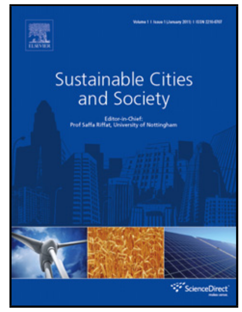
Journal Pre-proof



Addressing the Potential for Improvement of Urban Building Stock: A Protocol applied to a Mediterranean Spanish Case

T. Blázquez, R. Suárez, S. Ferrari, J.J. Sendra

PII: S2210-6707(21)00253-5

DOI: https://doi.org/10.1016/j.scs.2021.102967

Reference: SCS 102967

To appear in: *Sustainable Cities and Society*

Received Date: 21 January 2021

Revised Date: 21 April 2021

Accepted Date: 23 April 2021

Please cite this article as: Blázquez T, Suárez R, Ferrari S, Sendra JJ, Addressing the Potential for Improvement of Urban Building Stock: A Protocol applied to a Mediterranean Spanish Case, *Sustainable Cities and Society* (2021), doi: https://doi.org/10.1016/j.scs.2021.102967

Addressing the Potential for Improvement of Urban Building Stock: A Protocol applied to a Mediterranean Spanish Case

T. Blázquez [a, *]; R. Suárez [b]; S. Ferrari [a]; J. J. Sendra [b]

[a] *Department of Architecture, Built Environment and Construction Engineering (ABC), Politecnico di Milano, Milano (Italy)*

[b] *Instituto Universitario de Arquitectura y Ciencias de la Construcción, Escuela Técnica Superior de Arquitectura, Universidad de Sevilla, Sevilla (Spain)*

* Corresponding author.

E-mail address: mariateresa.blazquez@polimi.it

Full postal address: Dept. ABC - via Ponzio 31 – 20133 – Milano, Italy

Highlights

- Bottom-up protocol to rate urban stock energy behaviour before building upgrading.
- Geographic Information System ease to store and analyse building-related data.
- As built and upgraded energy models provide for buildings shortcomings.
- The protocol is applied to a Mediterranean climate-dominated Spanish city.
- The achieved benefits allow stakeholders in decision-making of buildings upgrading.

Abstract

Current plans to combat the environmental global impact of the building sector have encouraged research on sustainable actions for increasing the renovation rate of many buildings whose performance is far from meeting current energy standards.

This paper presents a protocol for analysing the existing residential stock towards planning building upgrading actions. A Geographic Information System with building-related data is used to assess the housing stock following a bottom-up approach. The urban study sample is established using several criteria at building level. The potential for improvement of buildings is ascertained using DOE 2.2 energy models which incorporate standard passive strategies to reduce the current primary energy demand and the associated CO_2 emissions.

The protocol is applied to the existing public housing developments built in the southern Spanish city of Córdoba, under Mediterranean conditions, during the urban expansion period which spanned 1951 to 1980.

The extrapolation of results to the urban study sample shows a 25 % reduction in CO_2 emissions and a 40 % decrease in annual energy demand. Furthermore, the impact of typology and position on the energy behaviour of a given building is acknowledged.

The benefits achieved aim to help stakeholders in the implementation of energy retrofitting urban plans.

Keywords: *public housing developments; Mediterranean housing stock; buildings energy performance; urban analysis; GIS for urban building model; UBEM.*

1. Introduction

Despite joint efforts from EU countries to reduce CO_2 emissions further measures must be implemented if Europe is to reach the objectives set for 2030 [1]. A key issue for this is the renovation pace of existing buildings, as most European building stock is still in need of updating [2].

Establishing an effective strategy aiming to meet the European targets for energy efficiency in the housing sector first requires a thorough assessment of the energy deficit of existing buildings before implementing the appropriate retrofit strategies. In keeping with this, in recent years, many researchers have focused on the growing need to learn more about the status quo of the existing building stock [3], especially the residential sector. However, further in-depth research of the building stock (in situ assessment, monitoring of environmental parameters, user surveys, representable archetypes, prevailing patterns within the existing stock) is needed to establish more reliable margins for improvement [4].

Top-down and bottom-up approaches are often employed in the study of urban stock [5]. The former focuses on generalized data (i.e., national, or regional consumptions) attempting to predict individual aspects at a macro-scale within a population or stock [6], while the latter examines specific cases in order to identify common assumptions which can be applied to the rest of the analysed stock [7]. Lately, there has been a prevalence of bottom-up approaches due to a greater availability of disaggregated data and to the options for estimating the energy potential of individual buildings to support the update of urban areas [8].

There is currently no standard procedure for the assessment of urban building stock and various methods leading to a diversification of results can be found in the reviewed literature. According to M. Brogger [9], Urban Building Energy Models (UBEM) need to offer transparent results to ensure consistence in the energy performance of real cases, so that the energy improvement potential of building stocks can be estimated with precision. Several works have been found to validate bottom-up UBEMs with data on a national scale for energy demand [10], space heating and domestic hot water [11], and energy-use to address different climate-change scenarios [12], resulting in many cases in differences between simulated and measured results within a range of 3 % [13].

However, finding real and robust data is not always that straightforward. Macro-scale energy expenditure or consumption results and the environmental performance of individual buildings are not always publicly available, either for reasons of data protection or because of planning required for long-lasting tasks in order to obtain this kind of information. In this respect, UBEMs offer the possibility to evolve. This means that the databases generated can be established with the means readily available (i.e., cadastre data, age of construction, morphological building features, size, compactness, thermal envelope constructive definition, energy simulation results) and be updated continuously as energy-related data input becomes feasible and is used to support the results.

Moreover, the assessment of existing building stock involves a broad sample of items to be addressed. A painstaking cataloguing process for building details can be time-consuming and add complexity to the procedure with no major benefit in results. However, excessive generalization can lead to an increase in cumulative errors and result in overestimations [14]. Therefore, these sorts of assessments must be based on balanced representative samples or building “archetypes” of the analysed stock, in an attempt to simplify the most prevalent architectural, constructive, and energy-related features at different scales (local, municipal, regional, or national) [7]. There is a strong correlation between influential energy-related parameters and urban building energy approaches in terms of the building age, type, and compactness ratio of outer surface to heated volume [15].

To simplify this task, the European project TABULA [16] is an effective tool to test wide scope urban building stock, guiding the generation of representative archetypes based on a study carried out over 13 European countries, which provided exemplary catalogues of local traditional building typologies [17]. Within this database several works have been found on representative national stocks. I. Ballarini [18] in Italy and E. Daskalaki [19] in Greece, among others, develop analyses of the local urban residential building stock in order to run energy performance assessments at territorial scale. P. Florio [20] establishes an algorithm-based relation between the French Enquête Nationale Logements (ENL) with TABULA defined typologies for the French stock, aiming to label existing buildings in order to certify their energy performance in a simplified manner. T. Loga [21] uses TABULA archetypes to generate simplified building stocks for each European country involved in the database, providing a cross-country benchmarking of building energy features at national and regional scale. D. Groppi [22] generates an UBEM to address thermal energy consumptions and usable solar energy potential in two Italian districts, transposing TABULA methodology to classify the building stock analysed by age and typology and correlating each category to a defined compactness ratio.

Urban building energy approaches can also be used to plan global strategies or design energy policies to promote building updating [23] by analysing hindrances in the retrofitting process [24]; making the users aware of their homes' potential for improvement [25]; detecting critical areas that need to be addressed beforehand [13]; or assessing the impact of socio-economic features in the regeneration potential of the building stock [26].

Indeed, a common framework that blends and coordinates all the involved agents within a sustainable approach to building stock performance is still needed towards a clear path to address integrated energy planning strategies [27].

Lately, GIS tools have become essential in the urban stock analysis developed as they offer many possibilities linking spatial and temporal data with existing buildings and allowing macro-scale analysis at different urban stages in order to promote more sustainable city energy planning [28]. C. J. García-Ballano et al. [29] estimate energy saving in recently retrofitted near zero Energy Buildings using a parametrized GIS and conclude that the buildings' potential for improvement closely correlate with the age, type, and thermal envelope composition, resulting in an improvement of around 30-58 % in energy behaviour in individual buildings. V. D'Alonzo et al. [30] substitute archetypes and energy simulation methods for GIS tools to estimate energy balance at building level in a sample of 42,000 buildings in the region of Valle d'Aosta (Italy), and achieving a useful methodology for estimating the heating demand of buildings which can also be applied at different scales.

Recent studies focus on different parts of the world, examining different countries and climate zones. This is the case with M. Braulio-Gonzalo et al. [31] where a bottom-up approach to the building stock in a Mediterranean Spanish city is used to analyse buildings' passive energy behaviour and the impact of urban morphology on indoor conditions. Also, in Spain, F. Martín-Consuegra et al. [32] study the impact of energy losses through the building thermal envelopes in an obsolete neighbourhood on the outskirts of Madrid, where the population is exposed to energy poverty. The methodology can be applied to any other building stock, using building cadastre data to estimate energy-related defined indexes (urban overall heat transmission coefficient, energy losses due to conduction across the envelope, urban energy efficiency indicators) by means of GIS tools. Based on data from the Italian cadastre, P. Caputo et al. [33] define a methodology to estimate energy consumption at urban scale by generating building archetypes representing the building stock in Milan (both residential and commercial). As well as the analysis of retrofit barriers in some Italian municipalities [34], they propose a new energy framework at urban scale and GIS tools to encourage building updating by correlating census data and real data, and expecting the results generated to be implemented continuously as more information becomes available [35]. A recent collaboration by P. Caputo on the use of 3D-GIS to study the retrofitting potential of façades with BIPV applied to the Swiss residential sector can be found in [36]. S. Torabi Moghadam et al. [37] present a work-in-progress database, a bottom-up model for estimating energy consumption for space heating of the residential stock applied to a medium-sized city in Italy, combining GIS tools and Multiple Linear Regression (MLR) analysis. By doing this, the authors highlight the most influential factors on building energy consumption (period of construction, heated volume, type of ground floor, occupation factor, air temperature, type of roof and the installed heating power). The final model thus becomes a powerful Multi-Criteria Spatial Decision Support System visualization tool which is used to define green urban systems. Another example of a mix of GIS tools and MLR analysis is included in A. Mastrucci et al. [38], where a bottom-up statistical approach is used on Rotterdam's residential stock, estimating energy savings at dwelling level through typical retrofitting measures to complete the energy updating of 300,000 housing units within a more sustainable urban plan. Furthermore, bottom-up approaches can be used to forecast the annual energy consumption in future climate scenarios [39].

Although the specific aims are diverse (i.e., predicting energy-saving potential, analysing hindrances in the retrofitting process, raising awareness among users of their homes' potential for improvement, etc), urban building energy approaches are generally used by political decision-makers, from local authorities to public and private stakeholders, as guidance to boost energy policies and urban planning for building upgrades.

Nevertheless, to date few urban studies have been found on the current state of buildings under climate conditions such as those of the southern Mediterranean arc, with important daily fluctuations throughout the year, and with temperatures expected to increase in the coming decades. In fact, the common lack of thermal insulation and centralized active systems in a high portion of the existing stock make the buildings highly sensitive to weather changes. This, in combination with low-income user-profiles results in poor passive energy performance and frequent situations of thermal discomfort indoors [40].

This paper aims to bring to light the prevailing energy status quo of residential building stock located in the Spanish Mediterranean arc. In doing so, it presents a protocol for a territorial assessment of existing public housing developments created in urban expansion processes in the post-war period between 1951 and 1980. The proposed protocol is validated through its application to the existing residential stock of Córdoba, an inland city in the south of Spain.

Differently from other works, the present research raises from a thorough description of the analysed building stock through an exhaustive documentation of Archive files and original projects, backing up results based on an extensive sample of real building features. The statistical screening of architectural and constructive prevailing patterns together with a cross-check analysis of building census and cadastre data brings about the representative energy models that will serve as a base to assess the stock's passive energy performance in terms of primary energy consumption and CO_2 emissions, and to establish suitable standard strategies for large building stocks. The results above, in combination with GIS, enable passive upgrading actions to be applied at urban as well as district levels.

