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Research article

Analysis of thermal insulation in social housing in Spain (1939–1989) and its possible adaptation to the Sustainable Development Goals (SDGs)

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Abstract: The construction of protected housing in Spain during the period analysed (1939–1989) reached its maximum between 1950–1980 with the construction of almost three million homes per year. The analysis of the homes built for railroad workers from this housing stock is distinct for four main reasons: it is a housing stock with a representative number of homes in relation to the total of social housing built in Spain, which is still mostly in use and covers all the typologies used in the country and which is dispersed throughout it. Thus, for the present analysis, there is a sample that is adequately representative of the whole stock of social housing constructed in Spain, this sample enables a comparative global analysis that can be extrapolated to the remaining stock. The objective of this study is to analyse the energy efficiency of homes through the thermal analysis of the envelope, as well as to acknowledge the specific constructive limitations of these homes and if possible, their rehabilitation that guarantees compliance with the required standards regarding sustainability and energy efficiency set by the Sustainable Development Goals (SDGs) established in the 2030 Agenda. This is a crucial goal to achieve, as the Spanish building stock currently consumes 30% of the total energy consumed, in addition to the socioeconomic profile and the potential for energy poverty, there is a portion of social housing with a precarious construction lacking the heating facilities, which is required due to the weather, with a significant potential for savings and the incorporation of renewable energies.

Keywords: social housing; circular architecture; rehabilitation; insulation; construction materials; sustainability

1. Introduction

For this analysis, it is necessary to briefly discuss two prior topics: first, protected housing in Spain and the contextual factors that affect its implementation as a starting point for the research; second, the Sustainable Development Goals (SDGs) and the degree to which they have been incorporated into Spanish housing as a point of arrival. Both of these difficulties provide the opportunity to create a realistic framework for the existing chances that the examined dwelling stock has of conforming to the present insulation standards.

Protected or social housing [1–5] is one that receives significant public aid despite being promoted by private agents. It is a concept that was extended in Spain in the second half of the 20th century as a result of the inability of the working class to access affordable housing and the lack of sufficient public construction to fulfil the demand brough on by substantial migration from the countryside to the city. Housing development was one of the primary economic activities of the country during those years due to the high rates of population increase, economic expansion and migration [6,7]. This turnaround is also justified by the development of legislation promoting the privatization process of housing construction in Spain: Law of Housing of Limited Income (1954) and Land Law (1956) and, also, the specific legislation for the development of cooperatives: the Law of Cooperation (1942) and its regulations (1943) [8].

This analysis is part of the research which, since 2018 [9] is being carried out on the constructive, architectural, urban, economic and immaterial characteristics of railway housing in Spain as there is a representative sample of social housing in the country for the reasons given in the summary. From the total number of homes analysed, located in 99 towns throughout the country (Figure 1), 260 developments and 19,927 homes, 34% were protected housing promoted by the national railway company RENFE, 55% were protected housing promoted by the railway workers themselves organized in cooperatives and the remaining 11% by other railway companies. Figure 2 shows the number of dwellings which are subject of this analysis, built by developers and each year. It is worth mentioning that, until the 60s, RENFE was essentially the only promoter, however, subsequently, it was the railway workers organized in cooperatives. It should be highlighted that 30% of the residences in the so-called municipalities of demographic challenges, where this housing stock makes up a substantial portion, were built before 1960 [10].

