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Improvement of energy performance metrics for the retrofit of the built environment. Adaptation to climate change and mitigation of energy poverty

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ABSTRACT

Energy retrofit of existing buildings was highlighted as an efficient massive action to decrease energy consumption and emissions of greenhouse gases. But, detecting the optimal retrofit strategies for groups of buildings is nowadays a highly complex problem. Their energy consumptions are influenced by *building-related* factors (climate, building envelope, building services and systems) and by *user-related* ones (building operation and maintenance, occupant behavior, and indoor environmental quality). Detecting the contributions of each factor and grouping buildings with similarities –in order to establish similar retrofit strategies – are the main issues that can be faced by statistical multivariate methods. In this paper, we present a new and broader view to propose *retrofit* strategies adapted to a climate change scenario and analyzed from the economic and energy-poverty points of view, by using multivariate and clustering techniques that include *building-related* and *user-related* metrics influencing the energy consumption of groups of buildings. A group of 10 *single-family* houses in Argentina were selected as a case-study. The contributions of eleven *building-related* driving metrics and four *user-related* ones to the energy consumption were analyzed. Then, the more representative house of the cluster was selected for a retrofit analysis for current weather conditions and for future weather under a climate change scenario. The analysis also included an economic assessment in relation to the energy poverty. The higher CV values found in the *user-related* metrics highlight the influence of occupants in the energy consumption that can result in huge gaps between real and predicted energy performance of buildings. This holistic study contributes to reveal the internal structure of energy consumption and to generate useful knowledge about energy retrofit of the built environment in cities, particularly for those householders which are more susceptible to suffer the adverse effects of energy poverty and climate change.

1. Introduction

The building sector is one of the main actors responsible for environmental problems, as it uses about 40% of global energy and emits about 30% of world's greenhouse gases. The energy retrofit of the existing building stock is nowadays recognized as an effective action to reduce energy consumption and emissions of greenhouse gases in order to contribute to environmental sustainability [33]. Moreover, it is known that the demand for renovation and energy retrofitting will peak in the coming decades [26]. While detecting the optimal retrofit strategies for one single building was extensively studied in the literature, detecting the most influencing retrofit measures for sets of buildings is still a challenge [17,26,42]. To do this, groups of buildings sharing similar characteristics must be identified. In the past, the conventional grouping was based either on descriptive parameters called *building-related* metrics (age, type, building envelope, climate, etc.) or on the current performance called *user-related* metrics (energy consumption, building operation and maintenance, occupant behavior, and indoor environmental quality). But in fact, as highlighted by IEA [20,21], both are so highly interconnected that the analysis must be made including all factors together. In this case, a useful technique to deal with multivariate metrics is *Principal Components Analysis* (PCA), which allows detecting model data correlation and also determining dominant variables, tendencies, outliers, groups and similarities, in particular for small number of buildings and/or parameters which are not normally distributed. This technique was

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successfully applied into a variety of building types and climates [16,29,30,32].

The next step, once the main influencing metrics were detected, is to classify buildings into groups of similar characteristics. The application of *Hierarchical Clustering* (HCA) allows setting clusters of buildings that shares similar metrics. Thus, as highlighted by Geyer et al. [17], the development of retrofit strategies for clusters instead of individual buildings facilitates more effective strategy development, compared to dealing with each building individually, and makes it thus more feasible to address the complete building stock. Pioneer research on clustering applied to school buildings in Greece [35] used collected energy consumption data for a three years period. Later, a new methodology based on the use of the principal components analysis (PCA) and clustering was developed by Gaitani et al. [16] and applied in the Greek school building stock that allowed identifying sub-groups of school buildings with similar characteristics and investigating the potential for energy savings the typical school building of each energy class. PCA and HCA were used to evaluate historical consumption of natural gas for heating, between 1996 and 2009, in 72 apartments of multi-family buildings in La Pampa, Argentina [13]. Only *building-related* variables were considered in this study, and the results evidenced both, the relevance of the orientation and location of each apartment (apartments on extremes or on the top level are the most exposed to the severity of the climate) and the need of including *user-related variables* in future analyses. Very recently, a method to cluster buildings based on their sensitivity to different retrofit measures, focusing on the cost-effectiveness, was presented by Geyer et al. [17] and applied to a Swiss alpine village. Clustering integrated with and demographic-based probability neural networks were used to identify and classify occupants' behavior –a purely *user-related* metric- with direct energy consumption outcomes and energy time use data [7]. The authors claim that, with qualified and sufficient time use data, the model is capable of automatically estimating energy consumption of residential buildings on even larger geographic scales. It is concluded that, while clustering techniques were proved to be a useful tool to classify buildings, the use of clustering based on both, *user* and *building* related metrics, and linked to retrofit strategies was not completely investigated yet. This approach is of major interest for the development of retrofit strategies, as it is much easier to make retrofit decisions for groups of buildings that react similarly to energy efficiency measures.

Two more aspects of energy retrofit must be highlighted. The first one is that retrofit strategies must also consider the socio-economic challenges associated with the cost of energy retrofitting. Johansson et al. [26] conclude that, while energy retrofit can reduce the energy use of the existing building stock by up to 50% (relative to 1990), costs associated with renovation and energy retrofits of multifamily buildings can be problematic, especially in economically weak suburbs. De Lauretis et al. (2017) [6] suggests that income was detected as an obvious driver of energy and expenditure intensities, and it is revealed to influence time use as well. In this context, the "energy poverty" concept is relevant. It is defined as the situation when households cannot afford the cost of energy to meet their daily needs or when they use an excessive part of their income to pay energy bills at home (in practice, more than 10%). While in Europe about 50 million people has been estimated are fuel poor, in Latin America this value reached 211 million in 1999 [4] from which 63% live in cities. In this context, energy retrofitting of housing arises as an important, viable and sustainable solution for energy poverty in the long run (Tirado [3,27,34,40]). In the same line, Santamouris [37] claims that improvement of the energy efficiency of buildings would help to eliminate energy poverty. As shown, there is a general consensus that improving energy efficiency through building *retrofit* strategies would significantly reduce energy consumption and minimize vulnerability to unexpected changes in the family income or to growing energy costs.

The second aspect of energy retrofit is related to the climate change scenario. World Health Organization [43] advertises that cities are vulnerable to adverse effects of climate change on health and that these effects will be strongly localized, with different risk profiles in each country and regions. In central Argentina the climate change has being noticed in the last years. The Second National Communication of Climate Change [38] 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 [2]. 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 and increases between 1.8 °C and 4.5 °C in the mean temperature for 2080 [11]. Thus, the local and global climate change will seriously affect the future energy consumption of buildings, and retrofit strategies must be assessed for this new future climate scenario. There is a consensus that, due to the large variations found in the relationship between climate change and building energy consumption, it is important to assess climate change impacts at local scales, and that adaptation/mitigation strategies must be tailored to different building types [1,19,36].

The goal of this article is to present an integrated methodology that includes multivariate and clustering techniques (PCA and HCA) for both, detecting the main *building-related* and *user-related* metrics influencing the energy consumption of a group of buildings, and proposing *retrofit* strategies analyzed from the economic energy-poverty point of view and under a climate change scenario. This is a new and broader vision of how decisions on retrofit of groups of buildings could be made. A group of 10 single-family houses in La Pampa (Argentina) was used as case-study. *User-related* variables were accounted for by analyzing the operational energy, electricity and gas consumptions -with and without the presence of users- of the group of buildings, for 50 years period. Hierarchical clustering allowed to group buildings with similarities and to select one of them – representative of its own cluster- to analyze its energy *retrofit* for current weather conditions and for future weather under a climate change scenario. The analysis also included an economic assessment in relation to the energy poverty. In a context of huge housing deficit occurring in most developing countries, with an average in Argentina of 25.4% (and maximum in the Northwest region of 39%), according to the National Agency of Statistics and Censuses [22], this study will contribute to reveal the internal structure of energy consumption data and to generate useful knowledge about energy retrofit of buildings under a climate change scenario, particularly for those householders which are more susceptible to suffer the adverse effects of energy poverty. Such information can lead decisions in future policies for retrofit subsidies in developing countries.