The digitalisation of building-related information in a supporting dataset enables the accessibility to the constructive composition of the existing structures and shows the potential for improvement of extensive housing stock, providing public administrations with a valuable tool towards the design of comprehensive plans for a more efficient constructive sector.

The introduction in this paper is followed by a further three sections. Section 2 presents the methods and materials employed and provides a definition of the study sample; an architectural, constructive and energy assessment; the linkage of *spatial* and *alphanumerical* data in a GIS database; and the generation of base-case and upgraded energy models. Section 3 discusses the results relating to the current state of the buildings and their potential for improvement with standard passive strategies. Finally, Section 4 presents the conclusions and future lines of study for implementing further research in this field.

2. Methods

This paper introduces a protocol to detect prevailing patterns among the existing housing stock and predict suitable far-reaching interventions with standard passive strategies for improving building energy performance at urban scale, from district level to building detail.

To do so, architectural, constructive, and energy-related data have been extensively compiled for existing residential buildings dating from 1951-1980 and supported by a Geographic Information System (GIS).

The study sample defined takes into consideration information on groups of residential buildings (a public or private real estate development), multi-family buildings (a group of apartments) or housing units (apartments). The information collected is later used for an energy characterization of the selected buildings using energy simulation tools.

In order to ascertain the potential improvement to the buildings' current state, the energy evaluation carried out takes into consideration the status quo of buildings and an upgraded building model which incorporates a set of standard passive strategies. The energy results from both stages of the assessment (prior to and after the buildings' upgrading) are transferred to the GIS dataset to forecast the enhancements which can be achieved in the buildings.

In order to identify the impact at urban scale, the energy savings achieved are eventually extrapolated to the study sample considering the total heated and cooled surface of the buildings (Fig. 1).

A cyclical approach is followed (Fig. 1): in phase I, the collection of building data will bridge the gap of knowledge relating to the building's energy status-quo in phases II and III, before going on to plan potential energy enhancements in phase IV. The process is conceived as a sort of "work-in-progress" as accessible information on the housing stock is expected to become more readily available, in turn facilitating continuous updates on building datasets in phases I and II (Fig. 1). Simultaneously, the more comprehensive the constructive and energy characterization of buildings, the more precise the energy assessments in phases III and IV (Fig. 1), something which in turn leads to a better understanding of their performance and potential for improvement.

Substantially, this research will contribute to the drawing up of energy policies that promote holistic retrofitting strategies for the existing residential stock. Given the overarching objectives of this research, general findings are presented. Assumptions made are based on the most influential parameters impacting building behaviour, such as typology, orientation, and position, while in-depth onsite surveys would provide an accurate representation of real margins at building level [41].

To illustrate the feasibility of the protocol, the phases and steps considered are applied to the housing stock built in the period studied in the city of Córdoba (Fig. 1). In addition, aiming to align with the INSPIRE Directive [42], this approach can be tailored to fit in any other building stock from different European areas.

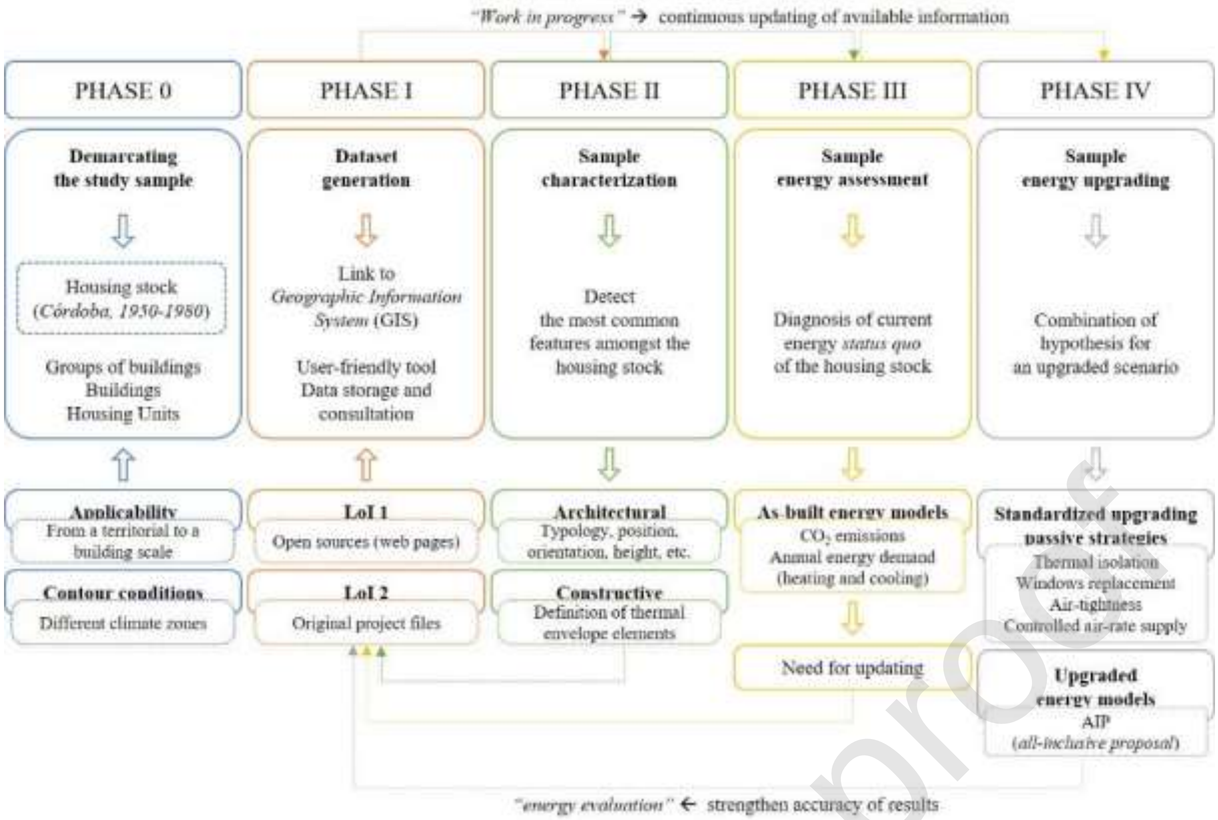


Fig. 1. Methodology flowchart.

2.1 Case study

The city of Córdoba is one of the most extensive inland urban cities of the Spanish Mediterranean arc, located in the southern area of the peninsula. According to current Spanish regulations [43], this location is within the B4 climate zone, which also corresponds to *Csa* [44], covering almost 34 % of the Andalusian territory and 40 % of the province of Córdoba. Winters are mild and wet (with average temperatures around 3.60 ºC in January and 111 mm rainfall and 79 % relative humidity in December) and very hot dry summers (exceeding 36.90 ºC in July and 40 % relative humidity on average) [45].

The proposed protocol applies to multi-family building groups built between 1951 and 1980, a time when a high demand for housing led to a sharp increase in housing stock, using cheap materials and speedy construction processes, and prior to the implementation of thermal regulations in 1979 [46]. As a result, much of the current housing stock is obsolescent in energy terms in relation to current standards and needs updating.

Similar architectural and constructive features can be identified throughout the housing complexes of the southern Spanish Mediterranean. Presuming that the local climate was a priori mild founded a dearth of heating or cooling centralized active systems (HVAC) in the construction of these buildings, which today count with other electric devices such as heaters and split heat pumps [47]. Furthermore, low-income user profiles are often found in this type of building, and the limited use of active equipment due to financial constraints leaves occupants at risk of energy-poverty conditions [48]. The lack of thermal insulation and uncontrolled operational habits to resolve energy losses or overheating situations highlights the weaknesses of the thermal envelope, as well as a wide range of improvements with the implementation of passive strategies in these buildings.

2.2 GIS dataset

The aimed dataset is linked to a GIS, enabling the interconnection of geometric (*spatial*) and geographic (*alphanumeric*) attributes of the different sample units (municipality, city district, building group, building and apartment).

The dataset is created in four main steps:

1) outlining the study sample, starting with an initial selection of housing building groups from Córdoba, developed in the period under study (1951-1980). A set of criteria is then applied to narrow down this initial sample to a selected sample of buildings.

2) generating the GIS dataset that will hold information on the buildings, structured into layers and attribute tables following the criteria established.

3) classifying the buildings through a transversal description, translating raw data obtained from different sources into architectural, constructive and energy features, in order to complete the GIS dataset attribute tables.

4) disclosing results through an accessible tool by generating specific web maps that will allow for a driven consultation of the study sample, from building detail to housing stock scale.

2.2.1 Step 1: Outlining the study sample

The identification of the buildings considered within the study sample follows a pre-set methodology [49] through vertical criteria summarized in Figure 2.

The total amount of housing units built in the study period is estimated based on the most recent Population and Housing Census [50]. However, other alternatives have to be considered as it is not possible to identify the actual buildings based directly on these numbers.

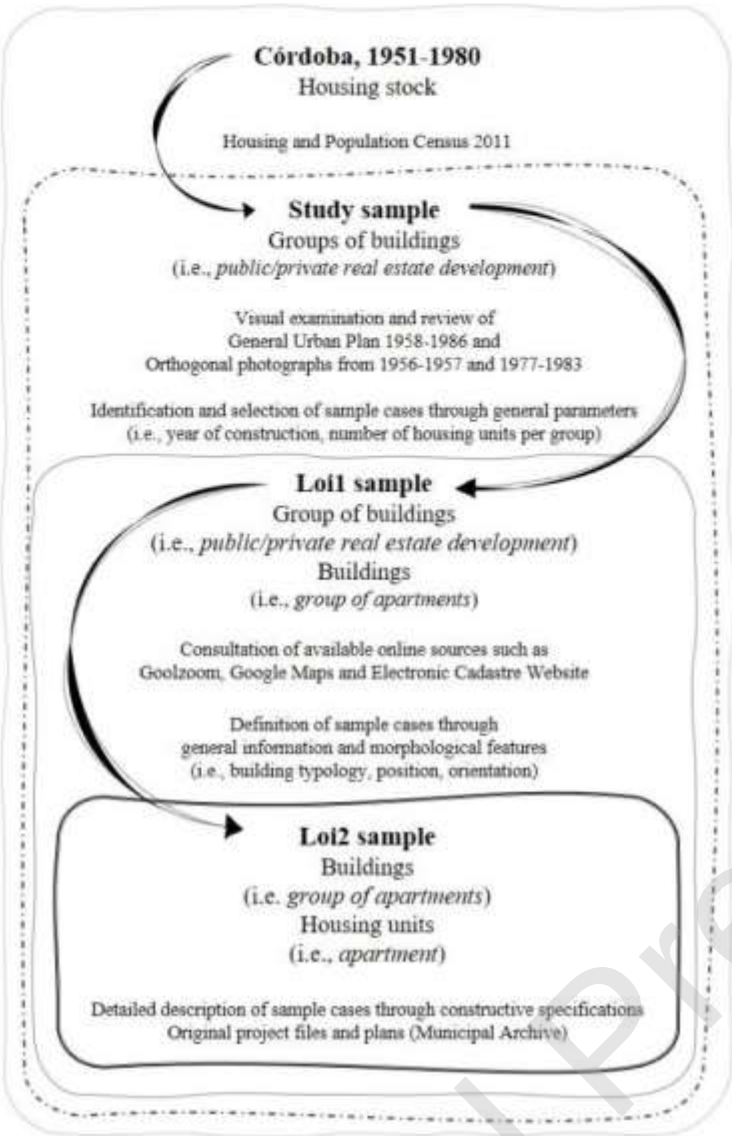


Fig. 2. Vertical criteria adopted to establish samples based on the sources of information available.

