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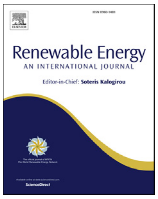

Retrospective analysis of the energy consumption of single-family dwellings in central Argentina. Retrofitting and adaptation to the climate change

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ABSTRACT

Two different analyses of the energy behavior of dwellings in Santa Rosa city (36°27′ S, 64° 27′ W, 182 m above sea level), in central Argentina, are presented. Firstly, a retrospective analysis of the operating energy -electricity and gas- of 10 compact housing in a period of 50 years is presented. Periods with missing data were fulfilled through predictive statistical models. Then, a "case study" was used to study different retrofitting strategies and to make a prospective analysis for future weather conditions calculated through the CMIP5-Coupled Model Intercomparison Project-Phase 5. The results indicate that the addition of thermal insulation in walls and roofs is highly beneficial, but the increase of glazed areas seems to be counterproductive. The energy demands for 2010 and 2039, for both the conventional and the retrofitted dwelling, show a decrease in winter and an increase in summer. We conclude that it is necessary to revise the dimensions suggested for the glazed areas, in order to deal with present and future indoor overheating. This paper presents the integration of past, present and future, towards a better comprehension of the challenges to be faced in the next decades.

1. Introduction

Evidence is nowadays overwhelming: local and global climate change presents serious global risks and demands an urgent universal and integral answer [74]. Global climate change - a serious threat to human beings- is, ironically, a threat created by human beings. One of the main factors influencing climate change is precisely greenhouse gas emissions (GGE), whose atmospheric concentrations at world level have increased since 1750. At world level the current predictions show that the CO_2 increasing tendency will continue. According to reports by the International Energy Agency, this increase is due mainly to globalization, the improvement of living conditions in emergent regions which promote the life styles of the developed countries, and the increasing tendency towards urbanization. At present, a quarter of the total CO_2 global emissions are related to energy use in buildings [49]. In particular, CO_2 emissions derived from fossil fuels combustion together with that produced by the manufacturing of Portland cement account for 75% of the atmospheric CO_2 increase since the 18th century [73]. In parallel, local climate change and in particular the urban heat island phenomenon is responsible for the serious increase of the urban ambient temperature [64]. Local and global climate change have a serious impact on human life because it increases both the energy consumption of buildings for cooling purposes and the concentration of harmful pollutants, and it deteriorates the outdoor thermal comfort conditions [66]. An urgent transition to a low-carbon economy in order to limit anthropogenic warming to less than 2 °C was is needed, which requires global net emissions of greenhouse gases to approach zero in the second half of this century. There are initiatives to achieve this target. In particular, the Deep Decarbonization Pathways Project [12] is a collaborative global research initiative of the Institute for Sustainable Development and International Relations (IDDRI) and the Sustainable Development Solutions Network (SDSN). DDP includes researchers of 16 countries (representing 76% of the current global CO_2

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emissions) that developed sector-by-sector blueprints of changes over time that can help making this transition. In particular, improvements in building sector are one of the strategies with high impact in CO_2 reductions.

The impact of climate change on building energy consumption has been already studied in the literature through different approaches. Huang and Gurney [35] classified the methods into three categories: observation-based regression/prediction, global/regional energy modeling, and individual building energy simulation. The first one uses historical relationship between energy consumption and climate variables to predict future energy consumption under a changing climate. As Huang and Gurney [35] explain, this method is based on historical data, so it is self-calibrated when fitted to a model, and the accuracy of the results rely on the quality of the selected regression model and its statistical evaluation. The second method, global/regional energy modeling, simulates energy consumption for multiple variables of different types (economy, technology, climate scenarios, population, energy policy, etc.). The third method -individual building energy simulation- simulates hourly thermal behavior of specific buildings, so it requires a very detailed data input of building characteristics and weather data. The mentioned methods were used by researchers all over the world in order to quantify the effect of the climate change on building energy consumption; only some studies are mentioned here. In US, Dirks et al. [13] studied by simulation 26.000 buildings and they found that the energy consumption by the end of the century is highly dependent on climate and building type, with increases of 12.75% (in Florida) or decreases down to −15.8% (in New York), for the annual energy consumption of residential dwellings, between years 2004 and 2089. In Germany, Olonscheck et al. [54] studied the residential building stock including the impact of building renovation, and the results indicated a decrease in heat demand of 44–78% for the studied period (2031–2060 compared to 1961–1990). Andric et al. [2] developed a dynamic model to estimate heat demand for large number of buildings that takes into account all significant building properties (geometry, thermal properties, occupancy profiles etc.). With this model the authors studied three buildings of different configurations (low rise and high rise, with and without shading) in Lisbon (Portugal) and they found that heat demand could decrease within the range of 22.3–52.4% in 2050 compared to 2010, depending on weather and renovation scenario studied. In Italy, Waddicor et al. [82] studied the effect of both ageing and climate change on the energy consumption of a specific building for A2 and B1 scenarios. They found a stronger impact of building ageing on the increase of the heating energy consumption that counteracts the reduction in the heating usage that occurs as a result of a warming climate. In the case of the cooling energy, the climate warming increased energy usage and at the same time there was an additional increase in energy consumption due to ageing. Finally, Huang and Gurney [35] quantified how the relationship between climate change and energy consumption varied with different buildings in 925 U.S. locations. They found large increases in energy consumption in summer and decreases in winter, with annual energy consumption changes ranging from −17% to +21%, at the spatial scale of climate-zones in US. They also conclude that the large variations found in the relationship between climate change and building energy consumption highlight the importance of assessing climate change impacts at local scales, and the need for adaptation/mitigation strategies tailored to different building types. The results suggest that heating demand in the future could decrease and cooling demand could increase, depending on the region, weather scenario, building type and building ageing.

In central Argentina the climate change has being noticed in the last years. The Second and Third National Communication of Climate Change [70] reports that, during the XX century, the precipitation levels in this region increased around 40% and the conditions of the summer noticeably extended to the autumn, which causes the differences between winter and summer to be reduced [5]. The predictions for 2020–2030 indicate that the average air temperature will increase around 0.7–1 °C (scenario A2 of IPCC, Intergovernmental Panel on Climate Change) and that the outdoor minimum temperatures in winter will grow around 2.7 °C. It is also expected an increase of the periods with extreme heat waves in summer. Thus, the local and global climate change will seriously affect the future energy consumption of buildings, as shown in several studies [3,65]. In central Argentina, previous work of the authors [21] showed that, nowadays, the application of bioclimatic strategies to buildings leads to good results in winter but also to some overheating in the hot periods. This situation, in combination with higher temperatures in summer due to the climate change, could drastically increase the energy needed for air cooling or, in case users don't use mechanical cooling, it could derive in a strong deterioration of the indoor thermal conditions.

The energy vulnerability of Argentina is a matter of concern (90% comes from fossil fuel) with a strong crisis nowadays due to the lack of energy. In the last years, there were restrictions to the electricity and natural gas consumption for industrial purposes so as to meet the demands of the more vulnerable areas in the residential sector [16,56,79]. The consumption of gas and electricity increases year after year: for instance, between 2001 and 2008 there was a 34% increase in consumption together with a 29% decrease of the natural resources [46]. Different factors can explain such a tendency: an increase in the amount of housing, greater comfort demands and also an increase in the electrical appliances installed in most households. In particular, there was a noticeable increase in the sale of cooling devices (growing from 220.00 units in 2003 to 1.072.000 units in 2013), a situation derived from the extreme weather conditions and the need of more comfortable indoor conditions [25,47,80].

Nowadays the energy consumption of the residential sector in different countries varies between 16% (Finland) and 50% (Saudi Arabia) of the energy consumed by all sectors with an average, at world level, of around 31% [60]. In Argentina, this value is of about 25%. According to figures from the National Energy Balance [51]; 55% of the electricity consumption comes from the residential, commercial and public sectors, that is, from the built environment. On the other hand, several studies proved that energy consumption in the Argentinean residential buildings is too high in comparison with other buildings located in similar climatic regions in Europe [26]. This is a consequence of both not compulsory legislation to save energy in buildings and also the poor knowledge of users and builders about the negative effects of low thermal efficiency in buildings. All these factors contribute to worsen the energy problem more and more. So, construction innovations are urgently needed, which may give way to a diversification in the use of materials, and also to professional and workers' training, among others. A thermally insulated dwelling which reduces maintenance costs constitutes a virtuous spiral which might allow for a moving demand and non-renewable energy resources saving [52,63,77,83].

In the last years, increasing interest in the study of buildings' energy use along their lives had been noticed. Energy used during the *operation* stage constitutes, according to the reports of many studies, the most important share of energy in most dwellings. There is a general agreement that the useful life period of a dwelling is 50 years, as suggested by Ref. [85]. Thus, over a 50-year time span, reducing the operating energy is normally more important than reducing the embodied energy [37]. Until recently, some decades ago, it was known that the operating energy involved 90–95% only considering the heating demand [67], but low energy buildings and net zero energy buildings are starting to change this trend. The reason is that in low energy buildings the operational energy is reduced but the embodied energy is increased due to the use of energy intensive materials both in the building envelope (e.g. insulation) and in the technical installations (e.g. PV system), as stated by Ref. [68]. In central Argentina, the operating energy involves the energy needed for air and water heating (mainly gas) and for air cooling, lighting and appliances (electricity).