2. Methodology

Fig. 1 shows the methodological framework used in this work. The analyzed houses constitute the architectural objects – which are defined by Wikberg and Ekholm [44] as those objects having technical, functional and aesthetic properties, representing real activity situations in a design project-. Firstly, a group of single-family houses was selected to analyze their energy performance variability and the user' influence by considering two situations: without and with the presence of users, i.e. situations A and B, respectively. Then, a range of *building-related* and *user-related* metrics (dimensional and morphological; thermal-physical, and en-

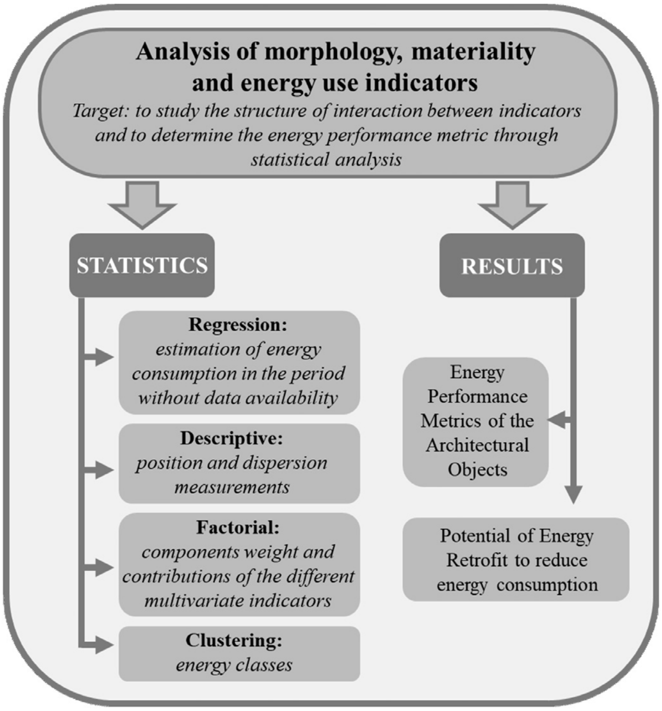


Fig. 1. Methodological framework.

ergy consumption metrics) that provides different perspectives on building energy performance was proposed, calculated and statistically described for each house. The next step was grouping the architectural objects in energy classes that shares similar metrics, by using principal components analysis and agglomerative hierarchical clustering. Finally, one house was selected to assess the intervention potential and cost effectiveness of the *retrofit* in order to reduce energy consumption for space conditioning.

2.1. Selection of buildings (architectural objects) and driving metrics

A global and direct observation of homogeneous areas in neighborhoods of low-building density was made in order to detect single-family houses in good conditions. A group of 10 houses - identified with an acronym to keep data privacy- with 50 years records of energy consumption was selected. They have a prismatic morphology, different orientations, no thermal insulation, and high thermal inertia($>400\,kg/m^2$, according to the type of building categories set by the New Method 5000). They were identified as VA_1, VA_2, VA_3, VA_4, VA_9, VA_{11}, VA_{15}, VA_{20}, VA_{21} and VB_1. Two houses (VA_1 and VB_1) were extensively monitored and described in detail in a previous work [12,14,15].

Fig. 2 shows the ***driving metrics*** that were grouped into *building-related* and *user-related* ones, accounting a total number of 15 variables. These metrics were chosen because they are capable of producing changes in energy consumption (kWh/m^2) in the analyzed houses. Table 1 shows the symbols, description and units used for the driving metrics, which were studied without and with presence of users (identified as A and B, respectively).

Building-related metrics include eleven variables describing dimensional and morphological parameters of the houses (calculated from the building geometry data), and thermo-physical and energetic metrics (calculated from thermal properties of materials and climate data). In particular, the embodied energy –that can be the equivalent of many years of operational energy- was estimated from the dwelling's total cost and its components. Thus our work considers the technology components which are integral part

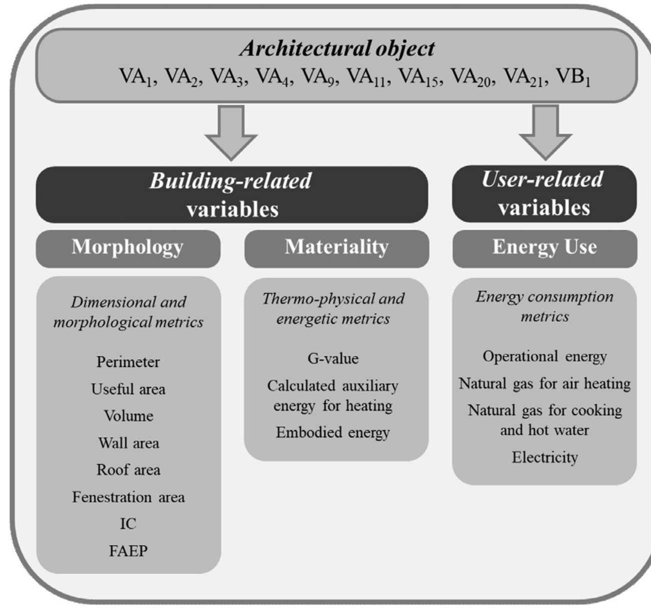


Fig. 2. Driving metrics of architectural objects.
References:
Useful area (m^2): living area (walls excluded).
IC: Compacity Index, is the percent relationship between the story envelopeś perimeter and the one it could have if it were circular [28].
FAEP: it is calculated like the envelopes surface divided by the covered surface [10]:
$FAEP = (St + Sm + Sve + Spu)/Scu$
where *St:* total roof surface (m²); *Sm:* total wall surface (m²); *Sve:* window surface (m²); *Spu*: door surface (m²); *Scu*: covered surface to be heated (m²).
G-value **(W/m^3-K):** it is the volumetric heat loss coefficient, that is, the total heat loss of a building through the envelope and ventilation divided by the heated volume and the temperature at which the loss occurs. It is defined in Argentinean IRAM-11,604, [24] Norm as:
$G - value = (\sum Km \cdot Sm + \sum Kv \cdot Sv + \sum \gamma Kr \cdot Sr + \sum Kp \cdot P \cdot \beta + \sum Km \cdot Sm)/V + 0.35n$
where *Km: thermal transmittance of walls in contact with external ambient (W/m^2-K); Sm: surface area (m^2); Kv: thermal transmittance of glazing (W/m^2-K); Kr: corrected thermal transmittance of each envelope element (opaque or transparent) in contact with non-heated spaces; γ:0.5 (in contact with heated spaces), γ:1 (other cases); Kp: Thermal transmittance of floor (W/m^2-K); P:perimeter of the floor (m); β:1 m; 0.35: air specific heat (Wh/m^3-K); V:volume of heated spaces; n:average air changes per hour (ach).*
Auxiliary energy for heating (kWh/year)= annual auxiliary heating load calculated as [24]:
$AH = N \cdot DD \cdot (G{-}value) \cdot V/1000$
where *N***:** number of hours of the day when the heating system is on; *DD*: annual degree-days for the thermostat set temperature; *V*: heated volume.

of the masonry horizontal and vertical planes (walls and foundations), horizontal and vertical finish and carpentry which absorb 71.17% of the total construction cost [28].

User-related metrics include four variables: operational energy, natural gas consumption for air heating, natural gas consumption for cooking and hot water, and electricity consumption. Operational energy–calculated in the studied houses as the sum of electricity and natural gas consumptions- depends on the occupants and is generally one of the most important resources used in buildings over their lifetime. Data were obtained from the gas and electricity bills over the 50-year period 1961–2011. The absence of data in the time series that was solved by using predictions from a retrospective analysis and linear regressions, previously developed in Filippín et al. [15], whose results around the operating energy fed the data needed in the present work.

After calculating the metrics for each house, the descriptive statistics (minimum, maximum and average values, standard deviation and coefficient of variation) together with a Jarque–Bera Test [25] were performed to check if each of the parameters was nor-

Table 1
Symbols, description and units of driving metrics according to Fig. 1. Shading in the last columns indicates the variables used in each situation (without and with users).

	Abreviation	Units	Users	
			Without (A)	With (B)
Perimeter	P	M		
Useful area	UA	m^2		
Volume	V	m^3		
Envelope: wall area	EAW	m^2		
Envelope: roof area	EAR	m^2		
Envelope: fenestration area	EAF	m^2		
Ic	IC	%		
FAEP	FAEP	-		
Volumetric heat loss coefficient *G-value*	G	$W/(m^3 K)$		
Auxiliary heating	AH	$Wh/(m^2 year)$		
Embodied energy	EE	MJ/m^2		
Operational energy	OE	MJ/m^2		
Natural gas consumption (for air heating)	NG (H)	kWh/m^2		
Natural gas consumption (for cooking and hot water)	NG (C-HW)	kWh/m^2		
Electricity consumption	E	kWh/m^2		

mally distributed. This is a goodness-of-fit test to check whether the data samples have the symmetry and kurtosis of a normal distribution –if all the calculated *P-values* are higher than the level of significance $\alpha = 0.05$, then the parameters are normally distributed. This allowed us to select the type of statistical analysis to be used later, minimizing errors in the final conclusion.

2.2. Statistical methods

As explained, the use of multivariate techniques allows detecting behavior patterns in dwellings. In this work, this type of technique is applied to assess the behavior/dimensional parameters variability, with and without the presence of users. *Principal components analysis* (PCA) and *Hierarchical Agglomerative Clustering* (HAC) were used. Since the analyzed parameters are measured in different units, standardization of data was considered in order to homogenize them and also to avoid the emergence of misleading results due to disparity among absolute values, units and expressions. Thus, variable transformation was carried out by means of

$$Z = (x - \mu)/\sigma \tag{1}$$

This transformation consists in substracting to each datum (x) the mean value (μ) and to dividing the result by the standard deviation (σ). This "Z punctuations" have mean equal to 0 and standard deviation equal to 1, eliminating all units between values.

