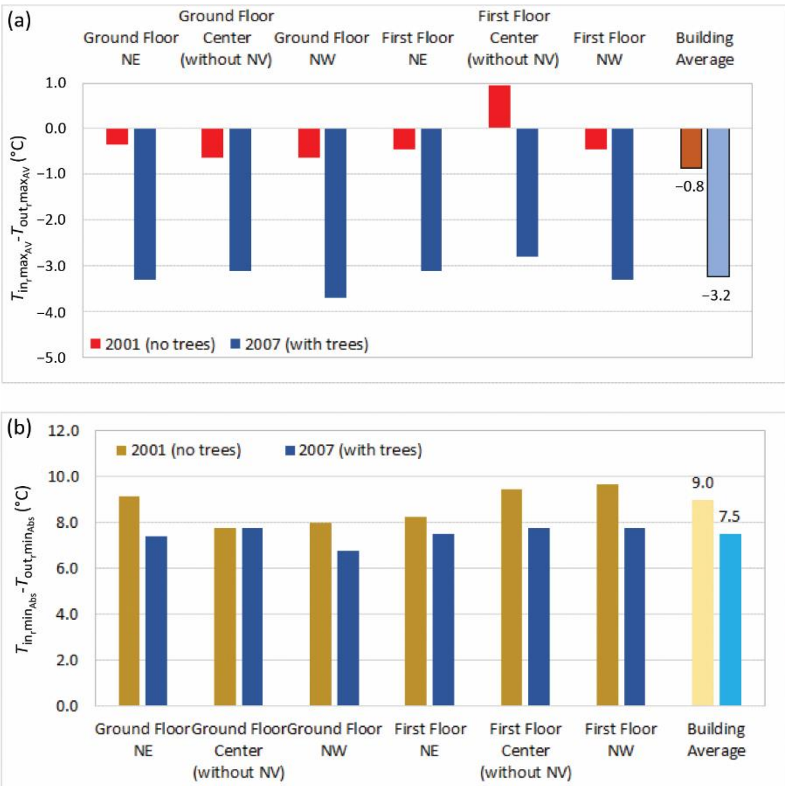


Figure 13 • Difference in the average maximum (a) and minimum (b) temperatures between the interior and exterior air of the six apartments, for the period December 1–21, for the years 2001 (without trees) and 2007 (with trees). In this case, trees noticeably increase the thermal difference in the maximum temperature (and decrease it in the minimum temperature) between the interior and exterior, which has a favorable impact on the interior environment.

Measurements show that temperature average values range from 23.8°C to 25.5°C in 2001 (see **Table S3,** Supplementary materials) and between 25.2°C and 25.7°C in 2007. These values fall within the comfort zone defined by the Argentinean IRAM Standard 11659-1, 2004 [67]. This Standard recommends temperature conditions between 22°C and 27°C and 40–60% relative humidity. However, the registered hourly temperatures in December 2001 and December 2007 ranged between 18.3 and 31.1, which falls outside the comfort zone and indicates poor thermal conditions of the indoor environment during the hottest days of summer. This situation was consistently found in other bioclimatic buildings in central Argentina.

A partly qualitative, partly quantitative summary would allow us to make some remarks. The growth of the trees was beneficial. Quantitatively, it caused a very marked decrease in the average maximum temperature (2.4°C compared to the situation without vegetation), a decrease in the average indoor temperature (1.7°C), and a decrease in the average minimum temperature (2.5°C).

3.2.5. A present-day approach through a survey during December 2023

The results of the surveys carried out in December 2023 to those residents living since 2017 or 2018 in the apartments are shown in **Figure 14**. In winter, 21.5% of students consider that the apartment is cold or very cold, and 78.5% of them consider that it is warm and very warm. It is likely that these subjective appreciations, which go beyond the apartment's location, are associated with the students' heater use habits (from "always in pilot" to "heater on 24 hours/day at medium level") and curtains opening and closing, among other aspects. In summer, 71.4% of students consider the apartment as warm and very warm, even though 75% of them open windows completely to cool the rooms. This perception is in line with the results we found from measurements and simulations evidencing summer overheating in the apartments. Another interesting fact to mention is that during summer the residents use fans. It is evident that in our case study, neither technology nor design could meet the diverse needs, habits, and customs of the 24 residents.