In this context, the general objectives of our work were to analyze the operating energy (electricity and gas consumption) of a group of 10 compact dwellings in a temperate cold climate in central Argentina (Santa Rosa, La Pampa) for a period of 50 years of useful life, and to predict the effects of the climate change in their energy consumption, under different scenarios of retrofitting (without retrofitting, with added thermal insulation, and with added insulation + increase of glazed areas and solar control). A single dwelling was selected for the retrofitting analysis. It was monitored and the experimental data was used to validate a physical model of the dwelling. This model was then used to predict the impact of the different retrofit strategies in the energy consumption needed to achieve the indoor thermal comfort in the future. Thus, retrofitted and non-retrofitted dwellings were simulated exactly for the same climate data and time period. The climatic data used in this study were obtained from different sources: for the period 1960–2010 they were obtained from historical records from the national database 3CN [69]; for the period 2011–2014 they were obtained from records of National University of la Pampa; and for the year 2039 they were simulated with CMIP5-Coupled Model Intercomparison Project-Phase 5 for global climate model under a scenario of RCP4.5, which is available via the 3CN database previously mentioned. To achieve these objectives, we divided our study in the following two phases:

1. Study of the operating energy for 50 years of useful life of a sample of dwellings:
   - Description of the site and climate.
   - Selection of the dwellings to be studied and calculation of the main dimensional and energy indicators, which are defined in the Methodology section.
   - Analysis of the calculated operating energy in relation to real energy consumption data for the period under study.
   - Statistical analysis of energy consumption (natural gas and electricity), in order to find models to predict historical energy consumption.
   - Retrospective use of the statistical models to predict the energy consumed in the period without available data.
2. Energy consumption analysis of a single dwelling and potential impact on global change.
   - Energy retrofitting: analysis of the strategies of energy improvement in one single dwelling (‘case study’).
   - Calculation of the energy required for space heating for the conventional dwelling and for the retrofitted one, in order to save energy.
   - Assessment of potential impact and adaptation to climate change through thermal simulation.

2. Site and climate

The province of La Pampa is characterized by having a cold temperate climate, with great seasonal thermal amplitudes of around 12 °C in winter (July) and 14.4 °C in summer (January). This reflects its continental character that increases towards the West. A simplified macro environmental classification of La Pampa depending on its geomorphology, altitude, rainfall and phytogeographical aspects, divides the territory into two very distinct regions, namely the East and the West. According to records provided by the Ref. [76]; the sub-humid eastern region has the greater socio-cultural development and greater productive and economic potential. In this region is located the city of Santa Rosa (36°27′ S and 64° 27′ W, 182 m above sea level), capital of La Pampa. The Köppen-Geiger climate classification for Santa Rosa is in the transition between Cfa and Bsk [57], that is, temperate arid steppe climate. The climate is classified as by the Argentinean IRAM Norm (Instituto Argentino de Normalización y Certificación [39]) as warm temperate and daily thermal amplitudes higher than 14 °C. Table 1 shows the main climatic characteristics of Santa Rosa while Fig. 1 shows the psychrometric Givoni's chart –which allow detecting the proper passive cooling strategy for the selected month- in which the average hourly temperature and humidity for each month are included [27]. In winter (July), the mean temperature is 9.8 °C, with minimum of 3.5 °C (absolute minimum of −11.3 °C). In summer (December), the mean temperature is around 22.2 °C with mean maximum values of 29.4 °C. Temperatures in summer can reach maximum values higher than 40 °C. Its annual heating degree-days (Base Temperature = 22 °C) is 2343.

Santa Rosa has more than 100,000 inhabitants, showing in recent years a marked growth of new buildings construction, especially towers of multifamily housing with large glazed areas without sunscreens. Between 2005 and 2007 new construction developments increased around 24% (85% are apartment towers). According to the Agency of Statistics and Censuses [36], building refurbishment and enlargement grew about 42.8%. As stated above, this rate is similar to the value found in other urban centres of the country. From the energy point of view, an increase in energy consumption in the city (electricity and natural gas) has been recorded in the residential sector. According to the Electricity Company, the electricity consumed was mainly used in the domestic sector. The consumption-per-user rate increased 35% between 2002 and 2014, with an average annual electricity consumption of 2547 kWh per-user [10]. According to the Gas Distribution Company, the average annual natural gas consumption per-user is 1420 m^3 from which around 67% is used to heat buildings.

3. Methodology

3.1. Selection of the dwellings to be studied and energy indicators

In Santa Rosa, 82.7% of the houses are single-family dwellings and only 16.3% are multifamily blocks [36]. Thus, because single-family dwellings are the usual tipology in the city, our study was focused on this type of buildings. Moreover, we looked for dwellings in Santa Rosa city with available real consumption data, in order to study a period of 50 years of useful life, in accordance with [85]. Thus, the analysis was focused on the operating energy of dwellings along their useful life phase. We also looked for dwellings in good conditions placed in homogeneous areas in neighborhoods of low building density, with historical energy consumption not interrupted along the studied period. Data privacy was carefully protected by identifying each dwelling with an acronym. The state of conservation of the dwellings was determined by direct observation from the exterior side of the dwellings.

For the selected dwellings, the dimensional and energy indicators were calculated. They are two dimensional ones, that quantify the lower or higher connection of the indoor environment with outdoors, and a third one related to the heat losses:

- *Ic*: compactness index, defined by Ref. [48] as the relationship between the perimeter the building envelope would have in

Table 1
Climatic data of Santa Rosa, La Pampa (Argentina).

Annual values	Temperature	Mean maximum	°C	23.4
		Mean minimum		8.1
		Mean		15.5
	Relative humidity		%	68
	Mean solar radiation on horizontal surface[a]		MJ/m^2	16.3
July	Temperature	Mean minimum	°C	3.5
		Mean [1]		9.8
		Mean maximum		16.0
		Absolute minimum temperature		−11.3
	Thermal amplitude			12.0
	Comfort temperature			20.2
	Minimum design temperature ([1]- 4.5 °C according to IRAM Norm 11605, 2004)			−1
	Mean wind speed		Km/h	10
	Relative humidity		%	73
	Mean solar radiation on horizontal surface[a]		MJ/m^2	8.1
Heating degree-days (temperature base = 22 °C)				2343
January	Temperature	Absolute maximum temperature	°C	42.1
		Mean maximum		29.4
		Mean		22.2
		Mean minimum		15.0
	Thermal amplitude			14.4
	Comfort temperature			25.2
	Design temperature according to IRAM Norm 11605, 2004			34.0
	Mean wind speed		Km/h	12.5
	Relative humidity		%	61.6
	Mean solar radiation on horizontal surface[a]		MJ/m^2	23.4
Cooling degree-days (temperature base = 25 °C)				52.2

[a] Grossi Gallegos y Righini (2007).

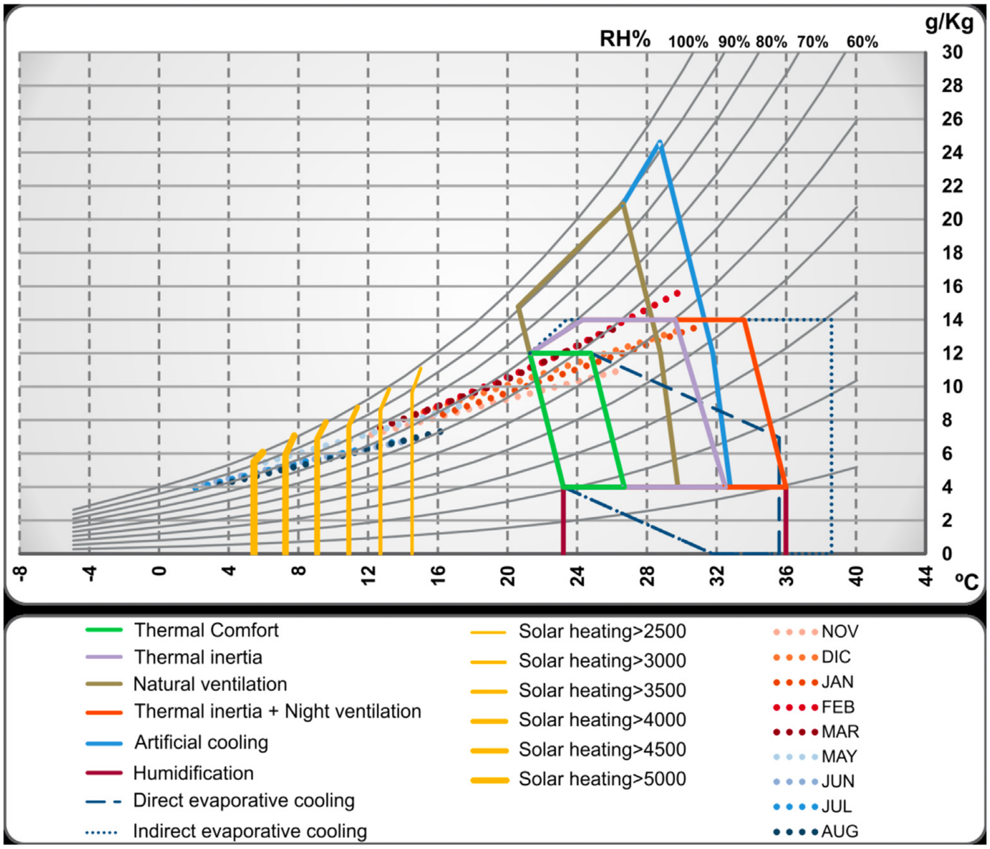

Fig. 1. Givoni's bioclimatic chart for Santa Rosa. Temperature and humidity monthly average values are shown together with the design strategies. The horizontal axis is the dry bulb temperature (°C), the vertical axis is the moisture content (g/kg of dry air). Chart developed with Gonzalo software (2003).