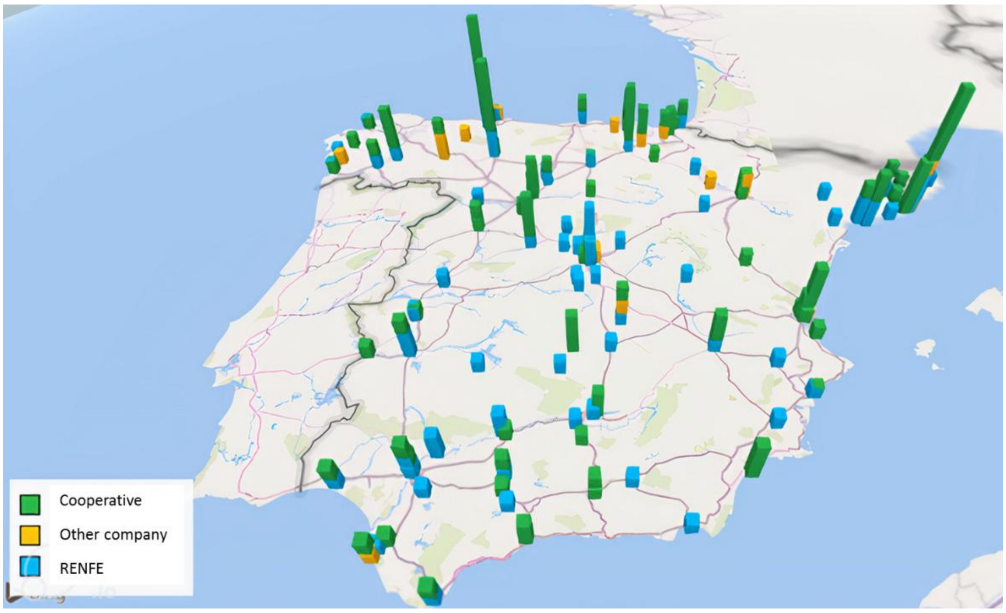


Figure 1. Location of the houses built for railway workers in the period 1939–1989 according to the developers. Own elaboration based on the projects and files analysed.

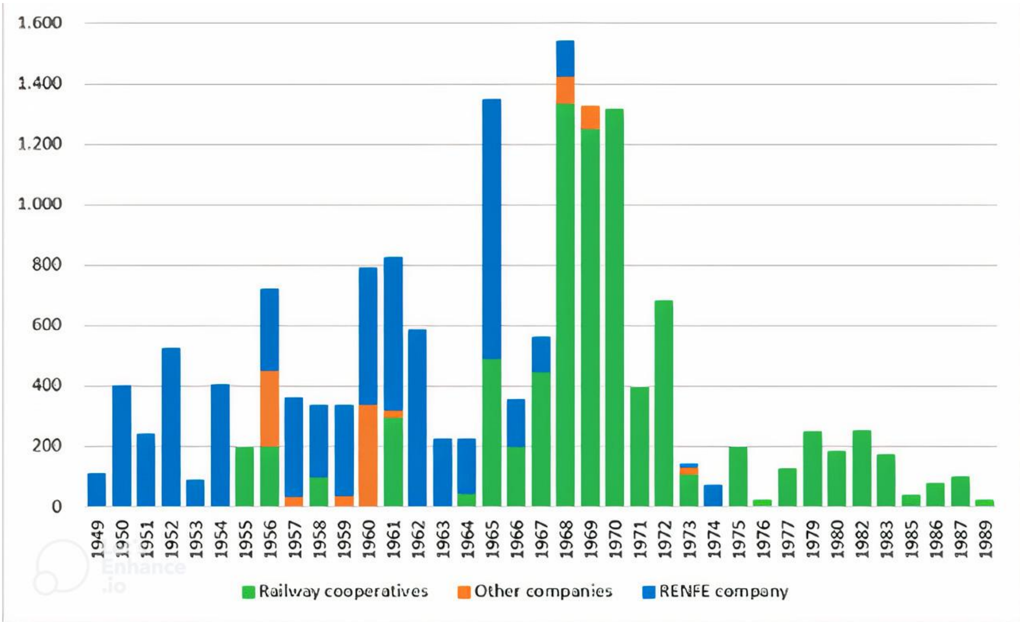


Figure 2. The number of homes per year by different developers. Own elaboration based on the projects and files analysed.

The chosen study period is justified by the existence of a common regulatory framework at the national level, which dates back to the first housing law passed under the Franco regime in 1939 and concludes in 1989, when the Supreme Court ruled that the Autonomous Communities should have jurisdiction over housing matters and left the Central Administration with a supervisory and coordinating role. It is, therefore, from the political point of view, a mixed period and of a certain complexity. On the one hand, there is the long dictatorship of Franco, of strong initial interventionism that is felt even in the contents of the technical projects, and the subsequent progressive liberalization. On the other hand, it also coexists in the period analysed, the recovery of democracy, coexistence with the consequences of the oil crises of the seventies, and the consolidation of the housing ownership model with a continuous inflationary process [9].

When it comes to the way of construction of these houses, the innovation and experimentation carried out by some architects deserve special attention as they happened during the Republican period [11], a period in which these architects intended to contribute to the Spanish panorama through executing research on social housing sector that was being carried out in other nations but was often ignored. Although there was no regulation regarding insulation or energy efficiency issues, these projects took into account passive strategies such as orientations, sunlight control through the arrangement of blinds, lattices, vegetation, eaves, etc, creation of shadows with the geometry of the building itself or another series of project resources that show an intention in this regard despite the non-existent regulations and that in the projects analysed, is lost [12–14].