Pearson (*n-1*) *Principal Components Analysis* is a statistical procedure that uses an orthogonal transformation to convert a set of observations of possibly correlated variables into a smaller number of uncorrelated variables called principal components. In this transformation, the first principal component accounts for as much of the variability in the data as possible, and each succeeding component accounts for as much of the remaining variability as possible. PCA is performed on a square symmetric matrix. If the variances of individual variables differ much, or if the units of measurement of the individual variables differ, the usual way is to define a correlation matrix. Thus, a data matrix $X_{n \times p}$ consisting of n rows $x_{(i)}$of p elements per row, is defined. Each row corresponds to a house and p is the number of variables measured for this house. The correlation matrix $R_{p \times p}$ is built from:

$$R = \left\{ r_{kj} \right\} \text{ with } k, j = 1, 2, ...p \tag{2}$$

where

$$r_{kj} = \frac{\text{cov}(x_{(k)}, x_{(j)})}{\sqrt{\text{var}(x_{(k)})\text{var}(x_{(j)})}} \tag{3}$$

Because this matrix is symmetrical, it is diagonalizable and its eigenvalues (or characteristic roots) λ_i verify that:

$$\sum_{i=1}^{p} \lambda_i = 1 \tag{4}$$

The eigenvalue for a given factor measures the variance in all the variables, which is accounted for by that factor. Thus, if a factor has a low eigenvalue, then it is contributing little to the explanation of variances in the variables and may be ignored as redundant with more important factors. Finally, the principal components are built from the base of eigenvectors of the matrix R. In our case, the data matrix X of dimension 10×15 includes the 15 *building-related* and *user-related* variables estimated for each one of the 10 houses analyzed in this paper.

Thus, PCA was carried out in order to represent the majority of the information contained in the original data set, and to interpret the variance of the energy and environmental parameters which characterize the different houses, with and without users. This analysis allowed us to detect the patterns which characterize the dwellings' total variance, particularly focusing on the energy and functional parameters, both in use and non-use situations. The initial phase consisted in a correlation analysis among all parameters. We applied Pearson correlation coefficients' analysis which assures normality in the variables distribution. The number of principal components was limited to those with an eigenvalue higher than 1. This decision was made because when carrying out the analysis with standardized data, the variance of each standardized variable is equal to 1. If one principal component cannot explain more variation than a single variable, then it is probable that it may not be important, thus ignoring those components whose eigenvalues were lower than 1. This made us select those components whose variability percentage was deemed sufficient for the analysis. When the variance was higher, the data contained was greater. The subsequent combinations of components were ordered in descending sequence according to the variance proportion in each case. Factorial punctuations and contributions (expressed as a percentage) for each parameter, and each dwelling, were estimated for those components with higher variance percentages and eigenvalues.

Once variables were selected through the PCA, the clustering process started. This process involved the selection of a clustering algorithm and the determination of the number of clusters that will arise. The available clustering algorithms are divided into hierarchical and no-hierarchical, being the first approach the one used in this research. *Hierarchical Agglomerative Clustering* consists in ordering objects in clusters so that the degree of association/similitude among members of the same cluster is stronger than among members of different clusters. One of the most used analyses in hierarchical clustering methods is the centroid method. Each cluster is defined by the objects that are part of it and its centroid, that is, the point where the sum of the distances among all the data of the cluster is minimized. This analysis was based on the calculation of a metric distance which defined similarities and differences between parameters of the dwellings in situation of use and non-use. In this case, we used the Euclidean distance d, which is defined in a multidimensional space as:

$$d(A, B) = \sqrt{\sum_{c=1}^{p} (x_{ic} - x_{jc})^2} \quad (5)$$

where $d(A, B)$ is the distance between the elements A and B, and x_k is the position of the element in the space of p dimensions given by $x_k = (x_{k1}, x_{k2}, \ldots.., x_{km})$.

The method of analysis was carried out by means of the Ward method (or Minimum Variance Method or Method of Sum of the Squares), which is the most efficient one when trying to get homogeneous groups. It calculates the distance between two clusters as the sum of squares between groups in the ANOVA and for all the variables. In each step, it minimizes the sum of squares within the clusters over all the possible partitions obtained, combining two clusters from the previous step. The new clusters are created in such a way to minimize the total sum of squares of distances within each cluster. The Euclidean distances were also used to determine the degree of association. Thus, for disjoint clusters C_i, C_j and C_k with sizes n_i, n_j and n_k, respectively, the cluster distance is given by:

$$d(C_i \cup C_j, C_k) = \frac{n_i + n_k}{n_i + n_j + n_k} d(C_i, C_k) + \frac{n_j + n_k}{n_i + n_j + n_k} d(C_j, C_k) - \frac{n_k}{n_i + n_j + n_k} d(C_i, C_j) \quad (6)$$

The hierarchical cluster analysis is characterized by the development of a tree structure named dendogram. In our particular case, the houses are the items or members of the cluster, with a set of variables defining the position of each one in the cluster. Thus, if the positions of the points representing the houses are close to the centroid, they could be considered representative of that cluster. This allowed us to identify the different clusters in each situation of use. Thus, a classification of dwellings was carried out which took into account the energy and dimensional parameters distribution.

The statistical analyses were performed using the XLSTAT 2015 software.

2.3. Cost-benefit analysis of the retrofit

The annual cost C_A of the heating energy of an insulated wall is given by Yildiz et al. [45]:

$$C_A = \frac{86400 \cdot DD \cdot C_f}{(R_i + R_w + x_{ins}/k_{ins} + R_0) LHV \eta_s} \quad (7)$$

where DD is the annual degree-days, C_f is the fuel cost ($/m^3 or $/kWh depending on the fuel type), R_w is the thermal resistance of the wall without the insulating layer (m^{2}K/W), x_{ins} is the thickness of the insulating layer (m), k_{ins} is the thermal conductivity of the insulation (W/m-K), R_i and R_0 the inside and outside air film, *LHV* is the heating value of the fuel (J/m^3 or J/kW-h, depending on the fuel type), and η_s is the efficiency of the heating system.

The analysis of the life cycle cost involves the analysis of the components costs over their useful life. To do this, the total heating cost over a lifetime of N years is converted to present value by multiplying it by the *present worth factor PW* that depends on the interest rate i and the inflation rate g. Therefore, the annual cost of the heating energy of an insulated building during its lifetime can be converted to a present value taking into consideration the *PW*:

$$C_t = C_A(PW) + C_{ins} x_{ins} \quad (8)$$

where C_{ins} is the cost of the insulation material in $/m^3, x_{ins} the insulation thickness in m, and PW is calculated as:

$$PW = \frac{(1+r)^N - 1}{r(1+r)^N} \text{ for } i < g \quad (9)$$

where $r = (g - i)/(1 + i)$ and N the useful life.

Finally the investments payback period *PP* in years is estimated as:

$$PP = C_{ins} x_{ins} / A_s \quad (10)$$

where A_s is the amount of the annual savings obtained by adding the insulation.

2.4. Description of the location, present climate and future climate change in the region

The study was carried out in the centre of Argentina, in a mid-size city of Santa Rosa (100,000 inhabitants), capital of La Pampa province (36°27′S, 64°27′ W, 182 m above the sea level). The Köppen–Geiger climate classification for Santa Rosa is in the transition between Cfa and Bsk [31], that is, temperate arid steppe climate. The national climate classification is bio-environmental zone *IIIa*, corresponding to cold temperate with seasonal thermal amplitudes higher than 14 °C [23]. The present climate characteristics for Santa Rosa are shown in Table 2. The mean annual temperature is 15.5 °C, with mean minimum temperature in winter about 7.6 °C, mean maximum in summer of 31 °C, Mean annual solar irradiance on a horizontal surface is 16.3 MJ/m^2, with 8.1 MJ/m^2 in winter and 24 MJ/m^2 in summer. The future climate data used in this paper was obtained from a previous work [15]. The data set was generated by simulation from the CMIP5 (Coupled Model Intercomparison Project-Phase 5) global climate model under a scenario of RCP4.5 (MRI-CGCM3_rcp45_FC_MM, [39]). 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 [41].

Santa Rosa has shown a marked growth of new building developments in recent years, especially towers of multifamily housing with large glazed areas without sunscreens. According to the Agency of Statistics and Censuses, building refurbishment and enlargement grew about 42.8%. Despite this increase, 83% of all households are single-family homes [22]. An annual increase between 5–6% in residential power consumption was also recorded. The average annual consumptions of electricity and gas are about 2570 kWh/household and 1420 m^3/household, respectively [5]. Thus, in average, about 13% of total consumption corresponds to electricity and 87% to natural gas. According to the Gas Distribution Company, around 67% of the natural gas consumed annually, and around 75% of the gas consumed during winter, is used to heat buildings. About 92% of households are connected to the grid. According to 2016 data published by INDEC

Table 2
Climatic variables of the city of Santa Rosa (La Pampa).

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/m^2	16.3
July	Temperature	Minimum average	°C	1.5
		average		7.6
		Maximum average		13.5
		Absolute minimum		-5.9
	Thermal amplitude	°C	12	
	Wind speed average	Km/h	10	
	Solar radiation on horizontal surface average*	MJ/m^2	8.1	
Heating degree-days (Tb = 18°C)				1545
January	Temperature	Minimum average	°C	15
		Average		23.8
		mMaximum average		31
		Absolute minimum		36.4
	Thermal amplitude	°C	16	
	Wind speed average	Km/h	14	
	Solar radiation on horizontal surface average*	MJ/m^2	24	
Cooling degree-days (Tb = 23 °C)				449

References: Argentine Air Force, National Weather Service, 1992, except solar radiation on horizontal surface [18].