case the envelope was a circle and the real perimeter of the project envelope:

$$Ic = (\mathit{Perimeter\ of\ circle}/\mathit{Perimeter\ of\ project}) \times 100\% \tag{1}$$

- *FAEP*: exposure factor, defined as the envelope surface divided by the covered surface (Esteves & Gelardi, 2013). It is an indicator that can be used to optimize the form of the building considering simultaneously the buildings materials and the thermal efficiency.

$$FAEP = (ST + SM + Sve + Spu)/SCu \tag{2}$$

where ST: roofs surface (m^2); SM: walls surface (m^2); Sve: windows surface (m^2); Spu: doors surface (m^2); SCu: covered surface to be heated (m^2).

- *G-value*: Volumetric Heat Loss Coefficient (W/m^3-K): it is the energy lost by a heated space per unit of volume, per second and per degree of temperature difference between indoor and outdoor air, in steady state. It is calculated according to the Argentinean Norm of Instituto Argentino de Normalización y Certificación [40]:

$$G - value = \left(\sum KmSm + \sum KvSv + \sum \gamma KrSr + KpP\beta + \sum KrSr\right)\Big/ V + 0.35\ ach \tag*{3}$$

where *Km*: thermal transmittance of walls in contact with the exterior environment (W/m^2-K); *S*: surface area (m^2); *Kv*: thermal transmittance of glazing (W/m^2-K); *Kr*: Corrected thermal transmittance of envelope (opaque or transparent) in contact with non-heated spaces; γ=0.5 (if the envelope is in contact with heated spaces), γ=1 (other cases); *Kp*: thermal transmittance of floor (W/m^2-K); *P*: perimeter of the floor (m); $\beta = 1$ (m); *V*: volume of the heated spaces (m^3); *ach*: air changes per hour (1/h).

3.1.1. Heating degree days and cooling degree days

The heating and cooling energy requirement of a building is related to the Heating Degree Days (HDD) and the Cooling Degree Days (CDD). HDD is defined as the sum of temperature differences between a design base temperature and the average daily temperature for the days when the daily average is less than the base temperature within the period [38]:

$$HDD = \sum_{i=1}^{N} T_{b,heating} - \frac{(T_{\max} + T_{\min})}{2} \tag{4}$$

where T_{max} and T_{min} are the daily maximum and minimum temperatures, *N* is the number of days of the selected month, and $T_{b,heating}$ is the base design temperature for heating. The most appropriate base design temperature for any particular building depends on the temperature that the building is heated to. However, for historical reasons HDD are often made available with base temperatures of 16 °C or 18 °C, which are the base temperatures that are approximately appropriate for a good proportion of buildings. The Argentinean [38] uses three base temperatures: 18, 20 and 22 °C. In this article we selected 22 °C as base design temperature for heating because this value describes the best comfort level included in the Norm.

On summer periods, CDD is used, which is defined as:

$$CDD = \sum_{i=1}^{N} \frac{\left(T_{\max} - T_{b,cooling}\right)}{2} \tag{5}$$

where T_{max} is the daily maximum temperature, *N* is the number of days of the selected month, and $T_{b,cooling}$ is the base design temperature for cooling. The Argentinean Norm [42] establishes values of the indoor design temperatures depending on the mean exterior air temperature. In accordance with this Norm, for the climate conditions of Santa Rosa the indoor design temperature is 25 °C, so we selected this value as the base design temperature for summer in the calculation of CDD.

3.1.2. Estimation of the annual consumption of natural gas for space heating

Also we estimated the annual consumption of natural gas for space heating by using two methods, one is based on the [40] and the other is based on the gas bills. The first method uses the *G-value* (that is, the global heat losses) and HDD to calculate the energy Q (kWh) that the heating system must supply to the indoor air:

$$Q_{\text{supply}} = 24\, G - value\ V\ HDD/1000 \tag{6}$$

where *V* is the volume of the heated spaces (m^3). The gas heaters commonly used in Argentina have an average efficiency of around 60%, as measured by Ref. [43]; that must be considered in the calculation of the gas consumption.

The second method uses the gas bills and the information provided by the Gas Distribution Company who suggests that, in average for La Pampa, around 67% of the total gas consumed by the dwelling is destined to space heating. This 67% is an average value that depends on the weather of the studied region (for example, in the North of Argentina, the percentage of gas consumption destined for heating much lower, because the climate is warmer). Thus, the gas bills are summed over a period of 1 year and then the gas consumption for gas heating is 67% of this annual consumption.

3.2. Statistical analysis of the energy consumption of the selected dwellings

3.2.1. Statistical analysis

The total operating energy, the gas consumption and the energy consumption were averaged for all dwellings in the period 1961–2011. For each averaged value, we calculated the *coefficient of variation* (CV), also known as relative standard deviation, which is defined as the ratio of the standard deviation SD (that is, the square root of the variance) to the mean. It is a standardized measure of dispersion of a probability distribution or frequency distribution and it is expressed as a percentage. In practice, CV can take any value higher than 0. However, as pointed out by Ref. [72]; values higher than 100% make evident an extremely high dispersion of data and the need of detecting the sources of this variability, usually errors in the data acquisition or post-processing. In energy consumption of a sample of houses, high CV values are usually found [50] because there is high dispersion in the data due to the morphological differences between dwellings (geometry, shape, orientation, materials, etc.) and due different to behavioral patterns between owners (related to user' preferences and attitudes).

To understand natural gas and electricity consumption behavior along the historical period with available data, we determined the equations which could describe the evolution of such variables for each of the studied dwellings. The data of gas and electricity consumption were obtained from the Gas Distribution Company and from the Popular Electric Cooperative –CPE-, respectively. The gas and electricity consumption values constituted the dependent variables whereas 'time' constituted the explanatory variable. The periods with available data of natural gas and electricity consumption went from 1996 to 2011 and 2000–2011, respectively. The fitting between variables was carried out through a wide variety of curvilinear models available in the statistical software STATGRAPHICS 5.0. Because the consumption pattern of each dwelling relies on its own dimensional and energy indicators and on the user behavior (user-dependency), the use of different fitting models allowed us to describe the behavior of gas and electricity consumption along time. For each dwelling and variable we selected the model with the best fitting curve, that is, with the highest *coefficient of determination* R^2 (defined as the proportion of the total variation in the dependent variable Y that is predictable from the independent variable X) and the *correlation coefficient r* (a measure of the strength and direction of the linear relationship between two variables that is defined as the covariance of the variables divided by the product of their standard deviations). In this way we could prove the *goodness of fit* of the different selected models with respect to data. The *statistical significance or explanatory power of models* was tested with the Variance Analysis (ANOVA), the result of which was subjected to the statistical Fisher F-test. This F-test is used when comparing statistical models that have been fitted to a data set, in order to identify the model that best fits the population from which the data were sampled. The P-value is the probability of obtaining at least as extreme results given that the null hypothesis is true whereas the significance level α is the probability of rejecting the null hypothesis given that it is true. When the P-value associated with the statistical F was lower than the level of significance ($\alpha = 0.05$), the null hypothesis (H_0) was rejected stating that time was a good predictor of the variables related to energy consumption in each dwelling. For this reason, it was possible to use these explanatory models to predict energy consumption for the period without data -between 1961-1996 or 2000- in accordance with the source, and to complete the 50 years of the life cycle suggested by Ref. [85].

3.3. Case study: improving the energy behavior of one monitored dwelling for the present and future climate through simulation

3.3.1. Energy consumption and thermal monitoring of the selected dwelling

For a deeper study, we selected one of the dwellings with the aim of studying if it is possible to improve its energy performance in order to save energy in the coming years and also, to diminish the impact of global change without giving up comfort. For this dwelling, we have real, uninterrupted, bimonthly data of the gas consumption (m^3) and monthly electricity consumption (kWh) since 1989. Before 1989, the dwelling was not connected to the gas network and it used bottled gas for which no data is available. Thus, we needed to estimate the gas consumption in the period previous to 1989. The simplest relation between two variables is the linear one, so we estimated the natural gas consumption through the "least squares" method, between the natural gas consumption annual rates (dependent variable) and time (independent variable), along the period with access to the gas network (1989–2009). The fit goodness was assessed through the determination coefficient R^2 (% of the Y variation which explains the model) and the model's statistical significance from the ANOVA, the result of which is subjected to the Fisher F test with a 95% confidence interval. Once the regression straight line was calculated and the strength, direction and statistical significance of the model tested, the $\hat{Y}$ values were estimated in accordance with the unitary change in the X values. Thus, using this equation, the straight line values were calculated corresponding to the first period without access to the gas network (1976–1988), replacing the independent term for the years in the historical series analyzed and completing the new series of the dwelling's natural gas consumption. The $Q_{(heating)}$ auxiliary value was calculated both for the conventional dwelling as well as for the energy intervened one between 1976 and 2011, according to degree days ($T_{base} = 22\ ^{\circ}C$), to G-value global loss coefficient, and considering gas heaters' efficiency of 60%.