In order to outline the study sample, the historical urban development of Córdoba in the study period (1951-1980) is examined using different General Urban Plans [51], as well as orthogonal photographs from military flights in 1956-1957 [52] and 1977-1983 [53]. The buildings to be analysed are then selected by applying several downscaling criteria according to two levels or scales of information:

i) *level of information 1* (Loi1) considers general and readily available data obtained from the consultation of online tools such as Goolzoom [54], Google Maps [55] and the Spanish Electronic Cadastre website [56]. Due to the wide variety of potential examples, only groups of multi-family buildings with standard typologies (H-plan, linear) with more than 100 housing units are considered in order to avoid incorporating cases with unique features that would hinder the robustness of global results. The buildings considered within the study sample are sorted based on the major indicator of age of construction.

ii) *level of information 2* (Loi2) focuses on detailed morphological and constructive information of the selected buildings, obtained from an in-depth examination of the available original project files found in the Municipal Archive of Córdoba [57]. Based on this, buildings are chosen considering accessibility to the necessary information.

2.2.2 Step 2: Structure of the GIS dataset

Open-source software QGIS (v.3.2.0) [58] has been used to generate the GIS dataset. Through a mass download of shapefile information layers, a supporting map with urban cadastre cartography (municipal, neighbourhood and building levels) [56] is created. Starting with a mother layer with the registers of all the buildings selected, a set of specific information layers with building-related data is generated following the pre-established criteria for outlining the sample (Fig. 3).

Information layers link graphical entities to dBase attribute tables. Graphical entities can represent built-up volumes at different levels of detail, from building level to the outlining of the municipal district, holding different data depending on the Loi (Fig. 3). For instance, a graphical entity representing the municipal district will contain the total number of housing units built in the years of study (Loi1), while a building-shaped graphic entity will hold general data for the building, obtained from online sources (Loi1), such as age of construction, typology or position, or a detailed description of the building's thermal envelope drawn from the consultation of the original project files and plans (Loi2).

Finally, the GIS dataset is made up of four Loi1 information layers (including a total of 1491 items and 28828 pieces of information) and eleven Loi2 information layers (including 7091 items and 126236 pieces of information).

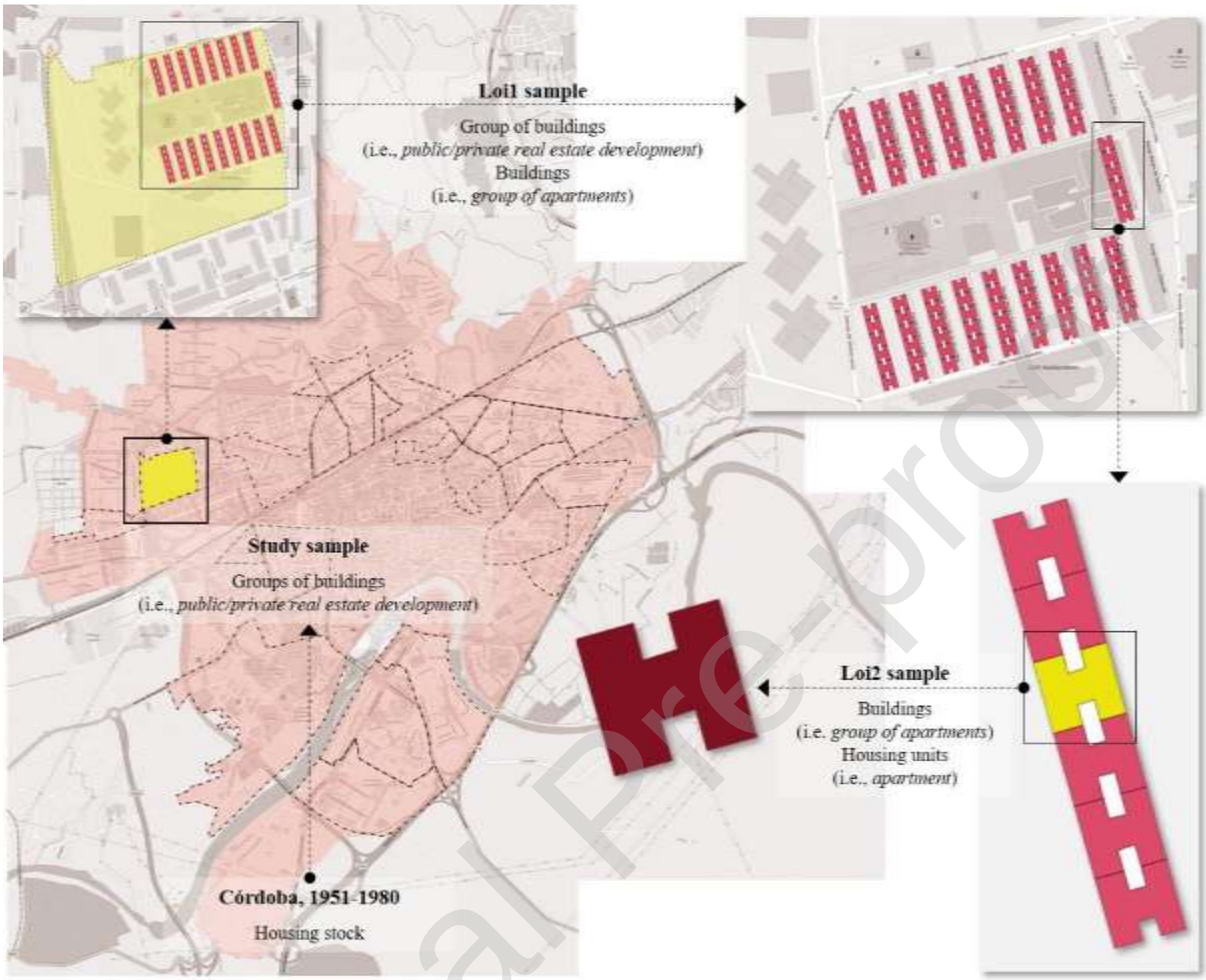


Fig. 3. Transposition of the vertical criteria adopted for outlining the study samples in the supporting GIS map.

2.2.3 Step 3: Characterization of the study sample

2.2.3.1 Architectural and constructive characterization

To address the architectural nature of the study sample, buildings are sorted into categorized information layers associated to the corresponding Loi and the scale approached (Table 1):

i) At Loi1, the analysis covers groups of buildings to single building level. Groups of buildings are characterized through indicators that are equally applicable to all the buildings covered, such as age of construction, total number of housing units and total built-up surface. Buildings are classified by prevailing characteristics, such as typology, orientation, position, and the number of storeys.

ii) At Loi2, the study covers from building level to housing unit scale. Buildings are characterized by their compactness (ratio between the enclosed volume by the thermal envelope of the whole building and the addition of the thermal exchanging surfaces of the enclosing envelope). Housing units are defined by their usable surface, number of bedrooms (as an indicator of how many people live in them), and floor-to-ceiling height.

Table 1. Scope and categorized information layers associated to architectural indicators.

Scope	**Title**	**Categories**
GIS of architectural characterization of housing buildings		
Loi1	*Number of housing units*	<200 200-400 400-600 600-800 800-1000 >1000
	Construction decade	50 60 70 80
	Typology	H-plan building linear building residential tower others
	Prevailing orientation	N-S E-W Northeast-Southwest Northwest-Southeast
	Building position	freestanding inner-positioned end-positioned
	Number of storeys	2-4 4-6 6-8 >8
Loi2	*Dwelling usable surface*	<50 50-65 65-80 >80
	Number of bedrooms	3 4
	Type plan floor-to-ceiling height	2.20-2.35 2.35-2.50 2.50-2.65 2.65-2.80
	V/S ratio	<1.00 1.00-1.50 1.50-2.00 2.00-2.50 >2.50

To detect typical constructive systems employed in the study sample, buildings are clustered following categorized information layers that address the composition of several thermal envelope elements (Table 2). These include the roof composition and trafficability, outer wall composition, ratio of openings per opaque surface in each façade, window joinery and glazing and the composition of internal partitions in contact with non-habitable spaces.

Table 2. Scope and categorized information layers associated to constructive systems.

Scope	Title	Categories
GIS of constructive definition of housing buildings		
Loi2	*Type of roof*	pitched, Andalusian, Catalan, double roof, non defined
	Roof trafficability	crossable, non crossable
	Wall solution	double layer, single layer
	Ratio of openings per opaque surface	<20 %, >60 %, 20-40 %, 40-60 %
	Windows joinery	metallic frame, non defined
	Windows glazing	non defined, single glazing 3/3, single glazing 6/6
	Wall solution adjacent to non-habitable spaces	1 foot, ½ foot, double-brick layer, double-air brick, various, non defined, non existent

2.2.3.2 Energy characterization

In line with the Spanish Technical Building Code [43] and the Royal Decree of Energy Certification of Existing Buildings [59], an acknowledged ad hoc Spanish software named CE3X (v.2.3) with DOE 2.2 calculation engine [60] is used to assess the buildings' current energy performance and foreseeable energy improvement through standard passive strategies.

The software carries out a calculation procedure based on comparison scenarios which refer to a forecast of the energy performance of the existing buildings. This is supported with a wide dataset of results from the energy simulation of representative buildings considering the possible combinations in terms of age of construction and typology (number of storeys, constructive system, the ratio of glazing surface and the main façade orientation), the different Spanish climate zones and the four main orientations. When the user generates a building energy model, the software provides an energy indicator which includes a letter from A to G in a decreasing scale of efficiency (A being the most efficient), and a corresponding value in $kgCO_2/m^2$, regarding the primary energy consumption and the subsequent CO_2 emissions, as a result of the "comparison scenarios" [61]. For each building, the calculation offers a general indicator, together with five other itemized ones for heating and cooling demands (in kWh/m^2) and heating, cooling, and domestic hot water emissions (in kgCO_2/m^2).

After the simulation of all the buildings considered, results are transferred to the corresponding information layers to sort buildings by energy rating both at a prior-to retrofit stage and under an upgraded scenario (Table 3).

Table 3. Scope and categorized information layers associated to the buildings' energy rating.

Scope	Title	Categories
GIS of energy assessment of housing buildings		
Loi2	*Energy rating*	D E F
	Heating demand	<15 kWh/m^2 15-30 kWh/m^2 30-45 kWh/m^2 45-60 kWh/m^2 >60 kWh/m^2
	Cooling demand	<20 kWh/m^2 20-30 kWh/m^2 >30 kWh/m^2
GIS of scenarios for energy improvement of housing buildings		
Loi2	*Upgraded energy rating*	D E
	Upgraded heating demand	<15 kWh/m^2 15-30 kWh/m^2 30-45 kWh/m^2 >45 kWh/m^2
	Upgraded cooling demand	<15 kWh/m^2 15-20 kWh/m^2 >20 kWh/m^2

To close the cyclical approach and return to the study sample scale, the reductions achieved in energy demand and CO_2 emissions obtained with the representative energy models are extrapolated to the rest of the buildings included within the study sample but not accounted for within the Loi2. Following a similar procedure to that identified in related works [62], buildings are clustered by year of construction and number of housing units per building. Then, averaged results for energy demand and emissions in each building cluster are converted through a coefficient-ratio between the gross and net residential surface of the buildings. Eventually, the converted results are correlated with the overall number of buildings within the study sample to broaden the impact of the enhancements.

2.2.4 Step 4: Open-source dataset as a tool for assessing housing stocks

To promote access to the information stored in the GIS dataset, an easy-to-handle tool with a user-friendly interface is generated with an open-source plug-in, *qgis2web,* for the software used [63]. The tool provides qualitative or visual features of the buildings through several interactive web maps to illustrate the spread of building parameters throughout the sample analysed. Furthermore, thanks to the detailed building description in the GIS dataset generated, the tool provides quantitative or statistical outcomes through simple calculations about the number of cases sharing similar features.

The tool is based on use of the web map *GIS of identification and definition of housing buildings* (see supplementary material) to support the GIS dataset. This web map presents building-related data sorted by information layers with different scopes: i) within Loi1, urban nucleus, neighbourhood, groups of buildings and buildings; ii) within Loi2, groups of buildings, buildings, structure, and thermal envelope constructive systems (roof, floor in contact with outdoor air, floor in contact with the soil, vertical partitions in contact with non-habitable spaces, horizontal partitions under/on top of non-habitable spaces, façades, and openings). Graphical entities within each information layer will appear providing their host layer is switched on, and the information of each building will appear in a pop-up window whenever a graphical entity is selected.