Table 3
Driving metrics value for each architectural object.

Driving metrics value															
Architectural object	P	UA	V	EAW	EAR	EAF	IC	FAEP	G	AH	EE	OE	NG (H)	NG (C–HW)	E
VA_1	31	39	141	71	43	14	70	3.3	2.5	312	5419	57,212	278	137	62
VA_2	36	62	108	89	69	5	82	2.6	4.3	210	4554	26,398	145	70	25
VA_3	32	50	140	58	50	7	77	2.3	3.0	290	8779	57,118	242	153	21
VA_4	43	92	229	84	92	18	78	2.1	2.7	130	4109	22,647	112	63	30
VA_9	42	86	234	89	86	21	78	2.2	2.9	75	3666	21,769	121	44	21
VA_{11}	55	90	267	147	103	16	61	2.9	3.7	190	3490	12,884	62	37	33
VA_{15}	41	85	220	78	85	29	80	2.3	2.9	194	4578	27,765	162	65	30
VA_{20}	50	93	257	54	93	23	68	2.1	2.7	131	4219	25,781	136	81	22
VA_{21}	54	75	226	153	75	24	56	3.3	3.5	166	5643	24,491	141	83	26
VB_1	41	80	190	54	80	16	70	1.9	3.0	95	5364	28,630	110	54	14

(*)Total operating energy in MJ/m^2 during the period 1961–2011 was obtained from [15].

in 2017, the region under study has 43,019 dwellings, 22.6% under the poverty line (monthly family income about US$ 511) and 4.4% under extreme indigence conditions (monthly family income about US$ 193). The monthly energy consumption of a conventional dwelling is 8577.5 kWh (70 US$) which takes 14% of the poor family income and 36.5% of the extremely indigent family income.

3. Results

3.1. Driving metrics

Tables 3 and 4 show the obtained values of the driving metrics for each ***architectural object*** and the corresponding descriptive statistics (minimum, maximum, average, standard deviation SD and coefficient of variation CV and Jarque-Bera test). The *building-related* metrics have CV values of between 19% and 41% (the highest ones for the envelope metrics), in general lower than the CV values of the *user-related* metrics. This can be explained by the occupants who can have large effects on building energy use. Thus, as expected, operating energy (a *user-related* variable) presents a higher coefficient of variation than the embodied energy (a *building-related* variable), −46% versus 29%-, as shown in Table 4. In average, 16% of the total energy consumption corresponds to the embodied energy and around 84% to the operational energy. The high P values (>0.05) resulting from the Jarque-Bera test demonstrated the normality of the analyzed variables.

A deeper inspection of the **embodied energy** was made in Tables A1 and A2. A detail of the embodied energy is shown per item (1: Walls and foundation; 2: Bracing; 3: Subfloor without pavement; 4: Roof, 5: Plaster; 6: Paint; 7: Windows and doors) in Table A1: it is worthy to note than walls and their foundations contribute with 67.4% of the total embodied energy, followed by the roof with a 16.0%. Carpentry (wooden, metallic, aluminum) on average shows a 4% of the total energy content, item that shows the highest coefficient of variation and probably the one which defines energy consumption variation/m^2. 75 and 16% of the total energy content would correspond to the vertical and horizontal envelope, respectively. These values agree with those defined by Zabalza et al. [46] who estimate about 71 and 18% for the pair wall-foundation and roof respectively.

3.2. Principal components analysis

The PCA results are shown in Tables 5 and 6. While nine principal components (PC_1 to PC_9) can represent the information in the data set (Table 5), in fact only two of them (PC_1 and PC_2, with high *eigenvalues*) are the main contributors in both cases -without and with occupants. Thus, their accumulated percentage reaches values of 78.4 (without occupants) and 77.1% (with occupants), respectively. To know the contribution of each metric to PC1 and PC2, Table 6 was performed. It allows observing significant differences in both situations.

Table 4
Descriptive statistics of driving metrics. References: SD: standard deviation, CV: coefficient of variation.

	Metrics	Min	Max	Average	S (n-1)	CV	Jarque–Bera test
Building-related	P	31	55	43	8.5	0.19	0.747
	UA	39	93	75	18.8	0.24	0.480
	V	108	267	201	54.2	0.26	0.614
	EAW	54	153	88	35.4	0.38	0.425
	EAR	43	103	77.6	18.0	0.23	0.568
	EAF	5	29	17.3	7.0	0.41	0.470
	IC	56	82	72	8.6	0.11	0.630
	FAEP	2	3	3	0.5	0.20	0.562
	G-value	3	4	3	0.5	0.16	0.424
	AH	75	312	179	77.6	0.41	0.743
	EE	3490	8779	4982	1521.8	0.29	0.051
User-related	OE	12,884	57,212	30,470	14,743.9	0.46	0.341
	NG(H)	62	278	151	64.2	0.40	0.526
	NG(C-HW)	37	153	79	38.1	0.46	0.420
	E	14	62	28	13.0	0.43	0.018

Table 5
Eigenvalues and variability contributed by each component in two cases: without and with occupants (A and B, respectively).

	A			B		
	Eigenvalue	Percent of variance (%)	Cumulative percentage (%)	Eigenvalue	Percent of variance (%)	Cumulative percentage (%)
PC_1	4.91	44.62	44.62	7.23	48.19	48.19
PC_2	3.72	33.82	78.44	4.34	28.93	77.12
PC_3	1.16	10.53	88.97	1.53	10.17	87.29
PC_4	0.61	5.59	94.56	1.19	7.91	95.20
PC_5	0.30	2.76	97.32	0.31	2.04	97.24
PC_6	0.17	1.56	98.88	0.19	1.24	98.48
PC_7	0.10	0.91	99.78	0.16	1.08	99.56
PC_8	0.02	0.14	99.92	0.04	0.27	99.83
PC_9	0.01	0.08	100.00	0.03	0.17	100.00

Table 6
Component weights and contributions of the different metrics in two cases: without and with occupants (A and B, respectively).

Metrics	A				B			
	Component weights		Contribution parameters (%)		Component weights		Contribution parameters (%)	
	PC_1	PC_2	PC_1	PC_2	PC_1	PC_2	PC_1	PC_2
P	0.945	0.221	18.19	1.31	−0.881	−0.337	10.73	2.61
UA	0.587	0.788	7.02	16.71	−0.909	0.330	11.43	2.51
V	0.749	0.538	11.43	7.78	−0.820	−0.014	9.31	0.00
EAW	0.853	−0.367	14.82	3.63	−0.551	−0.757	4.20	13.20
EAR	−0.490	0.846	4.90	19.22	−0.040	0.961	0.02	21.27
EAF	0.943	−0.240	18.12	1.55	−0.645	−0.722	5.75	12.02
IC	−0.766	0.341	11.96	3.13	0.380	0.727	2.00	12.19
FAEP	0.400	−0.824	3.26	18.27	0.138	−0.937	0.26	20.23
G_value	0.326	−0.318	2.17	2.71	−0.291	−0.332	1.17	2.54
AH	−0.372	−0.825	2.81	18.28	0.781	−0.504	8.45	5.86
EE	−0.511	−0.525	5.32	7.41	0.727	−0.116	7.32	0.31
OE	–	–	–	–	0.968	−0.083	12.97	0.16
NG(H)	–	–	–	–	0.953	−0.136	12.55	0.43
NG(C-HW)	–	–	–	–	0.903	−0.219	11.28	1.10
E	–	–	–	–	0.429	−0.491	2.54	5.56

In situation A (without occupants), the main contributors to PC_1 are the dimensional and morphological metrics: the perimeter (P) and the opening area (EAF), with 18.19% and 18.12%, respectively. The envelope wall area contributes 14.82%, the compacity index 11.96%, and the volume of the architectural object 11.43%. The main contributors to PC_2 are the dimensional and morphological metrics (the roof area with 19.22%, FAEP with 18.3% and the useful area with 16.7%) and one energy metrics (the auxiliary heat AH with 18.3%). It is worthy to note the irrelevant contribution of the global loss coefficient (*G-value*) in both components, given that its estimation involves most of the previously mentioned metrics and, in an indirect way, the auxiliary heat (AH) whose estimation involves the *G-value*. Also the contribution of embodied energy is neglectable.

In situation B (with occupants), the main contributors to PC_1 and PC_2 are different than in situation A. The main contributors to PC_1 are the operative energy (OE, 12.97%), and the natural gas consumption for heating (NG(H), 12.55%), followed by the useful area (with 11.43% is the only *building-related* variable). It is worthy to note that, while the percentage contribution of natural gas consumption metrics to PC_1 is remarkable, the same is not true for electricity. The reason is that electricity is responsible for only 11% of the total energy consumed by the studied houses per m^2 and per year and that 89% corresponds to natural gas [12]. These percentages are in agreement with the average value of about 87% given by the provincial statistics. Finally, the main contributors to PC_2 are –similarly to situation A- the roof area (EAR, 21.27%) and

Table 7
Component weights and contributions of the different houses.