This dwelling was extensively monitored during a winter period (August 6th-18th, 2010) and a summer period (February 1st–23th, 2011). Data loggers HOBO U8 and U12 (001 and 011) for air temperature and humidity measurements were placed in the functional areas of the studied housing. Outdoor conditions were recorded by a wireless weather station HOBO. All variables were registered at time steps of 15 min. Monitoring was complemented with an unstructured interview that intends to reveal the owners habits in order to understand her interactions with the built environment. The experimental data were used to validate the thermophysical model of the dwelling by using SIMEDIF, a simulation tool for transient thermal calculation of buildings described in the next sections.

3.3.2. Weather data sources

Due to the retrospective and prospective approach of the problem, which encompassed a period of 80 years, it was necessary to resort to secondary sources in order to obtain climate data about the area selected for this study. So, we looked for information in the 3CN National Climate Database [69], provided by the Secretariat of Environment and Sustainable Development of the Nation. This is the widest data reservoir for Argentina for past, present and future climate. It includes observed grid data and simulated data from several climate models. The database allows to generate data files (in GIS, metadata or text formats) by selecting the site via a grid point, the period to be studied (1960–2010, 2015–2039, 2075–2099), the variables of interest (maximum, mean, and minimum temperatures, precipitation and climatic indices), and the frequency (daily, monthly, annual). In this article, we generated monthly temperature records for Santa Rosa city (La Pampa) in the periods 1960–2010 and 2015–2039 via this reservoir. For the first period, 1960–2010, the data were generated from historical measured data with the methodology developed by the Climate Research Unit, College of Environmental Sciences, University of East Anglia, United Kingdom (CRU TS 3.20 data, [32]). For the second period, 2015–2039, the data were generated by simulation from the CMIP5 (Coupled Model Intercomparison Project-Phase 5) global climate model. The scenario discussed in this study derived from global climate simulations of CMIP5 (Coupled Model Intercomparison Project) Phase 5 (2015–2039). CMIP5 is the standard experimental protocol for studying the output of coupled atmosphere-ocean general circulation models, as established by the Working Group on Coupled Modeling (WGCM) under the World Climate Research Programme [84]. This model describes two scenarios of Representative Concentration Pathways, RCP4.5 and RCP8.5. as adopted by the IPCC in its Fifth Assessment Report (AR4) (2014).The purpose of these experiments is to address outstanding scientific questions that arose as part of the IPCC AR4 assessment process, improve understanding of climate, and to provide estimates of future climate change that will be useful to those considering its possible consequences. The projection simulations used in this study were under a scenario of RCP4.5 (MRI-CGCM3_rcp45_FC_MM, [78]) forced with specified concentrations consistent with a medium emissions mitigation scenario. Finally, to complete the missing data period (2011–2014) which is not covered by 3CN reservoir, we resorted to records of temperature monthly measurements carried out by the College of Agricultural Engineering, National University of la Pampa [81].

For two scenarios of Representative Concentration Pathways, RCP4.5 and RCP8.5, as adopted by the [37].

3.3.3. *Dwelling thermal simulation*

The hourly thermal behavior of the dwelling was simulated with SIMEDIF for Windows [71]. This software is free and it was developed in Argentina at INENCO (Non-Conventional Energy Research Institute), as a detailed tool for passive building design and for the simulation of transient thermal behavior of multi-room buildings. The first SIMEDIF version was developed in 1984 [7] and it has been largely validated throughout years of experimental work in Argentina [1,4,8,15,33,34,58]. SIMEDIF calculates, at hourly time steps, the air temperature inside the spaces of a building, the surface temperature of walls, and the auxiliary heating/cooling energy that is needed to maintain the spaces at a constant setpoint temperature. These outputs of the software are available in ".txt" format for data post-processing.

The thermal model of the building consists of dividing the building spaces into "thermal zones" (building spaces that can be considered isothermal) that are represented by an air node. The thermal zones are connected to each other and with the outdoor environment by elements that have any of the following thermal characteristics: storage and heat transfer by conduction (such as brick walls, adobe walls, concrete walls, etc., which are called *massive walls*), storage into a uniform temperature mass (such as *water walls* where the water is supposed to convect and to have uniform temperature), heat transfer by conduction without storage (such as wood panels, expanded polystyrene, etc., which are called *partitions*), heat transfer by conduction with two heat transfer coefficients (day and night, such as windows with night insulation), and heat transfer by air movement (such as openings in the walls, doors, and vents). The physical model of a building in SIMEDIF has been developed under the following assumptions [22]:

- The heat fluxes through the walls are considered unidirectional. Walls can be made of layers of different materials (characterized by their conductivity, density, specific heat and thickness).
- The heat transfer between the surfaces of the elements and the indoor/outdoor air is described by global convective-radiative heat transfer coefficients. They account for both convection and radiation and they are constants (radiation is therefore linearized).
- No view factors are taken into account in the computation of radiant energy exchange between surfaces.
- Solar incident radiation on any wall is uniformly spread over the entire wall surface. The building surfaces are described by a solar absorption coefficient and its orientation (slope and azimuth).
- Mass balances are not considered (humidity is not calculated).
- Air infiltration and ventilation are described by the air renewals of each thermal zone (constant values).
- Interior heat gains by metabolic load, heaters, and electric appliances, are entered hour-by-hour in each thermal zone.
- A set of nodes is established automatically for each building element ("surface nodes" on building surfaces, "massive nodes" for the interior slices in walls, and "air nodes" in each thermal zone). An energy balance at each node is made and the finite-difference explicit method is used in the massive nodes to obtain a set of equations that is solved by the numerical code.

The air temperature of a thermal zone at the next time $t + \Delta t$ is computed from the global heat balance equation valued in the previous instant t. In this balance equation, the air renewals in the room, inner heat gains, and heat transfer due to the different elements connecting the room with other zones in the building and with outdoors, are considered. A detailed expression for this balance equation can be found in Ref. [22].

The calibration of the model takes into account the most sensitive parameters, as seen by the authors in Ref. [23]; where the measured and simulated data sets agree with a mean deviation between 0.5 °C and 1 °C, and in Ref. [18]; which has a mean deviation between 0.5 and 0.8 °C. SIMEDIF also predicts, accurately, the thermal amplitudes inside the building and the effect of the heating system. Flores Larsen et al. [24] calculated the hourly temperature of wall surfaces with SIMEDIF by entering the hourly measured meteorological data and they found a very good agreement between the calculations and the experimental data.

4. Selection of the dwellings to be studied

A group of 10 compact single dwellings was selected, built in the 1950s-60s and even until the 1970s. The availability of natural gas real consumption data between 1996 and 2011 and electricity consumption between 2000 and 2011 allowed us to make a methodological decision: to carry out a retrospective analysis considering 2011 as the endpoint of the period of use. The year 1961 corresponds to the beginning of the operating energy estimate for the year 1960, the moment of construction. It should be noted that none of the dwellings (as stated by the Land Register Office) in this study was built after the study period.

The selected dwellings (study units) are located in low-construction density neighborhoods where single family one-story dwellings, between party walls, prevail. They generally have a prismatic morphology, they are massive and lack envelope thermal insulation. Although the dwellings look similar, they can differ in their energy consumption. In practice, energy use in buildings has been found to vary quite widely even between buildings of similar type [9], depending on geometry, orientation, modes of use, control and maintenance of services, air tightness, etc. Occupant behavior - even the purely stochastic energy uses- can have a very significant influence in the results [55]. The dwellings were named as VA_1, VA_2, VA_3, VA_4, VA_9, VA_{11}, VA_{15}, VA_{20}, VA_{21} and VB_1. Two dwellings of this group, VA_1 and VB_1, were described in detail and had been monitored in previous works [19,20]. The studied dwellings are massive and their functional areas are aligned with north-south and/or east-west orientations, allowing for adequate night cross-ventilation, which agrees with the design recommendations suggested by Givoni's bioclimatic chart.

The energy indicators in Table 2 include the *G-value*, the estimated annual consumption of natural gas for heating based on the heat losses of the dwelling (*G-value*), and the real annual consumption of natural gas from gas bills (total and only for space heating), according to the gas company records, as explained in the Methodology section. Table 2 shows that the estimated (according to *G-value*) and real annual consumption of gas are in good agreement. Finally, in order to check if the IRAM Norm requirements are met, a minimum value of degree days is stated (calculated for a base temperature of 20 °C). According to the estimates carried out with the technical documents available, what the Norm states is never reached which indicates a poor energy performance of the dwellings.