Another four web maps stem from the supporting one: i) *GIS of architectural characterization of housing buildings*; ii) *GIS of constructive definition of housing buildings*; iii) *GIS of energy assessment of housing buildings*; and iv) *GIS of scenarios for energy improvement of housing buildings*. In these maps, buildings are sorted into categorized information layers according to building-related indicators. The five web maps generated can be launched in any internet browser and can be consulted in the supplementary material of this article.

2.3 Representative energy models

As mentioned above, the energy characterization of the buildings is carried out through the energy simulation of both the prior-to-retrofit state and the predicted scenarios for improvement.

Considering the wide range of buildings analysed, in order to account for each possible combination energy models will be developed according to i) building typology, distinguishing between H-plan, linear, residential tower and others; ii) building position with respect to other adjacent or nearby buildings, classed as end-positioned (for those standing at the ends of a row of buildings), inner-positioned (for those standing in between of a row of buildings) or freestanding; and iii) the building orientation, according to the Appendix A of Building Code Basic Document on Energy Saving [43]. In all, a total of 212 different buildings representing 781 buildings are defined.

To shorten the time spent on the evaluation of this high number of cases, energy models will be generated at building level, just taking into consideration the volume covered by residential use for the purposes of energy simulation. Accesses to the building and vertical core (staircases or lifts), as well as ground-floor commercial premises, garages, and other non-residential spaces, are considered adjacent zones.

Input data will involve parameters recorded such as location, climate zone and thermal envelope definition, together with standard use and operation profiles, centralized active thermal conditioning (if applicable) and calculated domestic hot water supply [43].

To foresee the buildings' potential for improvement, the reduction in energy demand and corresponding primary energy consumption and CO_2 emissions are considered, comparing as-built energy models depicting prior-to-retrofit state with upgraded ones, which incorporate standard passive strategies for energy improvement. In line with the desired urban-scale applicability, the protocol entails an initial analysis at building level and a later transposition at urban level, to measure the global impact over the study sample.

2.3.1 Base-case energy models

The definition of as-built energy models implies:

- Current location and outdoor conditions, obtained from a downloadable weather file [64] with reference climate data for zone B4 [43], also corresponding to *Csa* [44].
- Normalized profiles for residential activity (internal loads) according to [43] depending on the use, density of internal heat sources (low, medium, or high) and period of use (8, 12, 16 and 24 hours).
- The constructive and energy characterization of the buildings' thermal envelope. For each individual element, the following are included: surface of thermal envelope, U-Value, mass, orientation, depth, perimeter, use of non-habitable spaces, number of similar items, G-Value, and solar protections.
- Thermal bridges, which are considered through linear U-Values, such as the intersection between roof-façade, slab-façade, inner pillar-façade and corner pillar-façade, exterior floor-façade, soil floor-façade, opening edges-façade, and shutters box-façade.
- The existing thermal conditioning systems. According to the original files [57], the analysed stock generally lacks centralized active systems (HVAC). In line with [43], energy models are implemented with natural gas-based heating production and electricity-based cooling production.
- The ventilation rates for private residential use are set at a default value according to a standardized profile of operation [43].

- The domestic hot water supply relies on an LPG boiler without accumulator. For private residential use, total daily water consumption is set according to [43].

2.3.2 Upgraded energy models

To improve the estimated energy performance of the buildings analysed, a set of standard passive strategies has been incorporated into the representative energy models. After a sensitivity analysis in previous studies [41], an all-inclusive proposal (AIP) has been defined integrating the following hypothesis:

$AIP = H_{TI} + H_{W} + H_{V1} + H_{V2\ (0.4\ ACH)}$

where:

- H_{TI} implies *the addition of thermal insulation.* Façades show improvement with a 50-mm CO_2 PUR injection into the existing air-chamber, while roofs are implemented depending on whether they are flat (with 60-mm filter slab) or sloping (with 80-mm filter slab). This strategy led to the U-values of walls and roofs complying with current regulations [43], with a decrease of 70 % and 80 % W/m^2K respectively and U-value deviations below limit by 4 % in walls and 12 % in roofs (Table 4).
- H_W means *implementing window glazing* depending on orientation. Existing single glazing is replaced with insulated glazing units (IG units) with a 16-mm air chamber and variable glazing thickness (4-mm external and 6-mm internal) to improve acoustic behaviour, together with Low-Emissive coatings for north-facing openings and Solar Control finish for south-facing ones. Like the previous strategy, it helps to meet U-values [43] and provides an overall reduction of 75.5 % and 73.7 % W/m^2K, respectively (Table 4). Moreover, the Solar Heat Gain Coefficient (SHGC) values go from 0.83 to 0.62 and 0.52 in the respective orientations.

Table 4. Averaged improvement in implemented thermal envelope solutions with AIP (HTI and HW) throughout the analysed stock and deviation according to the limit U-value for a B4 climate zone [43].

Position	Averaged U-Value	Upgraded U-Value	Limit U-Value	Average Improvement (%)	Average Deviation (%)
Opaque elements					
Vertical	1.80	0.54	0.56	70.0	3.6
Horizontal (roof)	1.89	0.39	0.44	79.4	11.4
Transparent elements					
North-oriented (low-emissive)	5.7	1.4	2.3	75.5	39.1
South-oriented (solar control)	5.7	1.5	2.3	73.7	34.8

- H_{V1} is for *increasing window airtightness* by replacing general metallic joinery with PVC-made ones, reducing air-leakage with Type 4 folding frames (3 $m^3/h/m^2$ under 100 Pa) [65].
- H_{V2} sets up *a controlled renewed air-rate* through a hygro-adjustable ventilation system that relies on occupation and shifts to natural ventilation during the night in summer [43]. For the purposes of calculation, air rates have been estimated at 0.4 ACH.

3. Results and discussion

The following section offers an overview of the achieved tool and the results from its application to the housing buildings built in Córdoba between 1951 and 1980.

3.1 Identification and definition of the study sample buildings

The application of the methodology to the housing stock built between 1951 and 1980 in the city of Córdoba has enabled the identification of 232 groups of buildings, consisting of 1699 buildings and 30079 housing units dating from the period studied. According to the

Population and Housing Census of 2011 this represents 43.54 % of the existing multi-family housing stock [50] (Table 5).

Table 5. Number of identified housing units and total number of housing units built between 1951 and 1980 in Córdoba.

Number of housing units 1951-1980 (*)	**Number of identified housing units**		
	Total	**Loi1**	**Loi2**
69078	30079	24926	14587
	(43.54 % of 69078)	(36.08 % of 69078)	(21.12 % of 69078)
		(82.87 % of 30079)	(48.49 % of 30079)
			(58.52 % of 24926)

(*) Data source: Population and Housing Census 2001 (National Statistics Institute [50])

The majority of these groups of buildings is spread out among the peripheral districts, with only two located within the urban centre, albeit still part of the areas of expansion of the city in the period studied (See supplementary material, *GIS of Identification and definition of housing buildings*).

To check the robustness of results, the size of the study sample is set according to the worst-case scenario (50 % heterogeneity among analysed items, 5 % margin of error and 95 % confidence). Based on this, the total number of items needed for the study is 258 buildings and 375 housing units.

During the period studied, the construction of multi-family groups of buildings in the expansive areas of the city shows an increasing tendency (Fig. 4). In fact, most of the groups of buildings analysed date from the last two decades of the period studied, when 94.3 % of the total of housing stock identified was built (40.9 % in the 1960s and a 53.4 % in the 1970s). The size of the groups of buildings also tends to increase, as in the second half of the period studied the number of buildings and housing units grows by 40 % to 45 %.

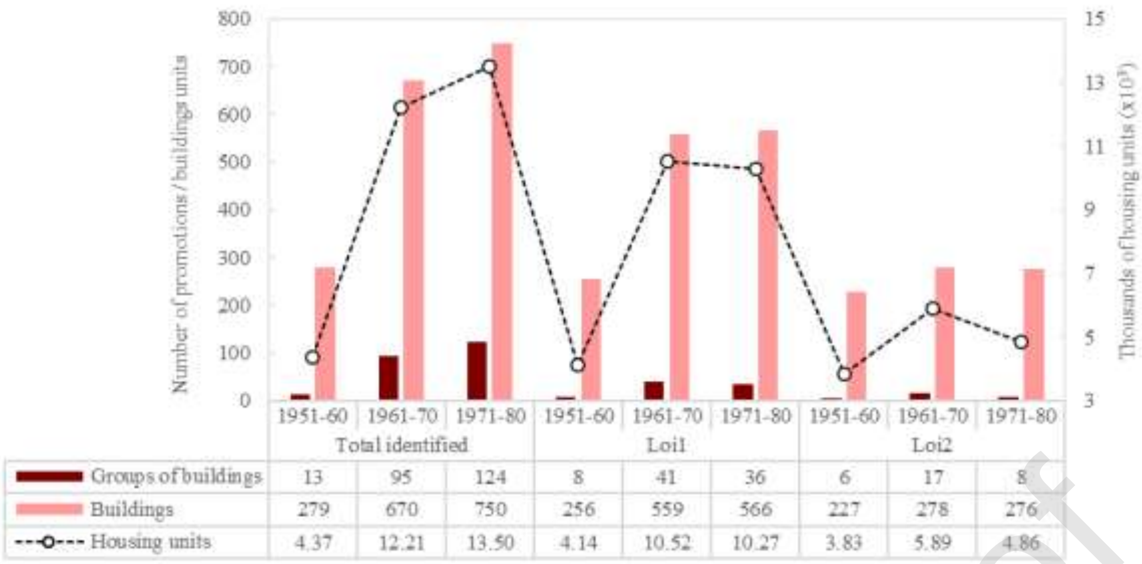


Fig. 4. Number of groups of buildings, buildings, and housing units identified throughout the study period.

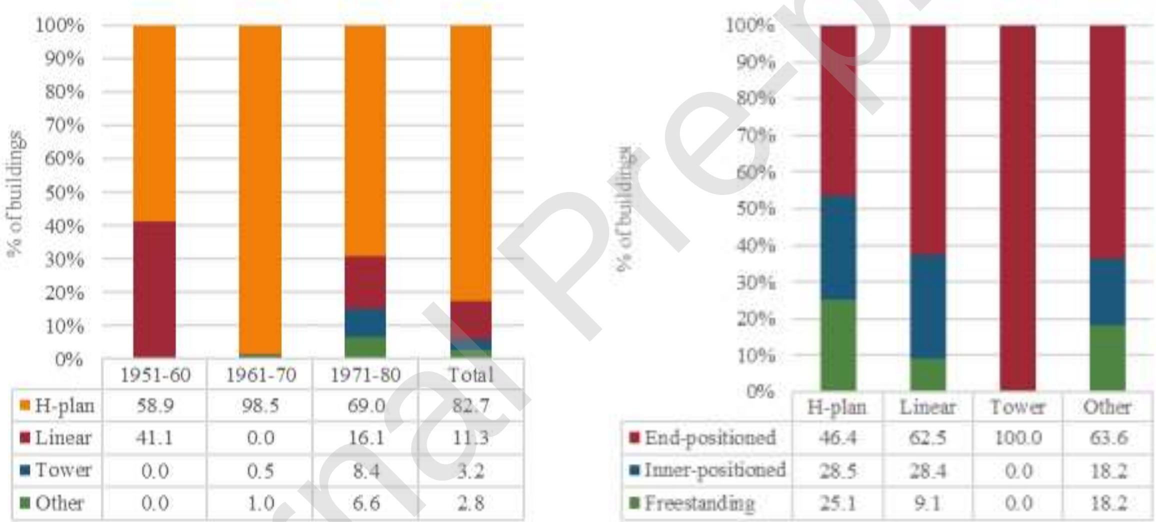
When applying the Loi1 filter, a total of 85 groups of buildings, with 1381 buildings and 24926 housing units (82.87 % among the identified cases), have been analysed. When applying Loi2 the total number of groups of buildings is 31, with 781 buildings and 14587 housing units (48.49 % among the identified cases and 58.52 % of Loi1 cases) (Table 5; Fig. 4).