Houses	A				B			
	Component Weights		Contribution parameters (%)		Component Weights		Contribution parameters (%)	
	PC_1	PC_2	PC_1	PC_2	PC_1	PC_2	PC_1	PC_2
VA_1	−1.898	−2.726	8.16	22.19	4.708	−2.027	34.07	10.51
VA_2	−1.533	−1.002	5.32	3.00	0.934	0.385	1.34	0.38
VA_3	−2.907	−1.933	19.14	11.16	4.448	0.037	30.41	0.00
VA_4	−0.259	2.035	0.15	12.37	−1.100	1.750	1.86	7.84
VA_9	0.067	2.020	0.01	12.19	−1.605	1.781	3.96	8.12
VA_{11}	4.180	−1.055	39.55	3.33	−3.687	−3.090	20.89	24.45
VA_{15}	−0.569	1.073	0.73	3.44	−0.103	1.121	0.02	3.22
VA_{20}	0.405	2.203	0.37	14.50	−1.277	1.520	2.51	5.92
VA_{21}	3.328	−2.007	25.07	12.03	−1.673	−3.418	4.30	29.91
VB_1	−0.813	1.392	1.50	5.79	−0.645	1.942	0.64	9.65

Table 8
Cluster analysis results by classes.

	A				B		
	Class 1	*Class 2*	*Class 3*	*Class 4*	*Class 1*	*Class 2*	*Class 3*
Objects	2	1	5	2	2	6	2
Intraclass variance	5.37	0.00	1.84	2.59	10.60	4.93	4.56
Minimum distance to centroid	1.64	0.00	0.70	1.14	2.30	1.27	1.51
Maximum distance to centroid	1.64	0.00	1.18	1.14	2.30	1.87	1.51
Medium distance to centroid	1.64	0.00	1.48	1.14	2.30	3.54	1.51
	VA_1*°	**VA_2***	**VA_4***	**VA_{11}***	**VA_1***°	VA_2	**VA_{11}***
	VA_3		VA_9	VA_{21}	VA_3	**VA_4***	VA_{21}
			VA_{15}			VA_9	
			VA_{20}			VA_{15}	
			VB_1°			VA_{20}	
						VB_1°	

References: (*) central objects; (°) measured objects.

the FAEP factor (20.23%), which are both *building-related* variables. Again, the components the contribution of embodied energy (EE) in situation B is irrelevant.

It is concluded that PC_1 and PC_2 offer the best explanation for the system's maximum variance, being PC_1 the component with higher influence. Without occupants, PC_1 is dominated by the perimeter (P) and the opening area (EAF). With occupants, PC_1 main contributors are those related with gas consumption (operative energy (OE) and the natural gas consumption for heating). The roof area (EAR) and FAEP are the items which contribute the most to the second component PC_2, in both situations, with and without occupants. The results obtained may orient either the design and/or the energy retrofitting of the architectural object (endogenous factors) in a given socio-environmental context which conditions users' energy consumption.

Finally, Table 7 shows the partial contributions of the different architectural objects to each of the first two PC. In general, it may be observed that in situation A (without occupants), VA_{11} is the object with higher contributions to PC_1, followed by VA_{21} with a 40 and 25%, respectively. In situation B (with occupants), which is more interesting from the *user-related* point of view, the highest contributions to PC_1 come from VA_1 (34%), followed by VA_3 and VA_{11} (with 30 and 21%, respectively). Due to this high contribution, VA_1 was selected as a 'case-study' for the energy retrofit described in Section 5.

3.3. Hierarchical agglomerative clustering

Table 8 shows the results of the HAC typological analysis for both situations, resulting in four Classes for situation A and 3 Classes for situation B. This grouping derived from the use of a HCA is illustrated by means of dendograms in Fig. 3. This type of representation allows appreciating in a clear way the grouping relationships among the different architectural objects, and even, among groups of architectural objects. The observation of the successive subdivisions offers an idea regarding the grouping criteria and the distance among data according to the relationships established.

Class 1 has the same elements (VA_1 and VA_3) in situations A and B, with the centroid being VA_1. Because both houses share a lot of similarities, a set of the same retrofit strategies can be stated for them. For example, both houses are oriented on a N-S axis, with similar perimeter, volume and compacity index. Both have similar values of embodied energy and consumption of natural gas for heating per m^2. None of them has hermetically sealed double glazing but they do have night protection. Both houses are massive, with exterior walls made of standard massive 0.30 m brick (thermal transmittance $U = 1.88\, W/m^2$-K). The roof's thermal transmittance is $U = 1.62\, W/\ m^2$-K. The house VA_1 was monitored during the extreme weather seasons described in detail in different previous works [12–14]. For this reason, its behavior might be extrapolated to VA_3. The indoor temperature in a cold period of August 2010 was 21.8 °C (outdoor temperature = 7.7 °C) and an average natural gas consumption of 0.22 m^3/m^2. It may be inferred that the winter thermal behavior in VA_3 is similar to that of VA_1, and that their users live comfortably. In relation to retrofit strategies, it must be noted that the contribution of the vertical envelope to the system's variability is of 18.12% (fenestration) and 14.82% (walls) in PC_1 and that of the roof is 19.22% in PC_2. From a potential energy intervention practice it may be possible to propose for these two cases belonging to energy Class 1, the retrofitting of the vertical and upper envelope without affecting their morphology, and obviously, their dimensional metrics (perimeter, volume and compacity index). This retrofit and its results will be described in the next section.

Class 2-situation B and Class 3-situation A have similar objects, except for VA_2. In both classes we find house VB_1 which was mon-

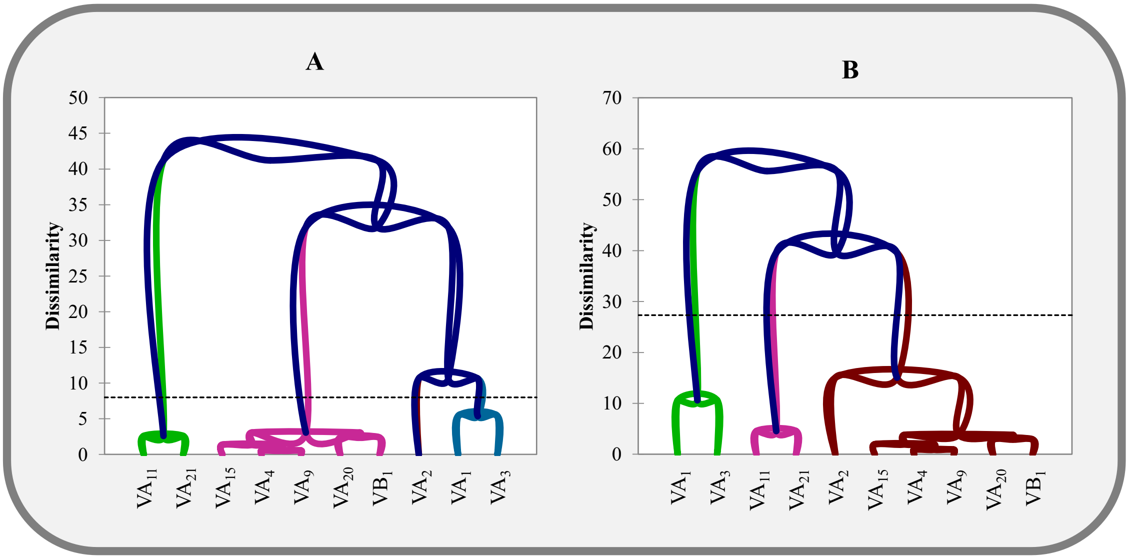


Fig. 3. Dendrogram by architectural object.

itored and studied in previous works. In situation B, Class 2 despite the fact of having 6 objects, shows a low intra-class variance (4.93) similar to that of Class 3 (4.56) with only two elements and much lower than that of Class 1 (10.6), also with 2 elements (see Table 8). This is a valid argument to assume that, in spite of the distance between VB_1 and the centroid, its energy behavior might be extrapolated to the other houses. VB_1 was monitored during the cold period of July-August. The mean indoor temperature was 17.9 °C (outdoor temperature = 7.4 °C) and an average natural gas consumption of 0.14 m^3/m^2. According to Table 6, the greatest percent contribution in PC_1, situation B corresponds to operating energy (OE, 12.97%). Since the embodied energy does not show an important relative contribution, for this study only the total is considered (EE + OE). It can be observed that the values range between 25.44 and 33.99 GJ/m^2 for VA_9 and VB_1, respectively, values that contribute with 86 and 84% of the total. Figures are lower than others in studied cases mentioned in the previous paragraph, which were in the order of 62.63 and 65.9 GJ/m^2 for VA_1 and VA_{23} respectively, with a 91 and 87% of relative contribution in the total.

In the case of Class 4-situation A and Class 3-situation B, a future task might be monitoring VA_{11} and/or VA_{21}. Data in Table 7 makes evident that both houses have an important contribution in PC_1 and PC_2 variability.

3.4. Retrofit of VA_1: Assembling PCA and HCA results

As previously explained, the selection of VA_1 as 'case study' was based in the PCA analysis that highlighted its important weight on the PC_1 y PC_2 components (34.07% and 10.51%, respectively, Table 7). Besides, HAC and PCA results stressed the importance of the vertical envelope in the energy retrofit. Therefore, under the premise of not modifying the morphology and dimensional metrics of the house (perimeter, volume and compacity index), we selected the metrics related to the materiality to work with. In particular, *G-value* -which is directly related with the envelope transmittance- affects the auxiliary heating energy and the embodied energy. Thus, the decision was to include thermal insulation in the vertical opaque envelope. This improvement allows intervening from the outer side of the wall without disrupting the inhabitants' activities.