4.1. *The 'case study' dwelling*

The 'case study' dwelling (VA1 from Table 2) (Fig. 2) is a one-story building without envelope's thermal insulation. The only occupant of this house is a retired woman who remains more hours at home than a usual worker. She lives alone during the week, while in sporadic weekends she receives two granddaughters that sleep in one of the bedrooms. During weekdays, this room serves as a

Table 2
Dimensional and energy indicators.

Sample of the studied houses		Perimeter (m)	Useful area (m^2)	Volume (m^3)	Envelope area (m^2)			Ic (%)	FAEP	G-value (W/ m^3-k)[a]	Annual auxiliary heating (Q)[b]					
											Estimated according to G-value			Measured average annual natural gas consumption during the period 1996-2011		
Identification	State of conservation										kWh/ year	Annual natural gas		m^3 [1]	Heating: 67% of [1]	
					Wall	Roof	Window					m^3	kWh/ m^2		m^3	kWh/ m^2
VA_1	Very good	30.9	39.1	141	70.6	43.2	13.7	70	3.3	2.51	12219.3	1251	312.5	1793.0	1201.3	299.3
VA_2	Good	36.0	61.7	108.0	89	69	5.2	82	2.6	4.3	12959.0	1327	210.0	2045.7	1370.6	216.4
VA_3	Very good	32.45	50.0	140	58.0	50.0	7.2	77	2.3	3.00	14501.2	1485.0	290.0	2218.2	1486.0	289.6
VA_4	Very good	43.4	91.7	229	83.6	91.7	18	78	2.1	2.69	11962.0	1225.0	130.5	1717.4	1151.0	122.3
VA_9	Very good	42.0	86.4	234.0	89.4	86.4	20.6	0.78	2.20	2.98	6464.0	926.0	74.8	1307.0	876.0	98.8
VA_{11}	Not very good	55.4	90.0	267.0	147.0	15.8	103.0	0.61	2.95	3.70	17095.0	1910.0	190.0	2828.8	1895.3	205.2
VA_{15}	Very good	40.7	84.8	220.5	78.2	84.8	29.35	0.80	2.30	2.87	16425.9	1835.3	193.7	2488.4	1667.2	191.0
VA_{20}	Very good	50.0	93.0	257.0	54.5	93.0	23.0	0.68	2.10	2.75	12230.0	1366.5	131.5	2028.6	1359.0	142.4
VA_{21}	Very good	54.6	75.5	226.5	153.0	24.5	75.5	0.56	3.35	3.50	12534.6	1283.3	166.0	1995.2	1336.8	172.5
VB_1	Very good	40.8	80.0	190.0	54.2	80.0	16.2	0.70	1.90	3.05	8400.0	922	105.0	1392.2	933.0	113.6

[a] G-value (Volumetric Loss Coefficient): the total heat loss of a house (through the fabric and ventilation), divided by the heated volume.

[b] Q: Annual auxiliary heating, the conventional (i.e. non-solar) contribution to the total load.

gym from 10 a.m. to 12 a.m. A 5000 kcal gas heater in the living room runs at maximum output during 6 h and at minimum output during 18 h. A 3000 kcal gas heater in the hall runs at maximum output during 6 h, at minimum output during 4 h and at pilot condition during 14 h.

The outer walls are made of ordinary 0.30 m brick with a thermal transmittance (K) of 1.88 W/m^2 K. The resistant structure of the roof consists of forged pre-stressed beams, ceramic blocks and concrete compression layer with a roof of slate fixed with mortar (K = 1.00 W/m^2 K). According to the categories per type of building established by *New Method 5000* [28], this dwelling shows high inertia with a value higher than 400 kg/m^2. Windows are made of aluminum, with roller shutters without insulation and single glazing. For this dwelling, the exposure factor is 73%, the compactness index is 70%, and the G-value is 2.51 W/m^3-K.

IRAM Norm 11605 [41] recommends maximum K values for walls and roofs during winter and summer and for the different bio-environmental zones in the country; values which correspond to two levels of thermal comfort (A and B). In the case study, the wall K- value does not reach the less demanding level (level B, K = 0.80 W/m^2 K). The roof thermal transmittance (1.62 W/m^2 K) is higher than the one recommended for summer by the same Norm (K between 0.19 and 0.48, levels A and B, respectively).

5. Results

5.1. Statistical analysis of operating energy: retrospective analysis

Table 3 shows the results of the best regression models selected between natural gas total annual consumption and that of electricity together with the historical period of measurement. 75% of the obtained models show statistical significance ($P\text{-value} < 0.05$). In two cases (VA_1 y VB_1) the results of the analysis show a relation between variables which is explanatory and not predictive (P-value

1: living room
2 - 3: bedroom
4: dining room – kitchen
5: multiporpose -room

Fig. 2. Particular “study case”.

Table 3
Best fitting models of natural gas and power consumption.

Sample of the studied houses	Natural gas consumption (Period: 1996–2011)			Power consumption (Period: 2000–2011)		
	Model	r	P-value	Model	r	P-value
VA_1 (period: 1976-2011)	$y = -54037.7 + 27.9364 \times x$	0.62	0.0080	$y = -53024.5 + 110534000/x$	0.45	0.1600
VA_2	$y = -172429.0 + 87.0544 \times x$	0.73	0.0004	$y = -161235.0 + 81.5871 \times x$	0.82	0.0023
VA_3	$y = \exp(57.2164-99220.0/x)$	−0.73	0.0014	$y = -26789.3 + 13.8667 \times x$	0.71	0.0241
VA_4	$y = -39224.7 + 20.4353 \times x$	0.61	0.0186	$y = -3727.87 + 1.2966300/x$	0.12	0.7200
VA_9	$y = 74390.5-36.4779 \times x$	−0.93	0.0000	$y = 1/(0.00369219-0.00000156581) \times x$	−0.26	0.4100
VA_{11}	$y = -38496.7 + 19.7235 \times x$	0.55	0.0256	$y = 1/(0.0530522-0.0000262624) \times x$	−0.91	0.0000
VA_{15}	$y = -59363.4 + 1.22654000/x$	0.54	0.0291	$y = \exp(-96.7907 + 0.0521516 \times x$	0.91	0.0000
VA_{20}	$y = \exp(46.3733-77465.0/x)$	−0.63	0.0086	$y = -81985.5 + 41.8909 \times x$	0.91	0.0000
VA_{21}	$y = -60258.8 + 31.0147 \times x$	−0.57	0.0242	$y = (2861.85-1.40492 \times x)\hat{} 2$	−0.83	0.0000
VB_1	$y = 1/(-0.00450251 + 10.4774/x)$	0.14	0.6200	$y = -74522.2 + 15179400/x$	0.52	0.1000

References: y (energy consumption); x (time); *r* (correlation coefficient); P-value (significance level).

$\geq$0.05, which shows that there is no significant statistic relationship for a level of confidence of 95% or higher). Despite these results, the correlation coefficients obtained in both cases were around 0.5, reflecting a relationship ascending between the variables. Even in these cases, we considered them due to the fact that the dwellings had been monitored during winter and summer. Thus, it can be concluded that the equations in Table 3 can be used to estimate the energy consumption of each dwelling since 1961.

Table 4 shows, for each dwelling and in average, the total operating energy (that is, the summation over 50 years) and the average annual operating energy, in the period 1961–2011. The total operating energy consumed during the 50-years period, averaged for all dwellings, is 2175738.0 MJ (CV = 22.6%). Electricity and gas consumptions are around 12% and 88%, respectively, of the total energy consumption (CV = 45% for electricity and CV = 13% for gas). These values ratify the higher relative share of natural gas consumption in the total operating energy consumed by the cluster of dwellings. The average annual operating energy (MJ/year-dwelling) in the period 1961–2011 is 65547.5, with a relative share of 58%, 30% and 12% destined to space heating, water heating and cooking, and lighting and electrical appliances, respectively. The relative share of natural gas consumed for heating is also high.

The high values of CV obtained for the group of dwellings confirm the results of other authors for samples, even bigger, due to the role of the occupants in the energy consumption. For example, Gram-Hanssen et al. [31] studied the electricity consumption from over 50,000 Danish homes in the same city (categorized by dwelling-type in detached, semi-detached, and apartment), and they found "huge standard deviations", with each category having CV values of 48–50%. Similarly, Guerra Santin et al. [29] have found large CVs of around 40–53% in energy demand for space and water heating in 15.000 Dutch homes. It is necessary to carry out an in-depth study of a particular case with available data, including use habits, in order to assess the intervention potential to save energy in the future and also, to mitigate the impact of the climatic change predicted for the site without compromising the thermal comfort of the inhabitants. Improving the envelope's thermal resistance might reduce, to a large extent, operating energy consumption, while meeting the indoor comfort requirements.

5.2. Energy retrofitting: a case study to reduce energy consumption

5.2.1. Monitoring and simulation results

For the simulation of the hourly temperature with SIMEDIF, the dwelling was divided into four thermal zones ("Living room & Kitchen", "North bedroom", "South bedroom", and "Multi-purpose room"). The weather data was obtained from measured data in the site (solar radiation on horizontal surface, air temperature and wind velocity). The geometric data -air volume for each zone, wall surfaces, etc.- were obtained from the architectural plans of the dwelling. Material properties (conductivity, density, specific heat at constant pressure) were obtained from tables of the available literature in heat transfer. Convective-radiative heat transfer coefficient *h* (W/m^2-K) was estimated through the dimensional

Table 4
Operating energy in the sample of the studied houses.