The approval of the 2030 Agenda, which incorporates the 17 objectives of universal applicability since 2016 among the countries that creates the United Nations and which aspires to achieve sustainable development by 2030, was one of the final outcomes of the historic Sustainable Development Goals (SDGs). Specifically, regarding housing and the subject of study, the SDGs of application would be, in a more generic way, No. 9 whose main aim is the development of resilient infrastructures, the promotion of sustainable industrialization, along with the promotion of innovation, and whose specific goals, with respect to the subject under study, would be target nº 9.5 which seeks to increase scientific research and the improvement of technological capacity by improving innovation in the companies and, more specifically, objective nº 11 that seeks "To make cities and human settlements inclusive, safe, resilient and sustainable" where specifically target 11.1 that aims to ensure the access of all individuals to safe and affordable housing and basic services, specifically affects the object of study since one of the basic requirements that housing must currently meet is energy savings [15,16]. Based on the analysis, some scenarios of starting and arrival point can be defined (construction and rehabilitation of housing alongside urban regeneration) as practically antagonistic, where the analysis of the constructive characteristics and the regulations will determine the degree of adaptability of the houses to the new scenario that marks the 2030 Agenda.

The article begins with the analysis of the thermal envelope and compactness carried out from primary sources, in this case, it is the review of the original existing house projects, as well as the study and implementation of the articles of application and specific thermal insulation regulations over the course of the study period. This is a period where the requirements or recommendations in this regard are practically non-existent until the basic standard of thermal conditions of 1979 (NBE-CT-79). It is based on an initial analysis of the envelope that is complemented by the current prescriptions of the Technical Code in order to be able to estimate the adaptive capacity of the assessed housing stock to the current demands of the analysed housing stock.

It is intended to simulate compliance with the new and restrictive standards set with the aim of reconciling these homes, which are still in use today and were built under minimum cost criteria, with the lowest energy consumption and, as a result, with greater energy efficiency and environmental sustainability after the analysis of the study and after the most recent update of the basic document of energy saving (CTE DB HE), recently modified, (RD 450/2022, of June 14). It is clear that the constructive obsolescence of these houses is determined both by the analysis of the projects, the existing regulations along with the fieldwork carried out and what is intended is to quantify, even approximately, to what extent and thereby determine the viability of their adaptation to current requirements. The following photographs (Figure 3) show the current state of some developments for each of the four periods analysed:

Figure 3. A) RENFE housing, Algeciras (1951). B) RENFE housing, Cádiz (1960). C) Cooperative Housing "San Juan de Dios", Granada (1970). D) Cooperative Housing "San Valero", Zaragoza (1981). Cuéllar-Martínez archive.

The analysis of thermal facilities controlled by the regulation of thermal installations in buildings (RITE) is excluded from the present research. This regulation was recently modified in 2021 as a measure of the development of the Action Plan of the energy saving and efficiency strategy in Spain (2005–2007) also contributing to achieve the objectives established by the Plan for the promotion of renewable energies (2000–2010) is left out of this study, promoting greater use of solar thermal energy, especially in the production of domestic hot water.

Globally, similar studies on social housing have been conducted, revealing a crucial issue that is consistent across all the cases analysed, despite the different methods of analysis, regulations and context: the need to implement active or passive techniques to improve energy efficiency in social housing, as it is a stock with very simple construction characteristics and where maintenance is practically non-existent for economic and social reasons [17–22]. Some particular case studies in historic centres are also unique or those that have an impact on maintenance standards, models or techniques [23–26].

This work is unpublished and forms part of the inventory on social housing promoted by railway workers in Spain. In order to be able to carry it out, since 2018 the authors have been visiting state archives (Ministry Archives, General Administration Archives), regional and local archives to locate the primary sources, which are the administrative files and projects, many of them incomplete, on which this analysis has been carried out. The interest of this analysis stems from the need to update the large stock of social housing in use in Spain in order to improve sustainability, comply with the commitments adopted by the 2030 Agenda and improve the comfort and habitability of the dwellings.