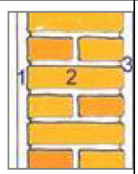
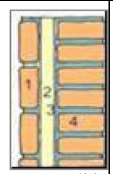
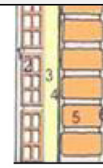
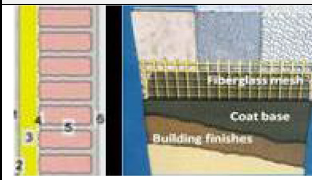
Although in Argentina the energy standards are not compulsory, we need to know its energy behavior or performance in relation to them. IRAM Norm 11604/5 (2002) recommends maximum thermal transmittance values of 0.31 and 0.83 $W/(m^2\ K)$ for walls for Santa Rosa city; values which correspond to two levels of thermal comfort (A and B). In the 'case study' house VA_1, the wall thermal transmittances do not even reach the less demanding level B [15]. Thus, the decision was to adopt an intermediate value of transmittance, between A and B, and a value of 0.56 $W/(m^2\ K)$ was set for the wall retrofit. This value is obtained from the addition of a 0.05 m thick layer of EPS. The position of the insulating layer and the wall technology were proposed according to the built and monitored bioclimatic buildings background of the region under study.

Table 9 shows the energy and economic indicators of the 'reference wall' (the original wall W_1) and three different technologies of improved walls (W_2 – 0.05 m thick plastered wall with bricks placed on their sides; W_3 - 0.08 m thick hollow ceramic brick wall; W_4 - Iggam base COAT[1]). The variation among the different technological proposals is seen in the last thermal insulation protective layer, which gives the mechanical resistance required for an outer wall. The operating energy savings with respect to the 'reference' W_1 range between 25% and 37% for heating and between 24% and 36% for cooling. This energy saving implies an increase in the envelope cost. For example, in 2017 a retrofit from W_1 to W_2 (the most expensive of the three technologies) implies an inversion of 97 US$/$m^2$ (thermal insulation + brick for mechanical protection of the insulation) while a retrofit from W_1 to W_4 (the cheapest one) implies an inversion of only 39.5 US$/$m^2$. Thus, an economic analysis of each technology proposal is performed in accordance with Yildiz et al. [45] and Dombaycı [9]. Because in Argentina the economic situation is highly variable and very complex, with a growing inflation each year (see exchange rates from 2013 to 2017 in Table 9), the analysis should include the inflation, payback period in the lifetime period of the retrofit. The next section deals with these subjects.

The embodied energy per m^2 of habitable surface for the retrofitted vertical envelope of VA_1 (about 2.6 GJ/m^2) and for the other houses of the group is shown in Fig. 4, together with values presented by different authors for other geographical locations [8]. A good agreement with other values in the literature was found. The percentage increase of embodied energy due to the incorporation of the thermal insulation into the technology component is shown in Fig. 5, value that does not exceed 3.5%.

[1] Base COAT is a cementitious material with additive polymer. It is used as an adhesive and as a coating base on thermal insulation.

Table 9
Energy and economic indicators for each vertical envelope technology. References: W_1 (massive 0.30 m brick wall); W_2 (0.05 m brick on its side); W_3 (0.08 m hollow brick); W_4 (COAT base); DD (Degree Days).

Vertical envelope technology		W_1 (reference wall)	Mechanical Protection		
			W_2	W_3	W_4
		 Solid brick. external and internal plaster and paint	 1: solid brick. 2: EPS. 3: vapor barrier 4: solid brick	 1: external plaster and paint; 2: ceramic block. 3: EPS; 4:	 1-2: COAT base; 4: EPS; 5: vapor barrier 6: solid brick 7-8: internal plaster and paint
Thermal transmittance W/(m^2 K)		1.88	0.55	0.50	0.56
G-value W/(m^3 K)		2.63	1.96	1.65	1.97
Heating energy consumption (m^3 of natural gas) Design base temperature: 21ºC (DD = 2038)	daily	6.5	4.9	4.0	4.9
	annual	947	706	594	709
Energy saving (%)	Heating		25.0	37.3	25.1
	Cooling Design base temperature: 23ºC (DD=128)		24.4	36.0	23.9
			Cost/m^2 = insulation + mechanical protection		
Costs	Year 2013	144.7	165.7	162.2	67.4
	Year 2015	129.0	147.7	144.5	60.0
	Year 2017	85.0	97.0	95.0	39.5

3.5. Cost-benefit analysis in VA_1 technology improving

Eqs. (1)–(4) were used to calculate annual costs and investment payback periods. In this paper, the adopted values were: interest rate $i = 24\%$ (interest rate issued by the Bank of the Province of La Pampa), inflation rate $g = 35\%$ (inflation rate according to the estimates of Argentina's National Congress, 2016) and useful life $N = 20$ years according to the background and state of conservation of the thermally insulated envelopes of buildings constructed in the region under study (10 years more than [45]). This gives a *present worth factor* of $PW = 2.27$. Results are shown in Tables 10–12. Table 10 shows the payback periods of W_2, W_3 and W_4 insulating envelopes for different situations of natural gas prizes: the one of the neighboring countries and the real one of Argentina (for 2013, 2015 and 2017). In the case of the prize of Argentina, the subsidies applied in each case changed from one year to the other. In particular, in 2015 the cost per m^3 of natural gas paid by users depended on savings with respect to the same period in the previous year, thus the user with savings higher than 20% were benefited with lower gas prizes.

In 2013, when the cost of the m^3 of natural gas is similar to that of the neighboring countries, the improved wall is economically feasible, with recovering periods between 5.3 and 6.5 years (W_4 and W_2 technologies, respectively). On the opposite, the high subsidies for gas prizes in Argentina discouraged the retrofitting of walls with a payback period of more than 50 years for any technology. In 2013, the gas cost was in average 33 times lower in Argentina than in the neighboring countries.

In 2015, the cost of gas suffered a drastic change –in order to install in users the idea of a more efficient consumption- and benefits were done to users that decreased their consumptions when compared to the same period in the previous year. The payback period depends on whether charges are subsidized or not. If a 20% saving in consumption is considered, for W_2 technology, the investment payback period is of almost 70 years and 23.3 years, with and without subsidy, respectively. For the users that save a value lower than 5% and for the same technology, the payback period

Table 10
Payback period of the different envelope technologies according to different energy costs in 2013, 2015 and 2017.

Year	Envelope technologies	Payback period (years)						
		Argentina						Average of neighboring countries
2013 (Exchange rate: $5.37/US$)		A: with subsidies 0.10 $/m^3			B: without subsidies 0.41 $/m^3			0.99 U$S * International comparison of natural gas rates for residential clients. June. 2013. Metrogas (Brazil = 1.7; Uruguay = 1.46; Chile = 1.17; Bolivia = 0.14; dollar/m^3)
	W_2	64.03			15.77			6.53
	W_3	60.39			14.88			6.16
	W_4	52.48			12.93			5.35
2015 (Exchange rate: $9.04/US$)*		Savings > 20% with respect to the previous period		Savings from 5% to 20% with respecto to the previous period		Savings < 5% with respect to the previous period		0.93 U$D ** International comparison of natural gas rates for residential clients. June. 2015. Metrogas (Brazil = 1.36; Uruguay = 1.42; Chile = 0.89; Bolivia = 0.04; dollar/m^3)
		A 0.055 $/m^3	B 0.165 $/m^3	A 0.13 $/m^3	B 0.39$/m^3	A 0.20 $ m^3	B 0.63 $/m^3	
	W_2	69.85	23.28	29.95	10.25	14.85	5.00	5.81
	W_3	65.88	21.96	28.22	9.64	18.65	6.26	5.24
	W_4	57.25	19.08	24.63	8.48	16.37	5.60	4.29
2017 (Exchange rate: $17.2/US$)		A: with subsidies 0.89 $/m^3			B: without subsidies 1.97 $/m^3			0.93 U$D** International comparison of natural gas rates for residential clients. June. 2015. Metrogas (Brazil = 1.36; Uruguay = 1.42; Chile = 0.89; Bolivia = 0.04; dollar/m^3)
	W_2	5.09			2.30			5.81
	W_3	4.62			2.09			5.24
	W_4	3.47			1.57			4.29

*The amount paid by users depends on savings with respect to the same period in the previous year (%).

Table 11
Estimation of energy consumption of VA_1 for different improvement strategies, under present (B, C, D) and future (E) climate conditions. The energy consumption of the conventional house VA_1 (without improvements) corresponds to real measured values. .