As regards size, the groups of buildings are generally made up of around 10 to 20 buildings, containing at least 200 housing units (and at times reaching close to 500) and almost 20000 m^2 of built-up area. Three major groups stand out in the study sample, accounting for 30 % of the total number of cases identified: one of these, built in 1960, contains 317 housing units, while the other two, built in the 1970s, each have over two thousand housing units.

3.2 Architectural and constructive characterization of the study sample buildings

In a prognosis of the energy performance of the buildings, morphological features such as typology, number of storeys and position in relation to other surrounding buildings affect the boundaries and thermal envelope surface of the building. In the following section, the distribution of common patterns will be assessed over the sample of buildings filtered at Loi2 to summarize results.

According to this, throughout the study period, two main typology trends were found to prevail (Fig. 5a): H-plan buildings, with four housing units per floor with different prevailing orientations, and a shared access through a vertical core, and Linear buildings with a base depth/width ratio of around 1/2 and two housing units per floor, all of them facing the main façade of the building, with double-sided orientation and cross-ventilation. Although it does not cover a large number of items a third category has been included in the analysis: residential towers, buildings with a square floor plan, four housing units and a common access core similar to that of H-plan buildings, albeit with more storeys and often freestanding.



	1951-60	1961-70	1971-80	Total
H-plan	58.9	98.5	69.0	82.7
Linear	41.1	0.0	16.1	11.3
Tower	0.0	0.5	8.4	3.2
Other	0.0	1.0	6.6	2.8

	H-plan	Linear	Tower	Other
End-positioned	46.4	62.5	100.0	63.6
Inner-positioned	28.5	28.4	0.0	18.2
Freestanding	25.1	9.1	0.0	18.2

Fig. 5. Distribution of analysed buildings in the study period according to (a; left) typology and (b; right) position.

There is a strong presence of H-plan buildings in the three decades studied, accounting for almost 82.7 % of the global number of cases (646 buildings and 12748 housing units) while as time goes on linear buildings show a decreasing tendency, totalling 11.3 % of the study sample (88 buildings and 842 housing units). A further 6 % of buildings fall within the less common categories of extended or undifferentiated typologies (47 buildings and 997 housing units), half of which are residential towers (25 buildings and 791 housing units) (Fig. 5a).

Common patterns can also be established at housing unit level. Almost 60 % of the flats have a usable surface of 50-65 m^2, in most cases including three bedrooms (98 %), which can be associated to standardized social housing features. Inner floor-to-ceiling heights are 2.20-2.35 m in almost half the cases (49.43 %), resulting in conditions which do not meet the standard habitability requirements for domestic activity, although many others have been found to reach ceiling heights of over 2.50 m (40.59 %) (See supplementary material).

The buildings in the categories mentioned above are often found standing in groups, rows, or arrangements of two or more buildings, although some freestanding ones have been found within the main categories. Based on the prevailing typologies, most buildings are placed at the ends, 46.4 % in the case of H-plan buildings (300 cases) and 62.5 % in the case of linear buildings (55 cases), covering all buildings with three or more different façade orientations (Fig. 5b). The other half of the sample is divided between inner-positioned, covering around 29 % in both cases (184 H-plan buildings and 25 linear ones), with two different orientations, and freestanding in 25.1 % of H-plan buildings (162 cases) and 9.1 % of linear ones (8 cases), with all façades exposed to outdoor conditions (Fig. 5b). However, none of the residential tower buildings are found freestanding individually, as all 25 cases in the set identified are found in pairs or adjacent to three or more surrounding buildings, partially sharing thermal envelopes.

The standardization of building typologies, together with the building height, directly sets the number of housing units per building. In any case, a ten-storey height is reached in the city of Córdoba. H-plan buildings can mostly take the form of buildings with 4-5 floors (82.13 %) or buildings with 7-8 storeys (17.87 %) like residential towers, while linear buildings are usually 4-5 storeys high. As a result, H-plan and linear buildings often account for 10-12 housing units and a total built-up area of around 2000 m^2, while residential towers have 28-32 flats and a surface of almost 4000 m^2. In the mid-1960s, almost half the buildings analysed (46.84

%) incorporated commercial premises on the ground floor, resulting in an increase in the thermal envelope surface, with first floors adjacent to non-residential spaces (See supplementary material).

Building compactness is defined in [43] as the ratio between the volume enclosed by the thermal envelope of a building or a part of it (*V*), and the addition of the thermal exchanging surfaces of the enclosing envelope ($S = \sum S_i$), expressed in m^3/m^2. Consequently, the thermal exchange surface is reliant on the typology, height, and position of a building, potentially impacting *V/S* ratio.

In general, the compactness range for analysed buildings is set at 1.5-2 m^3/m^2 (Fig. 6). Of the most common category, H-plan cases, the values of 80.65 % remain close to the mid-point of this range. Linear buildings present lower compactness and most remain below 1.50 m^3/m^2 (72.73 %). Overall, residential towers and other typologies remain below 1.5 m^3/m^2.

A larger presence of buildings positioned at the ends (Fig. 6) explains lower compactness values in most cases, while the existence of taller heights within H-plan buildings provides them with greater values overall in the inner-positioned cases (Fig. 6a). In line with their typology definition, the H-plan buildings studied present higher compactness than the linear ones, as a similar number of storeys, with four housing units per floor instead of two, leads to a bigger enclosed heated volume.

According to the definition of *V/S* ratio, the more exposed the surface, the lower the compactness for a similar volume. In energy terms, the lower the compactness (such as in linear buildings and residential towers, freestanding or in end positions), the greater the outer envelope surface area with impact on indoor conditions. Low compactness provides indoor spaces with higher levels of natural ventilation and daylighting, while favouring less stable indoor environments, thanks to the existence of thermal bridges and larger surfaces exposed to solar radiation.

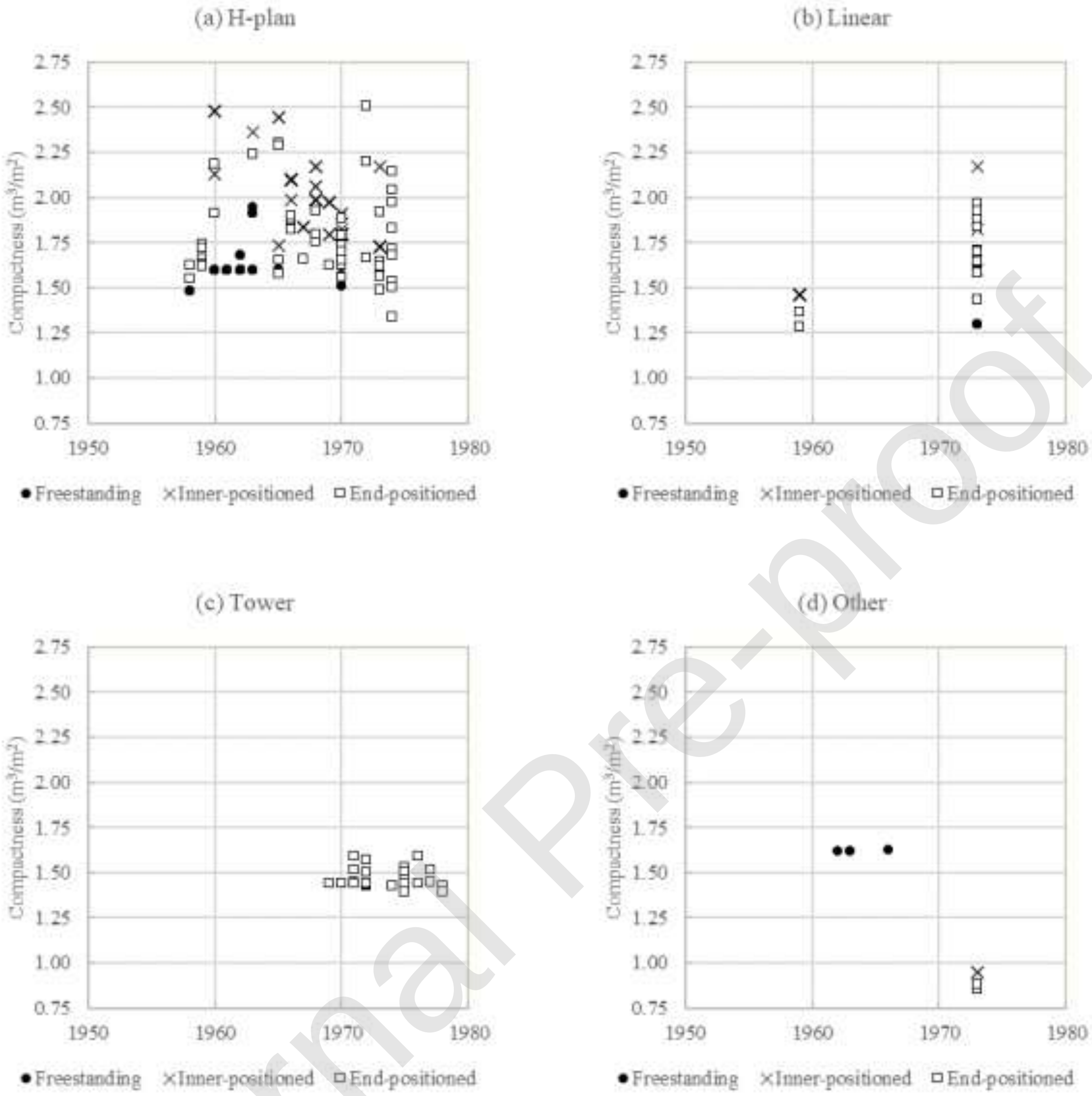


Fig. 6. Compactness of buildings (m^3/m^2) based on typology and position.

The repercussion of the exposed surface is greatly affected by the poor composition of the constructive systems identified in the study sample, where a widespread lack of thermal insulation is detected both in vertical and horizontal envelope elements, affecting the buildings' thermal resistance and setting U-values far removed from current standards [43] (Table 4). Overall, constructive systems were made of reinforced concrete slabs and structural pillars, with massive façades and indoor partitions made mainly of brickwork. There is, however, a trend to enlighten structural solutions by incorporating non-ventilated air-chambers in roofs and opaque façade solutions in the period studied, although these were not efficient enough.

Generally, façades are made mostly of two-layer brick solutions with plaster finishes: an outer double-brick wall, a non-ventilated vertical air chamber, and an inner single-brick partition, with an averaged U-value among the analysed buildings of 1.8 W/m^2K (Table 4). These have been detected in 70.12 % of the total executed façade surface and are found in 71.70 % of the buildings studied. The use of single-layer brickwork solutions during the 1950s is also notable.

Roofs are largely composed of horizontal slabs with non-ventilated solutions, which are found in over 48 % of the surface of the study sample buildings, while pitched roofs with a fibrocement finish layer are found in around 40 % of the roof surfaces analysed. The lack of any kind of insulation results in U-values of up to 1-2.5 W/m^2K of the roofs identified (Table 4), commonly resulting in dense and massive solutions. In most cases roofs could not be walked on.

But for more than 50 % of the study sample, for which no description of the openings was found, windows are generally double-glazed (with two 3-mm panes of glass) or single-glazed (one 6-mm piece of glass) and aluminium frames. No inner air-chambers or thermal breaks were identified. Solar protection in the form of blinds was preferred for use on bedroom windows but only identified in 50% of the buildings analysed.

In addition to building shape, building orientation has been addressed for its importance in a southern Mediterranean climate. Four main categories – North-South (N-S), East-West (E-W), Northeast-Southwest (NE-SW) and Northwest-Southeast (NW-SE) – were established for ease of analysis despite the fact that no regular pattern is observed among the buildings analysed. H-plan buildings present a similar percentage in all directions, while linear buildings are mostly in N-S (34.48 %) and NW-SE (40.00 %) orientations. Residential towers with square floor plans are also found in the four main orientations (N-S-E-W) (See supplementary material).