2. Materials and methods

The methodology, of our own elaboration based on studies such as [22,27,28] is part of the one developed for the ongoing inventory on Railway Social Housing. The elaboration of the inventory is based on basic analytical principles such as [29,30], among others. Mainly, the authors carried out an orderly and systematic recording of data considering that the information from reports, files and housing construction projects is very broad and uneven, to prevent getting overtaken by the data, its structuring is crucial. In fact, it is worth highlighting that the documents studied were not designed for consultation and study. They are very disparate in size, distribution and content and must be emptied of information, whether it is of interest to historians, architects, town planners or local researchers.

Within the first two categories (business housing for rent and cooperative housing for ownership) in the present case, the authors have so far managed data on 257 housing complexes, with 90 fields. In other terms, there is approximately 25,000 pieces of data, both quantitative and qualitative. For the registration of these data, we have established a classification and rules of use that allow easy consultation and avoid errors. This classification table establishes identification parameters (key name, current state, number of dwellings, among others), architectural parameters (building, structural, constructive, installations and supplies), urban parameters (typology, surface area, volume, orientation) and economic parameters (the price of the plot, material execution budget, minimum rent, among others). Specifically for the analysis carried out, mainly architectural parameters have been used. All this information is systematised using Excel tables after the establishment of validation lists with a consensus of the definitions used incorporated into them. The results of these tables are shown using dynamic tables and associated graphs. Zotero (Joseph, 2021) is used as a document manager, with the compatibility of other managers such as Mendeley or others. For more details on our own methodology, see [33].

2.1. Constructive characterisation of the elements analysed. Block type configuration

The main sources analysed are primary sources and constitute the construction projects of these houses, located in the archive of the former General Directorate of Architecture and Housing, preserved in the General Archive of Development, and in numerous municipal archives of the cities where these constructions were carried out. The extensive period of study, the volume and variety of these constructions, and the diversity of location provide a wide range of opportunities for analysing the characteristics, and also studying, as far as possible, the realization of improvements so that the homes can be used more sustainably in the years to come.

For the calculation of the thermal envelope, through the analysis of the typologies, functional distribution, and dimensions found in the analysed projects, it is proceed with the generation of the model building (Figure 4) that is designed based on the typologies and the average described characteristics found in the analysed projects. This type of building will be adapted to the four periods determined by the four regulations regarding thermal insulation existing during the chronological scope to be studied, and subsequently detailed.

Figure 4. Building type floorplan. Own elaboration from the analysed projects.

The building is a parallelepiped with a double structural bay, a floorplan of 22 by 8 meters, two symmetrical houses per level, and a central staircase core as a result of an examination of the current typologies in the consulted designs. The average block heights are generated through analysing projects along with the generation of the type I block, which has four stories, the type II block, which has five stories, and the type III block, with seven stories. Each home has an estimated built-in space that, on average, measures 10 m by 8 m. The following table provides an overview of the key typological and constructive traits of each type of block that was considered throughout the investigation (Table 1). A deeper study about in [14]: Thus, the main variables analysed in the simulation programmes used in all the standard blocks (I, II, III and IV) were: type of block and orientation, construction characteristics of the envelope (enclosures, joinery and roofs), use and heating of adjacent spaces (where applicable), the existence of basements and installations.

Table 1. Constructive characteristics type buildings.