	Estimated energy consumption								
A Conventional	Winter								Annual
	Gas				Electricity Lighting and appliances(kWh/day)	Electricity consumption for 150 days of using air conditioning for heating (kWh)	Daily average air conditioning for air heating (kWh/day)	Air conditioning for heating + Cooking + Lighting and electrical appliances (kWh/day)	Total (kWh/year)
	Energy used according to efficiency heating system				5.6				
	m^3/day 7.5	MJ/day 3.75*	kWh/day 148	 41.1		41.1*150 = 6165	16.9 (6165/365)	23.5 (16.9 + 5.6 + 1)	8577.5
B Refurbished air conditioning system with heat pump (Maximum rated power = 1 kW)	10.15 kWh: (1/4) * 41.1					10.15 * 150 = 1522	4.2	10.77 (4.17 + 5.6 + 1)	3931.0
C conditioning system refurbished + vertical envelope retrofitting	6.0	3.0*	118.4	32.9		8.2*150 = 1234.3	3.4	10.0 (3.4 + 5.6 + 1)	3650.0
			8.2 kWh: (1/4) * 32.9						
D conditioning system refurbished + vertical and horizontal envelope retrofitting	3.3	1.65*	65.2	18.1		4.5*150 = 675.0	1.8	8.40	3066.0
			4.5 kWh: (1/4) * 18.1						
E conditioning system refurbished + vertical and horizontal envelope retrofitting According thermal simulation for the weather conditions of 2039 [15]	4.7 (1)	2.35*	92.7	25.8		6.4 * 150 = 960	2.60	9.2 (2.60 + 5.6 + 1)	3358.0
			6.4 kWh: (1/4) * 25.8						
	2.5 (2)	1.25*	49.4 3.43 kWh: (1/4) * 13.7	13.7		3.43*150 = 514.5	1.41	8.01 (1.41 + 5.6 + 1)	2923.6

References: (*) useful energy for heating considering an efficiency of gas equipment about 50%;(1) thermal improvement of walls; (2) thermal improvement of walls and roofs.

Table 12
Payback period of the different proposals. A to D cases consider current weather, while E considers future weather conditions towards 2039. References: (1) thermal improvement of walls; (2) thermal improvement of walls and roofs.

Case (referred to Table 11)	Solar Photovoltaic Panels			Solar Water Heater
	Number of panels (a panel of 250Wp = 4 kWh/day)	Cost (U$S)	Payback period (years)	Payback period (years)
A	23.5	U$S 9407	11.1	16.7
B	11.0	U$S 4400	11.3 (75,680/$1.7/kWh*3650 kWh	
C	10.0	U$S 4000	11.1	
D	8.5	U$S 3400	11.2	
E	9.0 (1)	U$S 3600	10.8	
Under climatic conditions towards the year 2039 with energy value at the current price ($1.7/kWh)				
	8.0 (2)	U$S 3200	11.0	

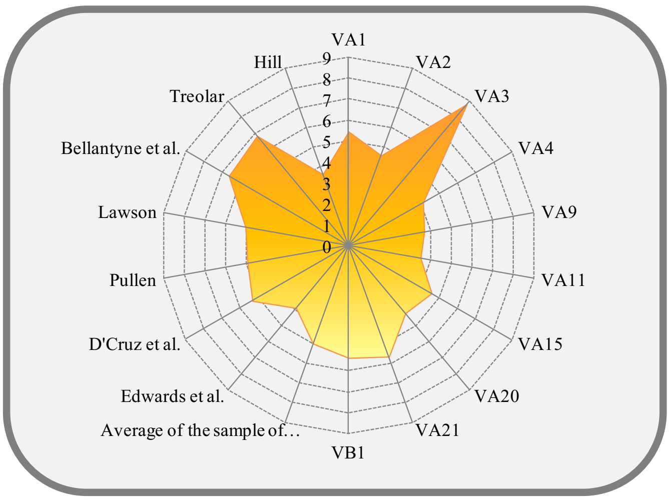


Fig. 4. Embodied energy by improving the thermal envelope of each house in GJ/m^2.

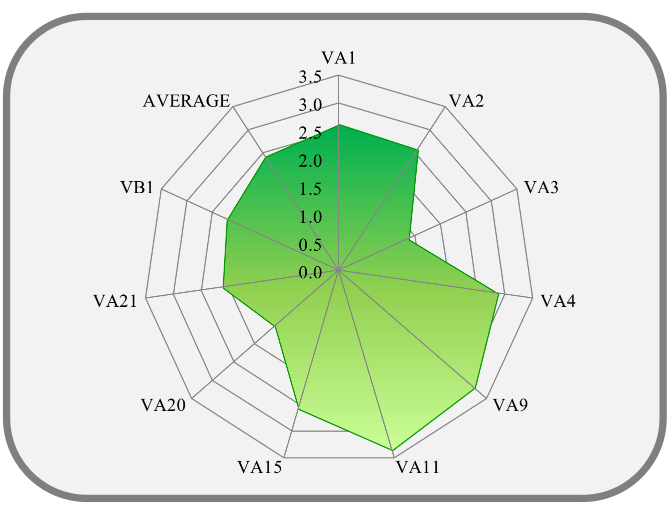


Fig. 5. Percentage increase of embodied energy due to the incorporation of the thermal insulation in the vertical envelope of each house.

strongly decreased to 14.85 and 5 years for situations A and B, respectively. For them, the wall retrofit starts to be a reasonable option.

In 2017, the new government decided to gradually reduce the energy subsidies and to increase the gas prize resulting in dramatic increments of the gas bills. Payback periods are about 5.09 and 2.30 years (with and without subsidies, respectively), for W_2 type wall. As it may be expected, the rate charged conditions the payback period of the cost overrun paid to improve the thermal quality of the envelope so that the envelope improvement option were economically viable. In particular, the W_4 technology presents the lower payback periods, with values lesser than two years.

3.6. Integrating envelope's technology improvement and a family's basic needs while adapting to climate change

A previous dwelling retrofit in the region [15] considering the impact of the climate change for 2039 showed that, for 2039 and due to higher temperatures both in winter and summer, the energy demand will decrease in the cool season and will increase in the hot season. To lower the energy consumption of gas and electricity, besides improving the envelope with thermal insulation, the improvement of the energy equipment efficiency and the use of renewable energy were suggested. Thus, for VA_1, the refurbishment of the air conditioners with heat pumps (nowadays, the installed equipment do not include them) and two renewable energy systems - photovoltaic (PV) panels to cover the summer consumption destined to air cooling and solar heaters for hot water provision - were proposed.

Four retrofit strategies for VA_1 were proposed (Table 11), including the refurbishment of the air conditioning and different levels of thermal insulation (only walls, and walls + roofs). Calculations were made for current weather conditions (retrofit strategies B, C and D) and for future weather (E). Results show that, for current weather conditions, the annual energy consumption of VA_1 of 8577.5 kWh. For 2016 values, it implies a 14% of the monthly incomes of a poor family and 36.5% of the extremely indigent family income. The annual consumption can be reduced to a 45% of its value if the air conditioning equipment is refurbished (case B), to a 42% of the annual consumption if air conditioning is refurbished and walls are insulated (case C), and to a 35% if also the roof is insulated (case D). In the case of future weather conditions, a reduction to 34% of the actual consumption can be obtained (case E).

Table 12 shows the PV panel area and payback periods for cases A to E. All of them present payback periods around 11 years. In the case of solar water heaters, with a consumption of 50 liters/person-day and cold water mean annual temperature of 17 °C, the useful energy required is about 4.8 MJ/day. If an efficient water heater is used (efficiency about 50%), it requires about 1 m^3/day of natural gas (41.8US$/year, without subsidy). Because in Argentina the solar water heater cost is about US$700, the payback period is around 16.7 years. Nowadays, the government is implementing a plan to subsidize the cost of the renewable energy systems.

It is concluded that the technological improvement of the dwelling's envelope and its energy retrofitting using a photovoltaic system together with water solar heating would allow that a percentage of dwellings under the poverty line could be part of an inclusion process, in agreement with natural resources preservation practices, and in an attempt to develop a more sustainable world. Options should be part of the strategies and actions taken to define a national policy to decrease energy poverty and to mitigate climate change. Thus, in view of climate change with less severe winters and warmer summers in the region under study, one of the mitigation options in the building sector (Case E) shows the least energy consumption value (with an increase of the envelope's thermal resistance). In the coming years, it is probable that the socio-economic variables in Argentina may vary, situation that will also change the 2039 scenario.

4. Conclusions

A sample of 10 compact houses built in the 1950s (prismatic and conventionally built) was statistically analyzed through PCA and HAC multivariate techniques. The *building-related* driving metrics included eleven variables (describing dimensional and morphological parameters of the houses, and thermo-physical and energetic metrics), while *user-related* driving metrics included four variables (operational energy, natural gas consumption for air heating, natural gas consumption for cooking and hot water, and electricity consumption). The higher CV values found in the *user-related* metrics highlight the influence of occupants in the energy consumption that can result in huge gaps between real and predicted energy performance of buildings. In average, 16% of the total energy consumption corresponds to the embodied energy and around 84% to the operational energy.

The contribution of each architectural object to the principal components allowed detecting house VA_1 as the most contributing, thus, it was selected as case study for *energy retrofit*. The economic viability and payback periods of the intervention proposal were compared in 2013, 2015 and 2017 under different economic scenarios, due to the different political and economical context throughout the period. The results indicate that an improvement of the envelope's thermal quality (this might only mean increasing 5% the embodied energy) before the elimination of subsidies reduce the payback period. A reduction of heating natural gas consumption (high contribution on the total consumption of natural gas) might allow to decrease the amount of fluid needed, to expand the networks and to provide gas to more low-income neighborhoods located in the cities' peripheral areas that do not have access to networks, thus alleviating energy lacks.