3.3 Energy characterization of the study sample buildings

The following section acknowledges the energy status of the buildings studied estimating the amount of CO_2 emissions and their annual energy demand through energy simulation, as well as the potential improvement of their energy performance with upgraded energy models.

3.3.1 Base-case energy models: Energy grading, CO_2 emissions and annual energy demand

The application of the protocol to the housing sample has enabled the estimation of energy indicators and CO_2 emissions for the existing buildings. According to the energy rating scale of residential buildings, cases range from D to F, although most of them are rated E (96.6 %) (Table 6). A general trend towards a better performance can be seen, with E-rated buildings' initial averages ranging between 36.0 $kgCO_2/m^2$ and 32.9 $kgCO_2/m^2$ when examining the final years of the period under study (Table 6).

Table 6. Averaged energy rating and percentage of similar housing buildings according to their decade of construction.

	Averaged energy grade ($kgCO_2/m^2$)			**Percentage of buildings (%)**		
Decade of construction	**D**	**E**	**F**	**D**	**E**	**F**
1951-1960	-	36.0	45.0	-	11.1	2.9
Fraction built 1951-1960				*0.0*	*79.4*	*20.6*
1961-1970	18.9	34.4	-	0.5	51.9	-
Fraction built 1961-1970				*1.0*	*99.0*	*0.0*
1971-1980	-	32.9	-	-	33.6	-
Fraction built 1971-1980				*0.0*	*100.0*	*0.0*
Total	18.9	34.1	45.0	0.5	96.6	2.9

Equally, the annual energy needs for primary energy decrease during the study years (Fig. 7). In fact, heating energy demands initially reached around 80 kWh/m^2, decreasing over time but remaining above 35 kWh/m^2 in all buildings, thus increasing the annual global energy demand (Fig. 7). The results for cooling energy demand are within the 10-30 kWh/m^2 range, although linear buildings dating from the 1970s occasionally display lower values (Fig. 7).

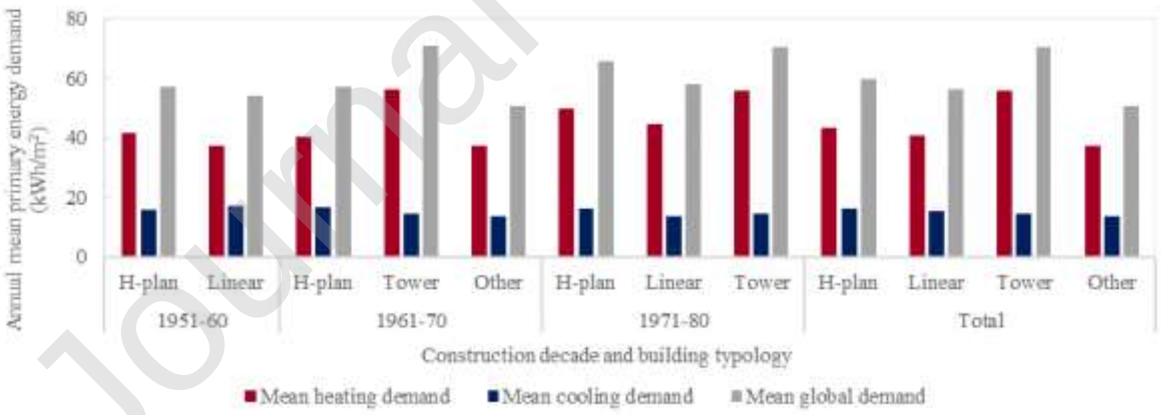


Fig. 7. Annual mean primary energy demand (kWh/m^2) during the study period according to building typology.

3.3.2 Upgraded energy models: Improved energy performance and reduction of CO_2 emissions

Buildings in which the AIP has been implemented have been rated from D to E according to the energy rating scale for residential buildings. Table 7 compares CO_2 emissions and average energy rated for the evaluated buildings prior to and after the incorporation of the AIP, sorted by decade of construction and presented along with the percentage of buildings with similar energy performance.

A general improvement can be observed as none of the buildings is F-rated after the AIP. 97.1 % of the buildings within the E-range display an average value of 26.2 $kgCO_2/m^2$, 2.9 % of the buildings are rated D, with an average value of 18.06 $kgCO_2/m^2$, which overall constitutes a 30 % reduction in CO_2 emissions (Table 7).

Table 7. Average energy rating of buildings and percentage of buildings with similar rating, before and after AIP implementation.

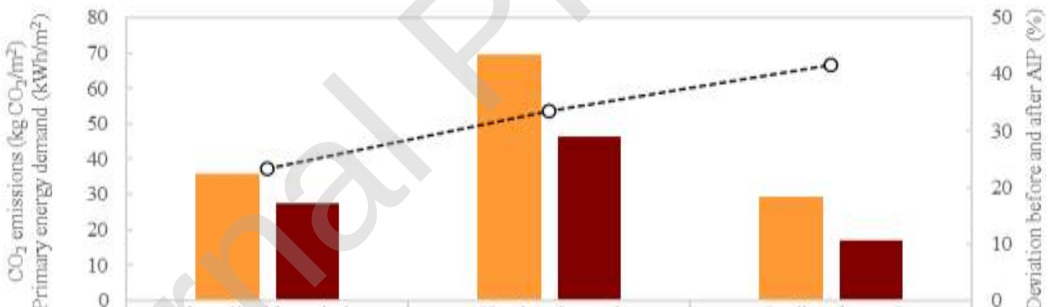
	Averaged energy rating ($kgCO_2/m^2$)						**% of buildings with similar rating**					
	Before AIP			***After AIP***			***Before AIP***			***After AIP***		
Decade of construction	**D**	**E**	**F**	**D**	**E**	**F**	**D**	**E**	**F**	**D**	**E**	**F**
1951-1960	-	36.0	45.0	-	27.1	-	-	11.1	2.9	0.0	14.0	-
1961-1970	18.9	34.4	-	17.6	25.9	-	0.5	51.9	-	2.1	50.3	-
1971-1980	-	32.9	-	19.3	26.4	-	-	33.6	-	0.8	32.8	-
Total	18.9	34.1	45.0	18.1	26.2	-	0.5	96.6	2.9	2.9	97.1	-

3.3.3 Impact of the AIP on the energy performance of the study sample

Figure 8 shows the achieved deviations in annual CO_2 emissions and primary energy demand for heating and cooling after the implementation of the AIP in the buildings assessed and the transposition of results to the study sample.

An overall improvement of results can be observed throughout the study sample, highlighting the major potential for a better performance of these buildings. A mean decrement of 23.3 % in CO_2 emissions is achieved for current environmental behaviour, from a previous mean of 35.7 kgCO_2/m^2 to an upgraded one of 27.4 kgCO_2/m^2 (Fig. 8).

Following the transposition of results to the study sample, a major impact of the AIP on the heating demand reduction of the analysed buildings is observed. Considering a previous average value of 69.3 kWh/m^2 for annual heating, the AIP offers a reduction of over 33.4 % with an average heating demand of 46.2 kWh/m^2 (Fig. 8), although there is still room for improvement. As regards annual cooling, the AIP results in a full amelioration of cooling needs over 41.6 %, ranging from a prior average value of 29.3 kWh/m^2 to an average of 17.0 kWh/m^2 annual cooling after the retrofit (Fig. 8). Globally, annual energy demand has decreased by 35.8 % on average, from an initial mean value close to 98.6 kWh/m^2 to a lower mean value of 63.2 kWh/m^2.



	Carbon dioxide emissions	Heating demand	Cooling demand
Before AIP	35.7	69.3	29.3
After AIP	27.4	46.2	17.0
Deviation (%)	23.3	33.4	41.6

Fig. 8. Annual mean CO_2 emissions, primary energy demand and deviation (%) before and after AIP implementation.

Sorting the study sample by years of construction can highlight a greater need for upgrading the older stock. Greater deviations can be observed in the buildings dating from 1951-60, with reductions of 21-34.2 % for CO_2 emissions in most cases, 29.8-53.9 % in heating demand, and 37.4-48.3 % in cooling demand (Fig 9). Towards the end of the period studied variability in these ranges is just 1-3 %, with reductions of 21.0-22.2 % in CO_2 emissions, and 27.7-30.3 % and 39.3-40.7 % in heating and cooling demands, respectively (Fig. 9).

In all, major reductions of 24.6 % in CO_2 emissions, 36.5 % in heating demand, and 43.5 % in cooling demand can be achieved, resulting in some cases with reductions of almost 35 % in CO_2 emissions and 55 % in primary energy demand (Fig. 9).

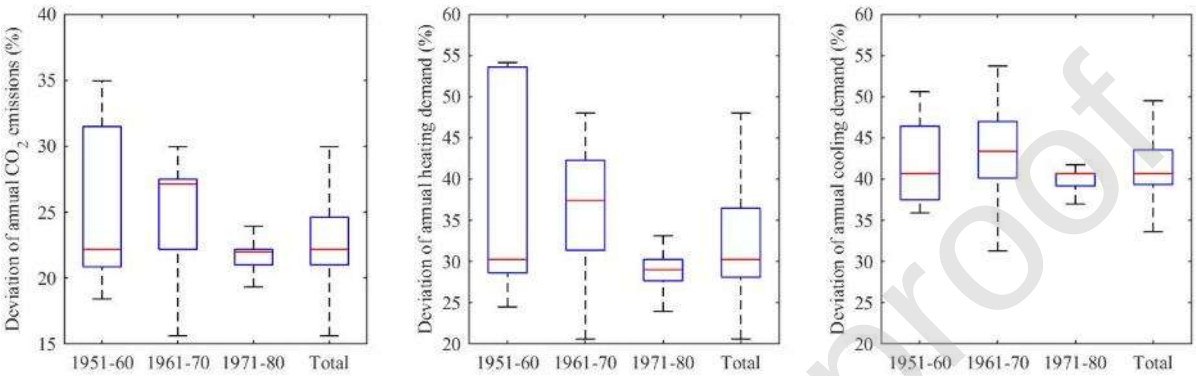


Fig. 9. Annual deviation (%) for CO_2 emissions (a; left) energy demand for heating (b; middle) and cooling (c; right) after AIP implementation.

As part of the analysis of the impact of the AIP on these buildings the annual mean deviations in energy demand have been addressed through morphological parameters such as typology, position, and orientation, which impact the building's energy performance (Figs. 10 and 11).

In this sense, significant deviations are observed in buildings with a higher exposed surface, such as linear buildings (with average decreases in heating and cooling of 38.5 % and 42.0 %, respectively) (Figs. 10a and 11a) as well as freestanding buildings (with average decreases in heating and cooling of 39.1 % and 44.8 %, respectively) (Figs. 10b and 11b), other than more compact buildings such as residential towers (with average decreases in heating and cooling of 26.3 % and 39.7 %, respectively) (Figs. 10a and 11a) or inner-positioned buildings (with average decreases in heating and cooling of 33.5 % and 40.8 %, respectively) (Figs. 10b and 11b).

Clear differences can be observed between the range of deviations obtained in freestanding buildings and those located in end or interior positions. While the former present deviations of around 30.0-47.2 % for heating and 39.4-48.6 % cooling demand, inner-positioned buildings range from 29.1-36.5 % for heating and 38.9-41.0 % for cooling, while those at the end are 27.7-33.0 % for heating and 39.4-41.5 % for cooling (Figs. 10b and 11b).

Results do not shed much light on the impact of the buildings' orientation on their energy behaviour. Nevertheless, the orientations with the most solar exposure present noticeable deviations thanks to the strategies implemented (Figs. 10c and 11c). Heating deviations around 28.1-42.3 % for Northeast-Southwest orientations show that these buildings may benefit from higher solar gains in winter (Fig. 10c), while other buildings with different orientations present 8-9 % ranges, around 28.4-36.5 % for East-West ones, 27.6-36.5 % in the North-South ones and 28.4-37.2 % in the Northwest-Southeast ones. Similarly, both Southeast and Southwest orientations increase the AIP benefit in the buildings, with average deviations of 41.8-42.3 % of cooling demands, and reaching maximum reductions of almost 50 % of the original cooling loads (Figs. 10c and 11c), picturing that solar control strategies also contribute to a better energy performance under a Mediterranean climate.