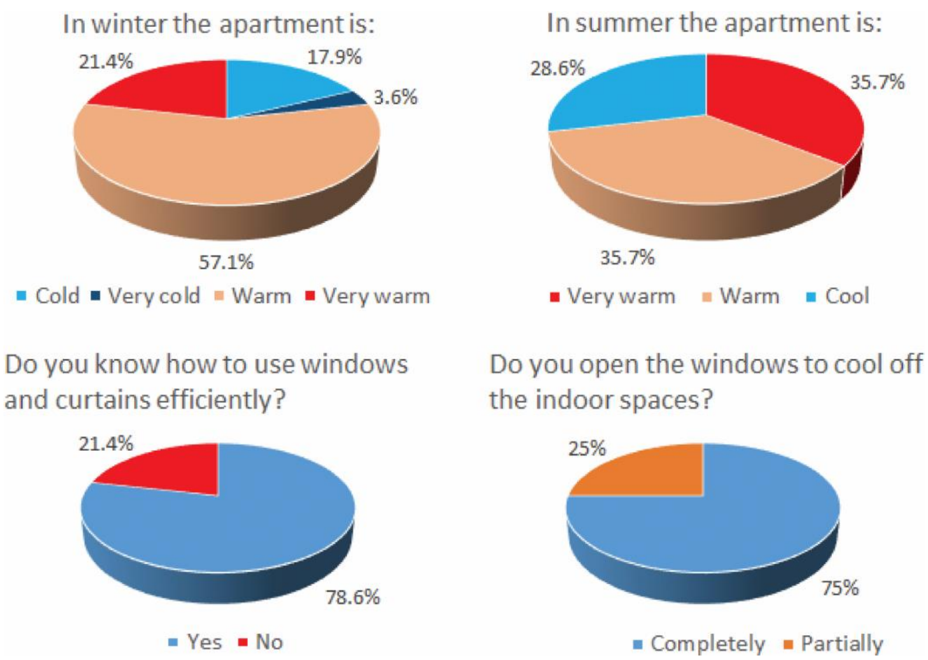


Figure 14 • Some results of the Students' Welfare Office of the National University of La Pampa, enquiries (December 2023).

4. Conclusions

Energy passivity and indoor ambient comfort in bioclimatic buildings, in particular when they are housed to human beings with different habits and customs, are complex aspects to meet within a context of limited economic resources available to construct a building. Despite this, in our case study and based on real measured and simulated data of 20 years, some important conclusions can be drawn about energy consumption, comfort, and health.

In relation to the energy consumption, *promising heating energy savings were obtained preserving at the same time indoor ambient comfort*. Over the entire period from 2001 to 2021, the average heating consumption was about 109 kWh/m²/year. In 2020, it was up to 24% higher due to the COVID pandemic (135 kWh/m²/year). The average heating consumption represents savings of 33% compared to other conventional apartment block buildings facing north in the same region, which is a promising value that evidences the benefits of the bioclimatic strategies. In a student residence characterized by high variability of users, we estimated an inter-annual coefficient of variation in the gas consumption between 20% and 32%. Furthermore, the difference in gas consumption among apartments could not be fully explained by design-dependent factors, but by the individual behavior of dwellers that differ in their habits of heating the indoor environment.

In relation to the comfort level and sleeping conditions, the monitored results obtained for winter confirmed that the building had a good performance, with a comfortable indoor environment temperatures between 18°C and 26°C. However, the results for the summer confirmed that *the passive design alone was not enough to ensure comfort and healthy conditions in summer*. Even the important shading of trees and vegetation, which reduced the average indoor temperature of the building by about 1.7°C and the contribution of fans and night ventilation, was not enough to obtain comfortable indoor temperatures. A deeper analysis of the comfort conditions measured during sleeping periods in summer showed that the average values of

PMV_{Sleep} on the night and nap periods were 0.7 and 1.1 (i.e., the environment is perceived as *slightly warm*), respectively. On average, the residents perceive as uncomfortable 80% of the hours during naps and 44% during nights, which can increase up to 80% during heat wave episodes. For the year 2013, considered the most extreme of the period due to the heat wave of December 2013, in the warm months December–March the comfort hours were only 12% (first floor) and 27% (ground floor) of the total hours. The sleeping conditions during this *These poor thermal conditions of the indoor environment during summer were consistently found in other bioclimatic buildings in central Argentina*. It is evident that in our case study, neither technology nor design could meet the diverse needs, habits, and customs of the 24 residents.

In relation to the temperature and health impact of the indoor environment, the results indicated that all apartments presented a number of overheating hours >10%, thus, not complying with CIBSE suggestions. Thus, *the building presented significant overheating in all its rooms, which will be in the future exacerbated by the gradual and constant increase in summer temperatures*. The analysis of the hourly HI values showed that, on average, the apartments were in non-safe conditions ("Caution" and "Extreme Caution" categories) about 20% of the time (1,750 hours) and up to 31% (2,710 hours) during hot weather and heatwaves. The worst situation occurred in the upper-floor apartments. The analysis of the indoor conditions during the 2013 heatwave (the most extreme of the period) evidenced alarming HI values that exceeded 33°C, an unacceptable situation for the occupants. Moreover, during 70% of the hours, the residents were exposed to indoor conditions that were potentially damaging to their health, which with prolonged exposure could cause possible sunstroke, muscle cramps, and/or heat exhaustion.

It also should be noted that the mentioned bioclimatic buildings were designed by considering the average climatic conditions of the last 20–30 years before starting their construction. In those years, buildings were designed according to the typical or average meteorological without accounting for the rapid increase of summer and winter temperatures in the last 20 years due to climate change. Today, computational power allows the simulation of a building considering the future climate. While it is not yet the usual practice among building professionals, it has been gaining importance in the last few years. In light of the present study of 20 years, it is evident that bioclimatic and energy efficiency design must, undoubtedly, be conducted considering the effect of climate change and the possible overheating in future years. Furthermore, nowadays, simulation tools allow building designers to evaluate an enormous number of possible designs, materials, and building management under present and future climate, through simulations and even using more sophisticated methods such as genetic algorithms and multi-objective optimization. It is crucial that they harness these powerful tools to design more energy-efficient and climate-resilient buildings.

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Author contributions

Conceptualization, C.F. and S.F.L.; methodology, C.F., S.F.L. and M.C.; software, S.F.L.; investigation, C.F., S.F.L. and M.C; data curation, C.F., and M.C.; writing—original draft preparation, C.F.; writing—review and editing, S.F.L. All authors have read and agreed to the published version of the manuscript.

Conflict of interest

The authors declare no conflict of interest.

Data availability statement

Data supporting these findings are available within the article, at https://doi.org/10.20935/AcadEnergy7304, or upon request.

Institutional review board statement

Informed consent statement

Not applicable.

Sample availability

The authors declare no physical samples were used in the study.

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