Argentina is characterized by a strong housing deficit. According to the 2010 National Population and Housing Census, in our country live 40 million people in 12 million dwellings. In order to analyze the deficit's evolution in the period between censuses, information from the EPH Survey (Housing Permanent Survey) can be used, from which it can be derived that for the year 2014 the housing deficit was of 1946,688 dwellings, out of which 64% is quantitative and 36% is qualitative. To this deficit, each year, the additional need due to net growth of the amount of homes or vegetative growth is added: 120,000 dwellings, 65,000 correspond to the most vulnerable sectors. Building dwellings in order to gradually meet this deficit brings about the uneven and dispersed growth of cities, growth which goes hand in hand with the lack of basic infrastructure. This process should be approached applying actions and strategies within a sustainable framework and preserving resources in a context of social equity. One of these strategies concerns energy efficiency (the use of the minimum energy resources possible to achieve the desired comfort level) applied to the dwelling's design as a priority. Consuming less energy to do the same activities mitigates the GHG emissions, preserves resources and decreases users' energy costs. Using less energy to have the same services, may allow those inhabitants with less economic resources to have access to those services, widening the scope of energy beneficiaries, alleviating energy lacks and achieving social equity.

The international experience shows that, in general, it is cheaper to save an energy unit rather than produce it. It is in this way that energy efficiency becomes a crucial protagonist of the energy matrices in developed countries since it is a low-cost source of energy, which at the same time does not contaminate the environment.

There are arguments that are certainly convincing: 1- there is a housing deficit in the region under study, and 2- 27% of the families live under the poverty and extreme poverty line (their monthly average income are 40% less than the Family Food Basket). This is associated with energy poverty since an important percentage of society cannot afford the conventional energy consumption to meet their basic needs and live comfortably in the 21st century. The dwelling studied in depth (monitored and audited both in summer and winter, whose historical energy consumption values were analyzed) may be considered a prototype of social housing to be part of a housing complex. The results of the retrofitting strategies, the change of the air conditioning system and the incorporation of photovoltaic panels can be generalized to the other sample dwellings in view of their technology similarities and the generalization of arguments to meet the housing deficit and improve the living conditions of those living in poverty and marginality. If the number of dwellings representative of the housing deficit were taken into account (4300), and considering an average of 50 m2/dwelling of conventional construction, the investment needed would be U$S 212,500.000 (at a construction cost of US$/$m^2$). The incorporation of envelope improvement measures (option W_4 in the Table), solar water heating and the use of photovoltaic panels applied to the conventional dwelling, in terms of July 2017 rates, would be 11.8% of the total cost. To achieve such a transformation in the housing policies implies a conceptual change that might approach the problem, including the energy problem, from an inclusive and holistic perspective, with the aim of promoting development within a social framework of equity.

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Appendix A: Embodied energy of the architectural objects and contributions of the technological components

Table A1
Embodied energy.

Technological component		Sample of the studied houses	Primary energy (MJ/kg)	MJ
Foundation and wall of solid brick		VA_1	2.85 MJ/m^2	146,716
		VA_2		179,550
		VA_3		349,404
		VA_4		261,630
		VA_9		209,301
		VA_{11}		236,236
		VA_{15}		237,006
		VA_{20}		266,760
		VA_{21}		279,072
		VB_1		237,006
Bracing lower and upper reinforced concrete ($k = 1.65$ W/m^2 °C)		VA_1	0.99 MJ/m^2	6000
		VA_2		2574
		VA_3		3564
		VA_4		3465
		VA_9		3094
		VA_{11}		–
		VA_{15}		1468
		VA_{20}		2153
		VA_{21}		2227
		VB_1		6497
Subflooring without pavement		VA_1	2.03 MJ/m^2 Authors' value according to a dosage of a HHRP (Poor hydraulic reinforced concrete: 1 lime, cement 1/8, 4 sand 8 rubble)	14,287
		VA_2		24,360
		VA_3		16,240
		VA_4		33,507
		VA_9		28,063
		VA_{11}		14,400
		VA_{15}		27,543
		VA_{20}		30,206
		VA_{21}		24,522
		VB_1		29,232
Roof	*French ceramic tiles on ceramic structure prestressed*	VA_1	Structure + tiles: 623.0[a] MJ/m^2	21,236
	Horizontal roof with aluminum membrane over resistant structure (hollow brick, prestressed girder and compression layer)	VA_2	490 MJ/m^2 and subflooring: 325 MJ/m^2	52,164
		VA_3		48,888
		VA_4		48,583
		VA_9		47,452
		VA_{15}		69,095
		VA_{20}		75,795
		VA_{21}		61,517
	Horizontal roof with aluminum membrane over resistant structure (arch between steel floor doble T N° 16 beems)	VB_1	2039 MJ/m^2 (Authors' value)	133,530
	Metalic lightweight roof and wooden structure without thermal insulation and horizontal roof with aluminum membrane over resistant structure	VA_{11}	219.5 MJ/m^2	17,367
			490 MJ/m^2 and subflooring (325 MJ/m^2)	12,480
Exterior and interior plaster and ceiling (40 kg/m^2)		VA_1	1.34	9166
		VA_2		20,604
		VA_3		18,974
		VA_4		21,172
		VA_9		14,215
		VA_{11}		23,584
		VA_{15}		16,080
		VA_{20}	1.40 MJ/m^2	10,967
		VA_{21}		27,202
		VB_1		20,207

(continued on next page)

Table A1 (*continued*)

Technological component	Sample of the studied houses	Primary energy (MJ/kg)	MJ		
Painting	VA_1				239
	VA_2				553
	VA_3				496
	VA_4				802
	VA_9				371
	VA_{11}				410
	VA_{15}				420
	VA_{20}				287
	VA_{21}				710
	VB_1				528
Carpentry	VA_1	Aluminium frame: 1240 MJ/m^2			14,260
	VA_2	Wood frame: 294 MJ/m^2			1176
	VA_3	Wood frame: 294 MJ/m^2			1411
	VA_4	Original: wood frame (294 MJ/m^2)	Changed by aluminium frame: (1240 MJ/m^2;)	1470	6200
	VA_9	Light ironwork			11,166
		Wood frame: 294 MJ/m^2			3087
	VA_{11}	Wood frame: 294 MJ/m^2			3087.0
		Wood frame: 294 MJ/m^2			6572.0
	VA_{15}	Light ironwork			16,794
		Aluminium frame: 1240 MJ/m^2			19,840
	VA_{20}	Wood frame: 294 MJ/m^2			6174
	VA_{21}	Aluminium frame: 1240 MJ/m^2			30,800
	VB_1	Wood frame: 294 MJ/m^2			2146
TOTAL		UNITS		MJ	MJ/m^2
		VA_1		211,904	5419.2
		VA_2		280,981	4554.0
		VA_3		438,977	8779.5
		VA_4		376,829	4109.4
		VA_9		316,749	3666.1
		VA_{11}		314,136	3490.4
		VA_{15}		388,246	4578.4
		VA_{20}		392,342	4218.7
		VA_{21}		426,050	5643.0
		VB_1		429,146	5364.3

[a] The value corresponds to a cover with thermal insulation, so its energy content is substracted in this particular case (5709 MJ). The considered value is 491 MJ/m^2.

Table A2
Embodied energy into each technological component (%).

		Sample of the studied houses										Descriptive statistics		
		VA_1	VA_2	VA_3	VA_4	VA_9	VA_{11}	VA_{15}	VA_{20}	$VA2_1$	VB_1	Average	SD	CV
TEE		211,904	280,981	438,977	376,829	316,749	314,136	388,246	392,342	426,050	429,146	357,336	70,426	0.20
TEE/m^2		5419.2	4554.0	8779.5	4109.4	3666.1	3490.4	4578.4	4218.7	5643.0	5364.3	4982.3	1443.7	0.29
TC	1	69.2	63.9	79.6	69.4	66.1	75.6	61.0	68.0	65.5	55.2	67.4	6.6	0.1
	2	2.8	0.9	0.8	0.9	1.0	0.0	0.4	0.5	0.5	1.5	0.9	0.7	0.8
	3	6.7	8.7	3.7	8.9	8.9	4.6	7.1	7.7	5.8	6.8	6.9	1.7	0.2
	4	10.0	18.6	11.1	12.9	15.0	9.5	17.8	19.3	14.4	31.1	16.0	6.0	0.4
	5	4.3	7.3	4.3	5.6	4.5	7.5	4.1	2.8	6.4	4.7	5.2	1.4	0.3
	6	0.1	0.2	0.1	0.2	0.1	0.1	0.1	0.1	0.2	0.1	0.1	0.0	0.3
	7	6.7	0.4	0.3	2.0	4.5	3.1	9.4	1.6	7.2	0.5	3.6	3.1	0.9

References*: TEE (Total embodied energy, MJ)*
TC (Technological component contribution, %): 1: Walls and foundation; 2: Bracing; 3: Subfloor without pavement; 4: Roof, 5: Plaster; 6: Paint; 7: Windows and doors.

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