Dwelling	Total operating energy during the period 1961–2011 (MJ)		Average annual operating energy (MJ) between 1961 and 2011 and relative participation (%) of different end-uses			
	Total (MJ)	MJ/m^2	Total (natural gas and electricity, MJ)	Heating energy consumption (%)	Water heating and cooking (%)	Lighting and electrical appliances (%)
VA1	2236987.6	57212.0	67111.5	58.3	28.7	12.9
VA2	1628773.0	26398.3	53195.8	60.4	29.2	10.4
VA3	2855890.6	57117.8	74926.0	58.2	36.8	5.0
VA4	2076696.2	22646.6	67293.3	54.7	30.7	14.6
VA9	1996266.2	21769.5	57815.7	64.9	23.8	11.2
VA11	1181428.1	12883.6	42934.1	47.1	28.1	24.8
VA15	2546043.2	27764.9	78560.0	62.9	25.3	11.8
VA20	2364086.3	25780.7	80043.0	57.0	33.7	9.3
VA21	2245870.5	24491.5	68047.9	56.4	33.3	10.2
VB1	2625338.0	28629.6	51252.0	61.6	30.6	7.8
Average	**2175738.0**	**23726.7**	**64117.9**	**58.0**	**30.0**	**12.0**
SD	**491693.4**	**5362.0**	**12413.2**	**5.0**	**3.9**	**5.3**
CV (%)	**22.6**	**22.6**	**19.4**	**8.6**	**13.1**	**44.8**

References: SD (Standard deviation); CV (coefficient of variation).

equation [14]:

$$h = 5.7 + 3.8\,v \tag{7}$$

where v is the wind speed in m/s. A heat transfer coefficient of 12 W/m^2 K was imposed on the external surfaces. On internal surfaces, convective-radiative heat transfer coefficients of 8 W/m^2 K and 6 W/m^2 K (for surfaces with and without solar gain respectively) were imposed. These values are found to give accurate adjustments of monitored data, based on the authors' own experience on building thermal simulation.

Natural ventilation was accounted for through a special element in SIMEDIF named “Openings” which allow the air exchange between zones when they are open. In fact, because the simulated period is in winter, natural ventilation is not used by the owner except in some very special days with higher outdoor temperatures and only during very short periods of time. In “Openings”, the heat transfer depends on the opening geometry (height and width), the temperature difference between zones, and a discharge coefficient that accounts for the geometry of the lateral surfaces of the opening. The air renewals of each zone are in fact the unknown values, so they are used as the variables for the adjustment between the simulated and monitored data sets. The on/off periods of the heaters were obtained from the detailed survey to the owner and they were included in the simulation through the internal heat gains.

The simulated and monitored data for the three thermal zones are presented in Fig. 3. A good agreement between them was found. The simulated values and the real ones were statistically analyzed for each functional area. Simulated values for the living room and kitchen (taken together as a thermal zone) agree with measured values with an R^2 of 0.96. For the South and North bedrooms R^2 is around 0.93 and 0.90, respectively, while for the Multi-purpose room R^2 is around 0.95. In all cases, the P-value was 0.0, indicating that there is a significant relationship between simulated and measured values for a confidence level of 99%. The obtained values of R^2 ($\geq$0.9) and the analysis of the P-values (<0.01) allow us to conclude that the physical model of the building predicts the real values with sufficient accuracy. This model is used to assess the potential impact of climate change, estimate energy consumption and review design strategies in the region under study.

5.2.2. Retrofitting of the “case study” dwelling: strategies for energy improvement

The buildings' envelope integrates opaque and transparent, fixed and mobile areas. The transparent areas allow the income of solar radiation to heat spaces. To evaluate the intervention potential with the aim of reducing the energy demand, two possible strategies are considered: direct solar gain and energy conservation. The first one is through direct solar gains, and the second one by incorporating thermal insulating material to the envelope so as to increase its thermal resistance. The energy-efficient dwellings built in the region under study show a direct solar gain area to the north of around 16% of the total useful area. In the case under study, the actual value is 9%. Thus, the strategy of direct solar gain included the increase of the direct solar gain area to around 16%. The strategy of energy conservation is technologically feasible and it would allow achieving thermal transmittance values in accordance with the relevant IRAM Norm recommendations. For this particular case, we only considered the thermal improvement of the opaque vertical envelope that would allow intervening from the outer side of the wall without disrupting the inhabitants' activities. In winter, the Norm ([41]; 2004) recommends a U-value for walls of 0.30 and 0.80 W/m^2 K, levels A and B, respectively, according to an outside design temperature of -6 °C. An intermediate level is adopted for this study (0.55 W/m^2 K) in agreement with the researchers of the LAyHS (Laboratory of Sustainable Environment and Habitat of the Faculty of Architecture of the National University of La Plata, Argentina) who suggest using this intermediate value [11,61,62]. Thus, a U-value of 0.55 W/m^2 K can be obtained with the addition of a 0.05 m thick layer of extruded polystyrene to the exterior facing.

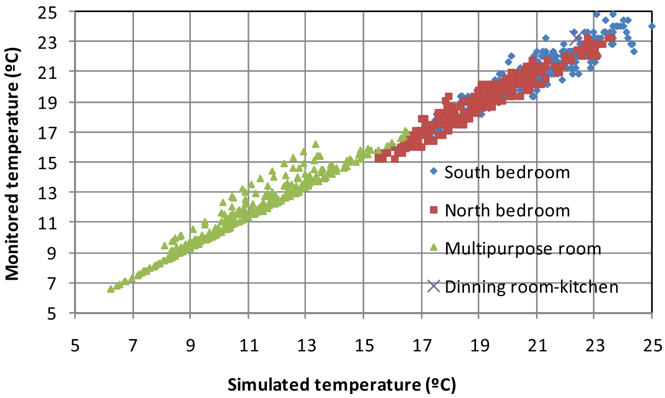

Fig. 3. Simulated temperature versus monitored one for each thermal zone, for the period from August 6th to 18th, 2010. A good fitting can be observed.

In a further step, a set of simulations with SIMEDIF for a series of days with the same daily monitored air temperature and solar radiation for the months of July and January 2010, were carried out. Table 6 shows the results. When comparing the original conventional dwelling and the retrofitted one, a 62.5% of energy saving in winter is obtained when including thermal insulation in walls and roofs (without increasing the solar collector area). If now we increase the solar collection area (to 16% of the dwelling useful area), the energy savings are only 58%. Thus, increasing the solar collector area appears to be counterproductive in winter because of the higher thermal losses through the glazed areas. In summer, we distinguished two cases: with ventilation and without ventilation. In the first case, a 100% of energy savings can be obtained when including thermal insulation in walls and roofs. In the second case (not ventilated dwelling), the energy consumption can be slightly reduced only if thermal insulation is added to walls and roofs and with complete shading. It is interesting to note that, if thermal insulation is added to the walls but not to the roof, the energy consumption significantly increases with respect to the original no insulated dwelling, due to the high temperatures reached by the roof in summer.

5.2.3. Potential impact and adaptation to climate change

Figs. 4 and 5 show the average maximum, minimum and mean temperatures for July and January, respectively, in Santa Rosa city, for the period between 1961 and 2039, with the linear fittings. It is worthy to note that the minimum temperature strongly increases along the years, the maximum temperature decreases and the mean temperature shows a softly increasing tendency. This behavior was also found previously by other authors for this region. The decrease in the maximum temperature is due to the increase of cloudiness and precipitation, in particular in December and January, which is the observed behavior in the last 70 years [45,75]. The trend of the maximum temperature in the period 1959–1998 was also found with negative slope by Ref. [59] while for minimum temperatures an increasing tendency of around 4 °C/100 years was found. Fernández Long et al. [17] predict an increase in the annual mean temperature of about 0.43 °C/100 year, mainly due to the increase in the minimum temperatures which will be stronger in

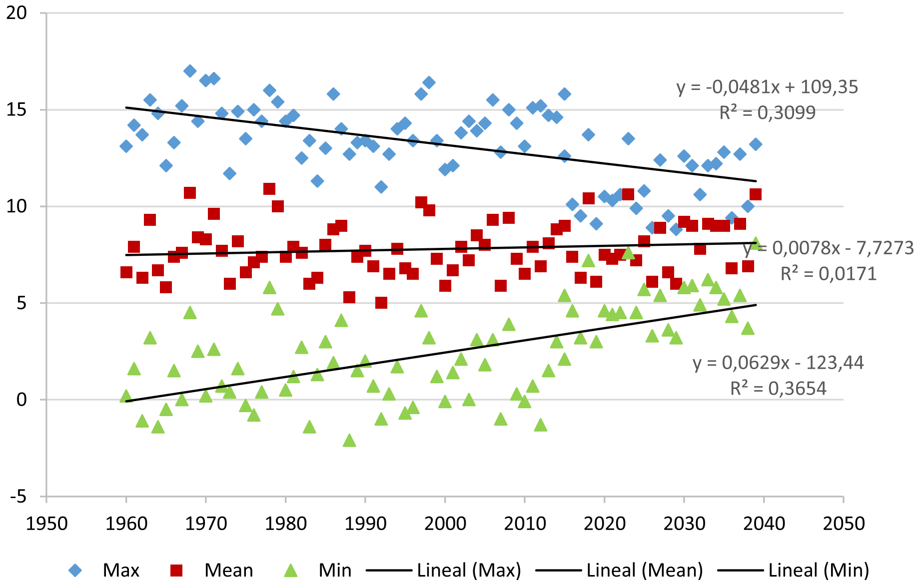

Fig. 4. Maximum, mean and minimum average temperatures for July, for the period 1961–2039, for Santa Rosa.

spring. These authors also mention that the maximum temperatures will not increase dramatically but more episodes of extreme hot waves will occur. They predict increases between 1.8 °C and 4.5 °C in the mean temperature for 2080 for the central (Pampa) region of Argentina.