Type Block	Urban Typology	Structure	Basement	Horizontal Wall ground contact	Enclosures/partition composition	Outdoor carpentry	Roof	Ground floor housing	Installations Heat Water/Heating/AC
Type I	• Opening blocks • 4 floors	• Loading walls 1 foot thickness • Unidirectional slabs. • Thickness: 15 cm	No	• Concrete scree d. Thickness: 15 cm	• Paint+Rev cem+LCM(1 foot)+GE Plaster+Paint • Partition walls: LDH • thickness:30 cm.	• Wood. No shutters. • Single glazing (2-3 mm)	• Sloped. Tile. • St. Wood • Chamber	Yes	• HW: Budget kitchen • HS: No • AC: No
Type II	• Opening blocks • 5 floors	• Loading walls 1 foot thickness • Unidirectional slabs. • Thickness: 15 cm	No	• Concrete scree d. Thickness: 15 cm	• Paint+Rev cem+LCM(1 foot)+GE Plaster+Paint • Partition walls: LDH • thickness:30 cm.	• Wood. No shutters • Single glazing (2-3 mm)	• Sloped. Tile. • St. Wood • Chamber	Yes	• HW: Budget kitchen • HS: No • AC: No
Type III	• Opening blocks • 7 floors	• Reticular RC • Unidirectional slabs. • Thickness: 20 cm	Mix (16%)	• Concrete screed. Thickness: 20 cm on gravel roof	• Paint+Rev cem+LP12+enf cem+air chamber+LHS+GE plaster+paint • CVV+air chamber+LHS+GE plaster+paint • thickness:25 cm.	• Metal. Folding Blinds • Double glazing (4 mm)	• Sloped. Tile • Plain roof. Tile	Mix	• HW: Gas/electric • HS: yec • AC: no
Type IV	• Opening blocks • 12 floors	• Reticular RC • Unidirectional slabs. • Thickness: 25 cm	Yes	• Slab (over basement)	• Paint+Rev cem+LP12+enf cem+air chamber+isolation+LHD +GE plaster+Paint • CVV+air chamber+isolation+LHD +GE plaster+paint • thickness: 29 cm	• Aluminum, Sliding. Blinds • Double glazing (4 mm)	• Plain roof. Tile. Isolation	No	• HW: Gas/electric • HS: yec • AC: no

Source: own elaboration based on the projects analysed.

Among the type I and II projects, there is a greater diversity of projects and constructive solutions derived from two issues: a greater variety of promoters (RENFE, MACOSA, and other railway companies) despite the predominance of RENFE and the overcoming of the autarchic period. There is a notable increase in the use of sanitary slabs compared to the previous period (from 25% to 35%) which, as well as other factors, improves the thermal behaviour of the ground floor. Regarding the enclosures, some developments employ inner folding or chambers, and when it comes to glazing, semi-double glass (3 mm) has started to be used instead of the basic ones (2 mm) that were earlier used primarily [11]. Due to the overwhelming prevalence of cooperatives as housing promoters, Type III and IV projects already display a larger project and creative diversity.

Although the houses under study were constructed across the entirety of the Spanish territory, and as a result, in those areas of extreme climatology, they will still be further from complying with the standards currently required, thus, in order to simply the general vision, it is adapted a favourable climatic zone (B3, map climatic zones CTE DB HE). A thorough case study will be conducted as part of this research on the large and varied field of casuistry.

The analysis and comparison of the current regulation during the period analysed constitutes the second main group of the sources analysed. Regarding the regulatory analysis of thermal insulation and its application in social housing in Spain, it is necessary to analyse both the prescriptions contained in the specific regulations of social housing and in that specific one, referring to the insulation and improvement of the energy efficiency regarding implementation in any housing project. It is necessary to reflect in advance that the regulatory changes are directed towards higher quality, duration of the comfort conditions of the houses, and, in the case of energy efficiency, towards achieving a rational use of the necessary energy reducing its consumption to sustainable limits and also achieving that a part of this consumption comes from renewable energy sources. The situation is also antagonistic to the existing regulations at the time of construction of the houses: ambiguous, practically non-existent, and without any objective of rational consumption or maintenance of the buildings. These are houses built in a stage where there was no approach to reuse or urban regeneration, and where volume, economy, and speed of construction prevailed, indicating that the needs were different.

Finally, for the calculation of the thermal transmission of each of the elements and to determine the standard energy efficiency, the simplified calculation program for the residential energy rating (CERMA V. 5.11, May 2022) and the unified ergonomic for verification of theDB-HE 2019 (version 2.0.2340.1172 of June 17, 2022) are used. It is based on a previous analysis that is completed in this work to cover issues related to the passive conditioning of the different model projects [11,34].

To do this, the parameters of compactness (number of floors, free height, % of façade with respect to the surface), materiality (enclosures and roofs with or without insulation, carpentry, and glass), hollow and solid relation are evaluated. Presence of solar control mechanisms (blinds, shutters, flights, setbacks, terraces, eaves, patios, and direct ventilation). The evaluation of the orientation is omitted when it is detected that, even though 79% of the analysed developments are set in an open building, the best orientation regarding the conditions of sunlight or energy efficiency is not chosen. From the analysis of the projects, it can be deduced that there were other factors that conditioned the choice of orientation (orography, vegetation, arrangement of connections or drains, alignment to roads, etc.).