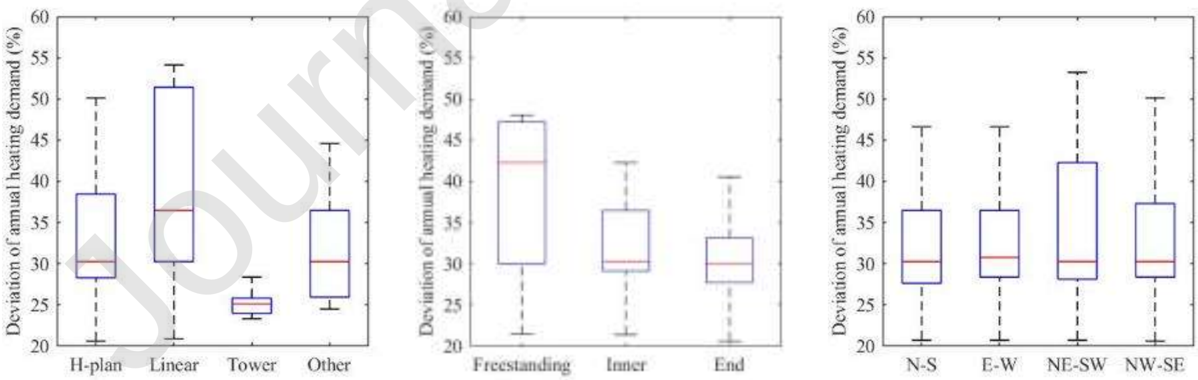


Fig. 10. Deviation in annual heating demand (%) sorted by typology (a; left) position (b; middle) and orientation (c; right) after AIP implementation.

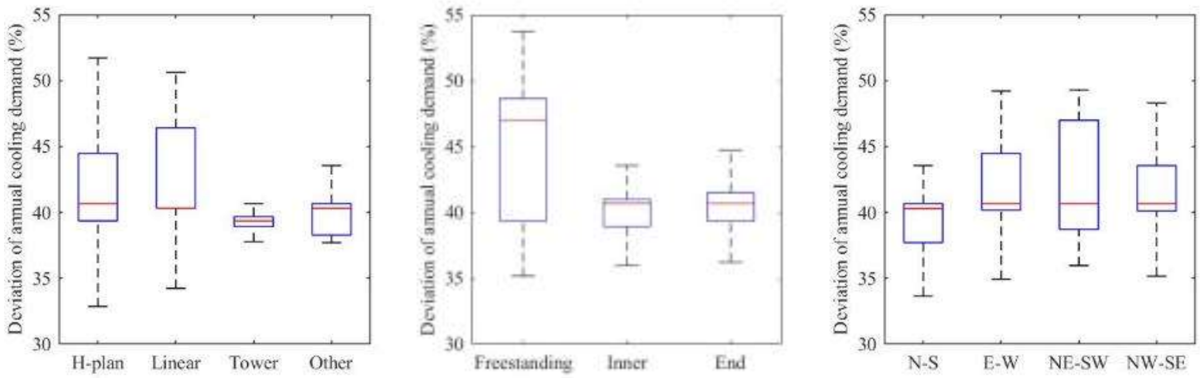


Fig. 11. Deviation of annual cooling demand (%) sorted by typology (a; left) position (b; middle) and orientation (c; right) after AIP implementation.

4. Conclusions

The proposed protocol in the present research aims to contribute to the body of knowledge by bringing to light the energy status quo of existing residential stock in Mediterranean areas. In the light of results, the collection of real buildings-related data at several detailed levels (Loi1 and Loi2) provides for a supporting source of information towards subsequent assessments of the environmental performance applicable to extensive residential stock. Within a foreseeable common integrative framework for sustainable projects at urban scale, accounting for real buildings features will enable more accurate assessments in the context of the building's location.

The use of GIS technology has become advantageous in the analysis of territorial sets of buildings, incorporating the development of a useful tool into the approach of overarching strategies for energy improvement. This paper tests the suitability of a GIS tool, designed through a protocol for assessing the energy *status quo* of existing housing stock and its potential for upgrading. The ongoing nature of the tool foresees future lines of implementation to ensure more precise results as more information becomes available.

The case study examined, the urban stock of the city of Córdoba, has served as an example to demonstrate the potential effectiveness and scope of this method, which could also be wellsuited for assessing other building stocks. The protocol has facilitated the detection of common architectural and constructive patterns throughout the different buildings selected, later used to define an all-inclusive proposal (AIP) to implement the analysed constructions. However, focusing on a specific section of the housing stock results in an unequal size for the variables analysed throughout the study sample (i.e., typologies, orientations). Whilst the accuracy of results is increased in some cases such as H-plan buildings, it is necessary to increase the number of other types of buildings (linear buildings and residential towers) in order to ascertain the extent to which integral passive strategies may improve energy performance in different types of housing stock.

Among the study sample, the widespread lack of thermal insulation causes 96.6 % of the buildings to score within the E-range, with average emissions of 34 $kgCO_2/m^2$ and annual heating and cooling demands of around 60-70 and 20-30 kWh/m^2, respectively. However, among buildings from the second half of the study period a trend can be observed which shows improvement, coinciding with the implementation of lighter constructive solutions thanks to the incorporation of non-ventilated air chambers.

The transposition of an all-inclusive proposal (AIP) to the study sample analysed at urban scale leads to an overall benefit of 25 % less of CO_2 emissions into the atmosphere, thanks to a reduction of one level in energy ratings among 3 % of buildings from the 1950s (from F to E), as well as in 3% of buildings from the rest of the sample (from E to D). Furthermore, decreases of 36.5 % and 43.5 % in the annual heating and cooling demands respectively are obtained, embodying a major decrease of 37.7 % in primary energy demand at territorial level.

The AIP defined implies a general upgrading of the buildings' thermal envelope, constant and controlled air renewal, night thermal dissipation and solar control, contributing to a greater extent in those cases with greater exposed surface areas. Less compact typologies, such as linear buildings, and freestanding buildings seem to benefit to a greater extent from the improvement brought about by the AIP (39.4-40.7 % average energy demand reduction). Moreover, the AIP provides a more controlled solar incidence inside the buildings, overall, in the most penalized orientations, East-West and Northeast-Southwest, with a reduction of up to 51.6 % and 48.1 % in annual energy demands, respectively).

The resultant energy performance indicators of the analysed buildings serve as a reference when similar contexts are addressed. Actually, the application of the proposed protocol to an existing building stock supports its replicability at different scales (e.g., district, urban, territorial) and its adjustable nature to other contexts contributes to broaden the accessibility to information on the existing residential stock in a common European frame.

Further lines of research could consider, within the digital transformation of the constructive process, the integration of the generated GIS dataset with a BIM environment, to boost the implementation of the generated tool and assist in the sustainable approach to the project's management. Moreover, cost-effective assessments of the proposed strategies would provide for an estimation of their investment returns. Indeed, it is expected that the protocol achieved will be incorporated into decision-making processes, encouraging regional public administrations and private stakeholders to boost upgrading plans of the city stock in order to meet the goals set for existing buildings within the current Horizon Europe framework.

CRediT authorship contribution statement

Teresa Blázquez: Conceptualization, Methodology, Software, Writing, - original draft. **Rafael Suárez:** Conceptualization, Methodology, Writing - review & editing. **Simone Ferrari:** Conceptualization, Methodology, Writing - review & editing. **Juan José Sendra:** Conceptualization, Methodology, Writing – review & editing.

Declaration of Competing Interest

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

Acknowledgements/Funding

The present work was partially funded by the VI Internal Research Plan of the Universidad de Sevilla and the TEP-130 research group.

References

[1] European Environment Agency. National action across all sectors needed to reach greenhouse gas Effort Sharing targets. n. d. https://www.eea.europa.eu/themes/climate/trends-and-projections-in-europe/national-action-across-all-sectors/national-action-across-all-sectors (accessed November 16, 2020)

[2] Commission Recommendation (EU) 2019/786 of 8 May 2019 on building renovation. Off J Eur Union 2019;127:34–79

[3] Reinhart CF, Cerezo Davila C. Urban building energy modeling - A review of a nascent field. Build Environ 2016;97:196–202. doi:10.1016/j.buildenv.2015.12.001

[4] Mata É, Sasic Kalagasidis A, Johnsson F. Building-stock aggregation through archetype buildings: France, Germany, Spain and the UK. Build Environ 2014;81:270–82. doi:10.1016/j.buildenv.2014.06.013

[5] Ferrari S, Zagarella F, Caputo P, D'Amico A. Results of a literature review on methods for estimating buildings energy demand at district level. Energy 2019;175:1130–1137. doi:10.1016/j.energy.2019.03.172

[6] Gatt D, Yousif C, Cellura M, Camilleri L, Guarino F. Assessment of building energy modelling studies to meet the requirements of the new Energy Performance of Buildings Directive. Renew Sustain Energy Rev 2020;127:109886. doi:10.1016/j.rser.2020.109886

[7] Kavgic M, Mavrogianni A, Mumovic D, Summerfield A, Stevanovic Z, Djurovic-Petrovic M. A review of bottom-up building stock models for energy consumption in the residential sector. Build Environ 2010;45:1683–97. doi:10.1016/j.buildenv.2010.01.021

[8] Nägeli C, Camarasa C, Jakob M, Catenazzi G, Ostermeyer Y. Synthetic building stocks as a way to assess the energy demand and greenhouse gas emissions of national building stocks. Energ Buildings 2018;173:443–60. doi:10.1016/j.enbuild.2018.05.055

[9] Brøgger M, Wittchen KB. Estimating the energy-saving potential in national building stocks – A methodology review. Renew Sustain Energy Rev 2018;82:1489–96. doi:10.1016/j.rser.2017.05.239

[10] Buffat R, Froemelt A, Heeren N, Raubal M, Hellweg S. Big data GIS analysis for novel approaches in building stock modelling. Appl Energy 2017;208:277–90. doi:10.1016/j.apenergy.2017.10.041

[11] Österbring M, Mata É, Thuvander L, Mangold M, Johnsson F, Wallbaum H. A differentiated description of building-stocks for a georeferenced urban bottom-up building-stock model. Energ Buildings 2016;120:78–84. doi:10.1016/j.enbuild.2016.03.060

[12] Shen P, Yang B. Projecting Texas energy use for residential sector under future climate and urbanization scenarios: A bottom-up method based on twenty-year regional energy use data. Energy 2020;193:116694. doi:10.1016/j.energy.2019.116694

[13] Delmastro C, Mutani G, Corgnati SP. A supporting method for selecting cost-optimal energy retrofit policies for residential buildings at the urban scale. Energ Policy 2016;99:42–56. doi:10.1016/j.enpol.2016.09.051

[14] Monteiro CS, Pina A, Cerezo C, Reinhart C, Ferrão P. The Use of Multi-detail Building Archetypes in Urban Energy Modelling. Energy Procedia 2017;111:817–25. doi:10.1016/j.egypro.2017.03.244

[15] Aksoezen M, Daniel M, Hassler U, Kohler N. Building age as an indicator for energy consumption. Energ Buildings 2015;87:74–86. doi:10.1016/j.enbuild.2014.10.074

[16] EPISCOPE. IEE Project TABULA. Typology Approach for Building Stock Energy Assessment. n. d. https://episcope.eu/iee-project/tabula/ (accessed November 16, 2020)

[17] Instituto Valenciano de la Edificación (IVE). Catálogo de tipología edificatoria residencial. 2016. ISBN: 978-84-96602-87-8

[18] Ballarini I, Corgnati SP, Corrado V. Use of reference buildings to assess the energy saving potentials of the residential building stock: The experience of TABULA project. Energ Policy 2014;68:273–84. doi:10.1016/j.enpol.2014.01.027

[19] Dascalaki EG, Droutsa KG, Balaras CA, Kontoyiannidis S. Building typologies as a tool for assessing the energy performance of residential buildings - A case study for the Hellenic building stock. Energ Buildings 2011;43:3400–9. doi:10.1016/j.enbuild.2011.09.002

[20] Florio P, Teissier O. Estimation of the Energy Performance Certificate of a housing stock characterised via qualitative variables through a typology-based approach model: A fuel poverty evaluation tool. Energ Buildings 2015;89:39–48. doi:10.1016/j.enbuild.2014.12.024

[21] Loga T, Stein B, Diefenbach N. TABULA building typologies in 20 European countries—Making energy-related features of residential building stocks comparable. Energ Buildings 2016;132:4–12. doi:10.1016/j.enbuild.2016.06.094

[22] Groppi D, de Santoli L, Cumo F, Astiaso Garcia D. A GIS-based model to assess buildings energy consumption and usable solar energy potential in urban areas. Sustain Cities Soc 2018;40:546–58. doi:10.1016/j.scs.2018.05.005

[23] Dall'O' G, Galante A, Pasetti G. A methodology for evaluating the potential energy savings of retrofitting residential building stocks. Sustain Cities Soc 2012;4:12–21. doi:10.1016/j.scs.2012.01.004

[24] Caputo P, Pasetti G. Boosting the energy renovation rate of the private building stock in Italy: Policies and innovative GIS-based tools. Sustain Cities Soc 2017;34:394–404. doi:10.1016/j.scs.2017.07.002

[25] Buffat R, Schmid L, Heeren N, Froemelt A, Raubal M, Hellweg S. GIS-based Decision Support System for Building Retrofit. Energy Procedia 2017;122:403–8. doi:10.1016/j.egypro.2017.07.433.