The average temperature in the period 1961–2039 is 15.8 °C (CV = 36.2%). Based on monthly mean temperature values, we estimated the heating degree days for a base temperature of 22 °C between 1960 and 2039. Thus, once we generated the HDD data set for the period 1960–2039 (with resulting average, SD and CV are 2376.8, 147.6 and 6.2%, respectively), we made a simple regression analysis between HDD and year. A negative correlation coefficient of −0.27 was found, showing a relatively weak relationship between variables and a decreasing slope which is consistent with milder winter conditions in the future. The R^2 coefficient shows that the model can account for 7.5% variability. The same analysis was carried out for July's monthly mean minimum temperature. The average mean minimum temperature is 2.4 °C, the standard deviation 2.4% and the variation coefficient 100%. R^2 shows that the model can account for 36.2% variability. The correlation coefficient is 0.60 and shows a moderately strong relationship between variables. Since the ANOVA P-value is lower than 0.01, the statistical relationship is significant for a confidence level of 99%.

Considering the monthly mean temperature values of January, we estimated CDD for a base temperature of 25 °C. The corresponding average CDD, SD and CV are 589.8, 185.7 and 31.5%, respectively. A linear regression analysis between the obtained values and the years, is carried out and we reach an $R^2 = 0.42$ with negative slope. Since the ANOVA P-value is lower than 0.01, the statistical relationship is significant for a confidence level of 99%. The correlation coefficient is −0.65 and shows a moderately strong relationship between variables. A negative slope is explained by the fact that CDD are calculated by using Eq. (5), where only maximum temperatures appear. These maximum temperatures are expected

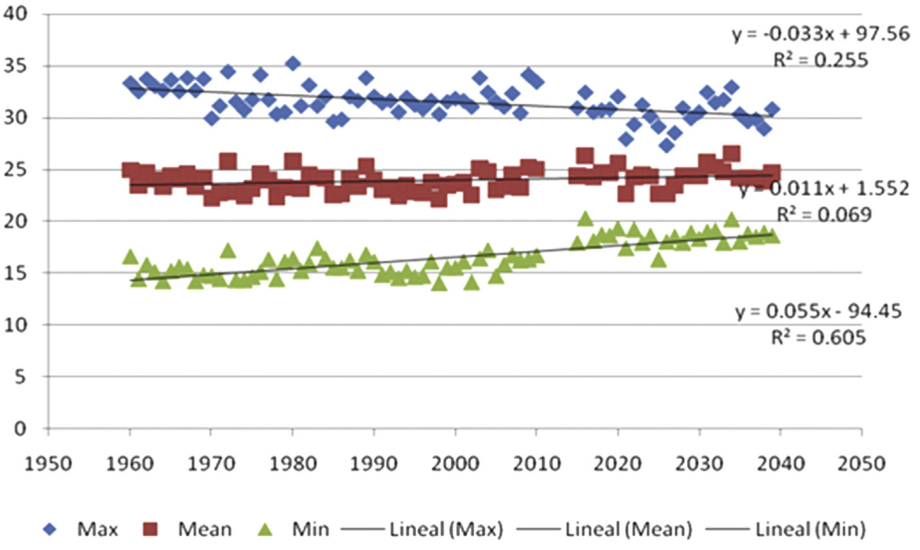

Fig. 5. Maximum, mean and minimum average temperatures for January, for the period 1961–2039, for Santa Rosa.

Table 5
Energy consumption obtained from transient thermal simulation during winter and summer for 2010.

Technology house	Winter			Summer			
	Indoor temperature	Outdoor mean temperature	m^3/day	Indoor temperature	Outdoor mean temperature	kWh/day	
						Night ventilation	
						Without	With
Conventional	22	9.3	6.0	25	23	5.2	0.3
Retrofitting (Conservation)			3.6			1.6	0.1

to decrease in the future due to higher cloudiness and precipitation. The same analysis is carried out for January's minimum and maximum temperatures. For the minimum temperature, the linear regression analysis resulted in an increasing slope of around 5.5 °C/100-years with $R^2 = 0.60$ is obtained (P-value < 0.01, so the statistical relationship is deemed significant for Sa confidence level of 99%). For the maximum temperature, there is a decreasing slope of −3.3 °C/100-years ($R^2 = 0.26$). Even though there is an increase in the minimum temperature, the maximum from which the cooling degree-day depends shows little variability. The regression analysis for CDD in January shows an R^2 of 0.23, with the ANOVA P-value lower than 0.01. The correlation coefficient is −0.47 which shows a decreasing relationship but relatively weak between variables.

Tables 5, 6 and 7 show the thermal simulation results and the energy demand for 2010 and 2039, both for the conventional as well as for the retrofitted dwelling, with two options: conservation and conservation plus increase of the transparent area collecting to the north (it varies from 9 to 16% with regard to the useful area). Both the decrease and increase of energy demand for winter and summer, 2010 and 2039 respectively, can be observed for the conventional and the retrofitted dwelling. Thus, the conventional dwelling will decrease its energy demand in winter by 22% and it will increase its energy demand in summer in around 8 times (considering that night ventilation is used). The retrofitted dwelling (insulation in walls and roofs) will decrease its energy demand in winter by 24% and it will increase its demand in summer.

Integrating the retrospective and prospective analyses, (1975–2039) it is possible to observe that the annual heating requirement for a G value = 2.51 W/m^3 °C shows a natural gas average of 1201.1 m^3 with a standard deviation of 79.3 and a variation coefficient between 1975 and 2039 of 6.6%. The average value is not distant from the historical average consumption measured between 1989 and 2010 (Table 2). The accumulated natural gas

Table 6
Energy consumption of gas (winter) and electricity (summer) calculated by thermal simulation with SIMEDIF, for the weather conditions of 2010.

Technology house	July		January				
	Outdoor temperature (°C) mean: 6.5, max: 13.3; min: −0.4; irradiance: 7.2 MJ/m^2		Outdoor temperature (°C) mean: 23.1, max: 30.6; min: 15.9 irradiansce: 24 MJ/m^2				
	Indoor temperature	m^3/day	Indoor temperature	kWh/day			
				Night ventilation			
				Without			With
Conventional	22	8.8	25			4.0	1.8
Retrofitting (Conservation)		W: 6.0 W + R: 3.3		Shading system (%)	100	W: 5.0 W + R: 3.8	W: 1.4 W + R: 0
Retrofitting (Conservation and solarization: Solar collection area = 16% of useful area)		W: 7.6			50	W: 9.8 W + R: 4.1	W: 2.7 W + R: 0
		W + R: 3.7			100	W: 8.1 W + R: 3.1	W: 1.5 W + R: 0

References: W (wall's thermal improvement); W + R (wall's and roof's thermal improvement).

Table 7
Energy consumption of gas (winter) and electricity (summer) calculated by thermal simulation with SIMEDIF, for the weather conditions of 2039.

Technology house	July		January					
	Outdoor temperature (°C) mean: 10.3, max: 13.8; min: 6.9		Outdoor temperature (°C) mean: 24.7, max: 30.8; min: 18.6					
	Indoor temperature	m^3/day	Indoor temperature	kWh/day				
				Night ventilation				
				Without			With	
Conventional	22	6.9	25			19.9	14.3	
Retrofitting (Conservation)		W = 4.7 W + R = 2.5		Shading system (%)	100	21.0 5.7	W W + R	9.6 3.4
Retrofitting (Conservation and solarization: Solar collection area = 16% of useful area)		W = 5.5			50	26.1 7.4	W W + R	11.9 5.2
		W + R = 2.7			100	20.7 5.6	W W + R	11.0 3.1

References: W (wall's thermal improvement); W + R (wall's and roof's thermal improvement).

consumption is 40594 m^3 (395548 kWh). Improving the vertical envelope's thermal resistance allows for a reduction of the G-value to 1.70 W/m^3 °C and it also helps to reach the G value accepted by Ref. [40]. Annual average consumption thus decreases to 813.5 m^3 with an accumulated consumption of 27494 m^3 (267901 kWh). This reduction would imply a 32.3% saving along 64 years of useful life, considering that, along the time span, there would be no architectural and/or technology changes, and/or construction pathologies.

According to Table 5 the summer situation is by no means similar. At the moment, the dwelling does not have a mechanical cooling system. The user reports not needing it; comfort is guaranteed by night ventilation. Results from monitoring in 2010 showed an indoor mean temperature of 25.8 °C (outdoor maximum and minimum mean temperatures were 28.5 and 18.3 °C, respectively. If the mean indoor temperature should be decreased down to 25 °C for the same outdoor conditions, the transient thermal simulation predicts an energy need for cooling of 5.2 (if night ventilation is not used) and 0.3 kWh/day (using night ventilation). The energy saving is around 31% since the retrofitting was carried out.

For a $\Delta T_{\text{indoor temperature}} = 1.9$ °C according to Table 6, the requirement is 4 kWh/day and 1.8 without and with night ventilation, respectively for a series of clear sky days, without temperature daily variation in January (permanent periodical period with indoor maximum and minimum temperatures of 30.6 and 15.9 °C). The same table shows energy consumption decreases (1.4 kWh/day) as a result of improving the vertical envelope's thermal resistance and the use of shading and night ventilation. A slight increase is observed when the windows area is increased. Towards 2039, to keep an indoor temperature of 25 °C, the conventional dwelling will need 19.9 and 14.3 kWh/day - without and with night ventilation, respectively-. These values decrease in the retrofitted dwelling. Considering the fact that the study dwelling's electricity historical consumption average in January is 158.32 kWh (variation coefficient of 13.2% for the period) and in the case that the current owner decided to set up an air conditioner and keep her night natural ventilation and transparent areas shading in a 100%, the increase in electricity consumption would be 27 kWh, on the basis of 15 days of persisting similar weather conditions (characteristic situation in the region in January). The use of the cooling system would take up 14.6% to keep an indoor temperature of 25 °C. If the envelope were improved and 100% shading of transparent areas consumption would be 12.4%. In a more problematical situation (without night natural ventilation and 50% shading) the total consumption in January in the retrofitted dwelling would be 305.3 kWh, 90% more than the electricity historical consumption average.

Toward 2039 and with an increase of 2.7 °C in the minimum temperature, the conventional dwelling, keeping the same habits would not consume the historical 185.3 kWh (appliances and air conditioning) but 372.8 kWh showing a 57% relative share in energy consumption so as to keep indoor temperature at 25 °C. If there were changes in the daily habits of dwellers, the cooling consumption would increase from 214.5 to 298.5 kWh, with a monthly total of 456.8 kWh (288% more with respect to the historical average). Improving the envelope's thermal resistance, night ventilation and 100% shading of transparent areas would reduce the monthly total consumption in the new climate scenario to 323.3 kWh, about 100% above the historical value, and the total energy consumption would be 50% air conditioning and 50% appliances and lighting. According to what was said earlier, air conditioning in 2010 shows a relative share of 14.6% (Table 7).

A further step was made, and thermal improvement of the roof was included in the study. The incorporation of 10 cm expanded polystyrene allows for a reduction of the G-value to 1.23 W/m^3 °C. Logically there is an extra-cost in removing the tiles and replacing the metal sheet with anchoring straps, which is not analyzed here because economic issues are beyond the scope of this paper. As seen in Table 7 the reduction of energy consumption in winter and in summer to keep the inside temperature at 22 and 25° C can be observed in all cases. By 2039 the worst situation for summer (50% shading, without night ventilation) could reduce cooling consumption by 71.6% with improved thermal resistance of the roof. The most satisfactory situation is achieved with a 100% shading and improved thermal resistance in walls and roof in accordance with the IRAM 11605, level A in walls and intermediate in roof in agreement with LAyHS (Laboratory of Sustainable Environment and Habitat of the Faculty of Architecture of the National University of La Plata-UNLP).

The increase of 2.7 °C in the outdoor minimum temperature between 2010 and 2039 favors energy saving during winter. But the situation in summer requires attention: even with night ventilation, the energy consumption exceeds by far the energy consumption in 2010. This situation can be worse in case the same user -or a new one- changes his habits and decreases the shading of the glazed areas and/or misuses the ventilation effect by opening the windows during hot outdoor conditions.

Results show how careful designers should be to consider the potential impact of climate change on architecture. An increase of the transparent area facing north in order to gain more solar energy will turn into a counterproductive design strategy in summer, especially if shading is reduced to 50%. An increase in minimum temperature might reduce the possibility of selective natural ventilation, strategy that was favored in the case study dwelling and which allowed living without a mechanical ventilation system. Although the January cooling degree days show a negative tendency, the tendency is positive regarding the increase in minimum mean temperature for January 2039 which might condition energy consumption so as to keep the dwelling's indoor temperature at 25 °C with 100% shading of transparent areas facing north (without night ventilation), consumption would vary from 8.1 kWh/day in 2010 to 20.7 kWh/day in 2039. It is possible, as well, then, that the vertical envelope's design might be subject to reconsiderations.

Taking into account the retrospective analysis carried out for all the dwellings as regards the energy consumption variability along the historical periods, data show a higher variation coefficient in the annual bimonthly natural gas consumption average, with an average value of 84.2 and 14.6% for natural gas and electricity, respectively. In the case of natural gas, the maximum and minimum values are 100 and 61%, respectively. Electricity shows a maximum value of 31.1% and a minimum one of 6.4%. Data reflect the incidence of seasons on natural gas consumption in the region. These arguments and the analysis carried out for summer show that in the event of climate change, the less favorable situation in summer would condition electricity consumption that would be highly marked by seasonality. This situation should be considered by the Electricity Distribution Company. The Electricity Cooperative of the city of Santa Rosa, in its annual Report 2013–2014, states that since 2001, a permanent increase of energy bought has been registered, with an annual accumulated growth rate of 4.9%. It also states that the residential sector has a high share in consumption (48%) and that the relationship consumption/user in that same sector was increased 35% between 2002-2003 and 2013–2014. Considering the annual Report for the period 1969–1970 the annual electricity consumption per user was 1668 kWh. The increase in the value of the last report represents a 52.7%. If, to this pre-existent situation, we were to add the effects of climate change, it would be reasonable that the Cooperative introduced changes to the service and distribution provided in order to meet the needs of a higher electricity demand.

6. Conclusions

The evaluation of retrofitted buildings for future climate can be a challenging task because there are uncertainties in both for retrofitting buildings and future climate [53]. The innovative contribution of this work is the integration of past, present and future periods in an integral analysis. The past is included through the retrospective analysis of the operating energy along 50 years; the present, through the detailed analysis of a "case study"; and the future, through the retrofitting strategies to face future weather conditions near the year 2040. Some issues arising from this study must be highlighted:

- Electricity and gas are around 12% and 88%, respectively, of the total energy consumption. There is a higher relative share of natural gas consumption in the total operating energy. 58%, 30% and 12% of the total energy consumption is destined to space heating, water heating and cooking, and lighting and electrical appliances, respectively.
- The high values of CV obtained for the group of dwellings (reaching 45% in electricity consumption) confirm the results of other authors about the determinant role of the occupants in the energy consumption.
- In the retrospective analysis, the problem derived from the absence of data in the time series, which implies a huge information loss, was fulfilled by determining predictive models that were found to be statistically reliable.
- The retrofitting strategies for present weather conditions show that 62.5% of energy savings in winter are obtained when including thermal insulation in walls and roofs. Increasing the area for direct solar gain, from 9% to 16%, appears to be counterproductive both in winter and summer because of the higher thermal losses through the glazed areas. In summer, night ventilation is of outermost importance.
- The energy demand for 2010 and 2039, for both the conventional and the retrofitted dwelling, shows a decrease in winter and an increase in summer of the energy demand. The inclusion of 0.05 m thick of thermal insulation implies energy savings of around 32% along 64 years of useful life of a dwelling. The situation could improve further if the roof's thermal resistance was increased. The results of the retrofitting strategies can be generalized to the other sample dwellings in view of their technology similarities.

A change in the paradigm of building design and in the attitude and procedures of the designers and engineers is needed. Buildings that were designed in past decades must satisfy the architectonic and functional requirements of the present time, and also they must consider the weather data for the future due to the climate change. In accordance with [44]; we consider that the design should be integral, that is, it should include a pre-design phase with light and thermal simulations, or the energy retrofitting based on detailed monitoring, energy auditing and data simulation including the role of the users. The need of computer assisted design and thermal simulation, with bioclimatic strategies adapted to the climate change, is emphasized.

Buildings' energy retrofitting appears to be the most appropriate solution in the long run to cope with energy scarcity and the adaptation to climate change. In the studied region, the addition of thermal insulation in walls and roofs is highly beneficial, but the increase of glazed areas seems to be counterproductive. Thus, it is necessary to revise and take a prudent attitude about the glazed areas to deal with present —and even stronger in the future-overheating. Other solutions such as green roofs and vertical envelopes with higher levels of shading should be considered. Cooling loads should be covered by photovoltaic electricity improving both, problems in the energy supply during the more demanding hours and the Argentinean electric matrix. The generalization of quantitative studies similar to this one, in other regions of the country with different future weather conditions, might widely justify the challenge of changing the current status of the existing legislation in Argentina, which should be compulsory and not merely optional.

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