[26] Mrówczyńska M, Skiba M, Bazan-Krzywoszańska A, Sztubecka M. Household standards and socio-economic aspects as a factor determining energy consumption in the city. Appl Energy 2020;264:114680. doi:10.1016/j.apenergy.2020.114680

[27] Moghadam S T, Delmastro C, Corgnati S P, Lombardi P. Urban energy planning procedure for sustainable development in the built environment: A review of available spatial approaches. Journal of Cleaner Production 2017;165:811-827. doi: 10.1016/j.jclepro.2017.07.142

[28] Ferrari S, Zagarella F, Caputo P, Bonomolo M. Assessment of tools for urban energy planning. Energy 2019;176:544–551. doi:10.1016/j.energy.2019.04.054

[29] García-Ballano CJ, Ruiz-Varona A, Casas-Villarreal L. Parametric-based and automatized GIS application to calculate energy savings of the building envelope in rehabilitated nearly zero energy buildings (nZEB). Case study of Zaragoza, Spain. Energ Buildings 2020;215: 109922. doi:10.1016/j.enbuild.2020.109922

[30] D'Alonzo V, Novelli A, Vaccaro R, Vettorato D, Albatici R, Diamantini C, et al. A bottom-up spatially explicit methodology to estimate the space heating demand of the building stock at regional scale. Energ Buildings 2020;206:109581. doi:10.1016/j.enbuild.2019.109581

[31] Braulio-Gonzalo M, Bovea MD, Ruá MJ, Juan P. A methodology for predicting the energy performance and indoor thermal comfort of residential stocks on the neighbourhood and city scales. A case study in Spain. J Clean Prod 2016;139:646–65. doi:10.1016/j.jclepro.2016.08.059

[32] Martín-Consuegra F, de Frutos F, Oteiza I, Agustín HA. Use of cadastral data to assess urban scale building energy loss. Application to a deprived quarter in Madrid. Energ Buildings 2018;171:50–63. doi:10.1016/j.enbuild.2018.04.007

[33] Caputo P, Costa G, Ferrari S. A supporting method for defining energy strategies in the building sector at urban scale. Energ Policy 2013;55:261–70. doi:10.1016/j.enpol.2012.12.006

[34] Caputo P, Pasetti G. Overcoming the inertia of building energy retrofit at municipal level: The Italian challenge. Sustain Cities Soc 2015;15:120–34. doi:10.1016/j.scs.2015.01.001

[35] Caputo P, Pasetti G. Boosting the energy renovation rate of the private building stock in Italy: Policies and innovative GIS-based tools. Sustain Cities Soc 2017;34:394–404. doi:10.1016/j.scs.2017.07.002

[36] Saretta E, Caputo P, Frontini F. An integrated 3D GIS-based method for estimating the urban potential of BIPV retrofit of façades. Sustain Cities Soc 2020;62:102410. doi:10.1016/j.scs.2020.102410

[37] Torabi Moghadam S, Toniolo J, Mutani G, Lombardi P. A GIS-statistical approach for assessing built environment energy use at urban scale. Sustain Cities Soc 2018;37:70–84. doi:10.1016/j.scs.2017.10.002

[38] Mastrucci A, Baume O, Stazi F, Leopold U. Estimating energy savings for the residential building stock of an entire city: A GIS-based statistical downscaling approach applied to Rotterdam. Energ Buildings 2014;75:358–67. doi:10.1016/j.enbuild.2014.02.032

[39] Ghedamsi R, Settou N, Gouareh A, Khamouli A, Saifi N, Recioui B, et al. Modeling and forecasting energy consumption for residential buildings in Algeria using bottom-up approach. Energ Buildings 2016;121:309–17. doi:10.1016/j.enbuild.2015.12.030

[40] Escandón R, Suárez R, Sendra JJ, Ascione F, Bianco N, Mauro GM. Predicting the impact of climate change on thermal comfort in a building category: The Case of Linear-type Social Housing Stock in Southern Spain. Energies 2019;12(12):2238. doi: 10.3390/en12122238

[41] Blázquez T, Ferrari S, Suárez R, Sendra JJ. Adaptive approach-based assessment of a heritage residential complex in southern Spain for improving comfort and energy efficiency through passive strategies: A study based on a monitored flat. Energy 2019;181:504–20. doi:10.1016/j.energy.2019.05.160

[42] Directive 2007/2/EC of the European Parliament and of the Council of 14 March 2007 establishing an Infrastructure for Spatial Information in the European Community (INSPIRE). Off J Eur Union 2007;108:1–14

[43] Ministry of Housing. Building Technical Code (CTE). Basic Document on Energy Saving (DB-HE). 2019. n. d. https://www.codigotecnico.org/pdf/Documentos/HE/DBHE.pdf (accessed November 16, 2020)

[44] Kottek M, Grieser J, Beck C, Rudolf B, Rubel F. World Map of the Köppen-Geiger climate classification updated. Meteorol Zeitschrift 2006;15:259–63. doi:10.1127/0941-2948/2006/0130

[45] Ministry of Development. General Directorate of Architecture, Housing and Land. Descriptive document of reference climates. 2017. n. d. https://www.codigotecnico.org/pdf/Documentos/HE/20170202-DOC-DB-HE-0-Climas%20de%20referencia.pdf (accessed November 16, 2020)

[46] Ministry of the Presidency. Royal Decree 2429/1979, of July 6th, by which it is approved the Basic Norm of Construction NBE-CT-79 on Thermal Conditions in Buildings. 1979. n. d. https://www.boe.es/eli/es/rd/1979/07/06/2429/dof/spa/pdf (accessed November 16, 2020)

[47] Sendra JJ, Domínguez-Amarillo S, Bustamante P, León a. L, Domínguez S, Bustamante P, et al. Energy intervention in the residential sector in the south of Spain: Current challenges. Inf Constr 2013;65:457–64. doi:10.3989/ic.13.074

[48] Escandón R, Suárez R, Sendra JJ. On the assessment of the energy performance and environmental behaviour of social housing stock for the adjustment between simulated and measured data: The case of mild winters in the Mediterranean climate of southern Europe. Energ Buildings 2017;152:418–33. doi:10.1016/j.enbuild.2017.07.063

[49] Blázquez T, Suárez R, Sendra J. Protocol for Assessing Energy Performance to Improve Comfort Conditions in Social Housing in a Spanish Southern City. Int J Energy Prod Manag 2017. 2(2):140-152. doi: 10.2495/EQ-V2-N2-140-152

[50] National Statistics Institute (NSI). Population and Housing Census 2011. n. d.

[51] www.ine.es/en/censos2011_datos/cen11_datos_inicio_en.htm%0D (accessed November 16, 2020)

[52] Town Planning Institution (Córdoba City Council). Historical City Planning. n. d.

[53] http://www.gmucordoba.es/urbanismo/planeamiento-historico (accessed November 16, 2020)

[54] Regional Ministry of the Environment and Territorial Planning (Regional Government of Andalusia). WMS Digital Panchromatic Orthofotograph of Andalucía 1956-57. Andalusian Environmental Information Network. n. d.http://www.juntadeandalucia.es/medioambiente/site/rediam/menuitem.04dc44281e5d53cf8ca78ca731525ea0/?vgnextoid=d0e8542e27998110VgnVCM1000000825e50aRCRD&vgnextchannel=48f87d087270f210VgnVCM1000001325e50aRCRD&lr=lang_es (accessed November 16, 2020)

[55] Regional Ministry of the Environment and Territorial Planning (Regional Government of Andalusia). WMS Digital Panchromatic Orthofotograph of Andalucía 1977-83. Andalusian Environmental Information Network. n. d.http://www.juntadeandalucia.es/medioambiente/site/rediam/menuitem.04dc44281e5d53cf8ca78ca731525ea0/?vgnextoid=61142e62ea1a3210VgnVCM1000001325e50aRCRD&vgnextchannel=48f87d087270f210VgnVCM1000001325e50aRCRD&lr=lang_es (accessed November 16, 2020)

[56] Goolzoom. n. d. https://www.goolzoom.com. (accessed November 16, 2020)

[57] Googlemaps. n. d. https://www.google.es/maps. (accessed November 16, 2020)

[58] Spanish Electronic Cadastre Website. Ministry of Housing. n. d. https://www.sedecatastro.gob.es/. (accessed November 16, 2020)

[59] Córdoba City Council. Municipal Historical Archive. n.d. https://archivo.cordoba.es/ (accessed November 16, 2020)

[60] Quantum GIS. v2.18.16. n. d. https://www.qgis.org/es/site/. (accessed November 16, 2020)

[61] Ministry of the Presidency. Royal Decree 235/2013, of April 5th, aproving the basic procedure for Energy Certificaton of Existing buildings. 2013. n. d. https://www.boe.es/buscar/pdf/2013/BOE-A-2013-3904-consolidado.pdf (accessed November 16, 2020)
[62] CE3X Acknowledged Document for the Energy Certification of Existing Buildings. E.P.E. Institute for the Diversification and Saving of Energy (IDAE). Ministry for the Ecological Transition. n. d. https://www.efinova.es/CE3X. (accessed November 16, 2020)
[63] Institute for Energy Diversification and Savings (IDAE). Energy rating scale for existing buildings. 2011. n. d.https://www.idae.es/uploads/documentos/documentos_11261_EscalaCalifEnerg_EdifExistentes_2011_accesible_c762988d.pdf (accessed November 16, 2020)
[64] Dall'O G, Sarto L, Sanna N, Tonetti V, Ventura M. On the use of an energy certification database to create indicators for energy planning purposes: Application in northern Italy. Energ Policy 2015;85:207-217. doi: 10.1016/j.enpol.2015.06.015
[65] Qgis2web. QGIS Python Plugins Repository. n. d. https://plugins.qgis.org/plugins/qgis2web/ (accessed November 16, 2020)
[66] Ministry of development, Secretary of State for Infrastructure T and H, General Directorate for Architecture H and L. Description of Reference Climates. n.d. http://www.arquitectura-tecnica.com/hit/Hit2016-2/20150723-DOC-DB-HE-0-Climas de referencia.pdf (accessed November 16, 2020)
[67] Spanish Asociation of Normalization (AENOR). UNE-EN 12207 Windows and doors - Air permeability - Classification. Madrid: 2017.