2.2. Analysis of applicable regulations. Insulation and carpentry

The first technical standards that regulated the building sector in Spain were promoted by the Ministry of Housing and developed by the General Directorate of Architecture, an agency under the Ministry of the Interior created in 1937. These were the so-called MV basic standards that were a set of ten standards that covered: the actions to be considered for structural calculation, steel structures, load-bearing walls of brick factory, and waterproofing of roofs with bituminous materials. The approval of these occurred between the years 1962 and 1976. Subsequently (RD 1650/1977), these standards were integrated into the well-known Basic Building Standards.

Regarding thermal insulation, there were no previous specific regulations until the approval of the Basic Standard of Thermal Conditions (NBE-CT-79) approved in 1979. As it is analysed below, the general regulations only had a few ambiguous articles in this regard. The aforementioned basic standard will remain in effect until the Technical Code was approved in 2006, and specifically with regard to subject of study, an update of the fundamental energy-saving document (recently modified in June) was approved in 2019 due to the need to decrease the effect of climate change and reduce the energy dependence of the buildings.

The first standard that regulated with a general and ambiguous character the hygienic conditions that the houses had to meet, was the Order of February 29, 1944 (BOE nº 61, of March 1944) that, with tangential character to the subject that concerns us, only focused its efforts on the adequate ventilation of the houses regulating minimum dimensions, mandatory ventilation in all rooms, free floor heights, the surface of ventilation holes and minimum dimensions of patios. Since it was common to have dwellings on the ground floor, it prescribed the need to separate the floor of these dwellings through a waterproof layer or a ventilated chamber.

With respect to the thermal insulation, it was extremely ambiguous since it only required to ensure the thermal insulation "to protect it from the rigors of the temperatures of each region" where the building was located, but without specifying climatic zones or characteristics of the materials to be used, as well as methodology or approximation of calculation or any limit value of the transmittance (conductivity/thickness (Wm^{2}K) for the different elements. Nor was there any kind of prescription about the carpentry section or glazing thickness. It is necessary to point out that it is a rule elaborated in the middle of the autarchic period (1939–1959) and therefore, with a great shortage of construction materials [35,36].

The following standard is constituted by the Technical Ordinances and constructive norms for "limited income housing" of 1955 (BOE nº 197, of July 16, 1955) which, in the first place, establishes different conditions depending on whether they are homes belonging to the first or second group and also, within those of the second group, creates a 1st, 2nd or 3rd category. In the present case, all the houses built under this regulation belong to the second group with 2nd and 3rd categories, therefore the application criteria will be discussed.

In order to provide optimum ventilation, the heights of open floor plans in houses are therefore set at a minimum and a maximum that, in an urban setting, range between 2.50 and 3.00 meters. Additionally, it prescribes the double bay block width in the newly built cores to favour direct ventilation and controls the minimum dimension of the courtyards based on the height of the building. It also regulates the block height depending on the width of the roadway.

This is the first regulation that presents a climatic distribution but considering three zones: extreme climate zones (temperatures above 30 ºC and below −5 ºC) (group I), benign climate zones (possibility of working more than 300 days outdoors and where there is no thermal difference between sun exposure and shade greater than 8 ºC. This group included the Balearic Islands, the Canary Islands, the literal area of Huelva and Cádiz and the Mediterranean to Castellón) and the rest of Spain (group II).

The aforementioned regulation establishes maximum numerical values of transmittances for the three sections, which must be met without any restrictions on a constructive section, insulating materials, or external carpentry in the case of enclosures, which must be restricted to the thickness of the walls. As with enclosures, the choice of finishing material and the usage of insulating materials are all that is required for roofs, while no specific materiality or constructive section is specified.

The following regulation is the Order of May 20, 1969 that, with respect to energy efficiency continues in the line with the previous standard: maintains open floor plan heights, dimension of the interior patios in relation to the block height, establishes a minimum of 3 m in one side of the patio, for patios that have are no main rooms to ventilate, admits general collector ventilation chimneys, prescribes the south orientation of buildings as far as possible or, failing that, the most favourable and maintains the minimum ventilation dimension of each room at one-tenth of its surface.

Regarding constructive aspects, it prescribes that the walls and enclosures comply with the conditions of insulation and waterproofing although without specifying either values of conductibility of materials or constructive sections that guarantee compliance with the maximum values of transmittance established in this standard and slightly more restrictive than in the previous regulations. The only detailed technical requirement is the obligation to provide a sanitary slab for dwellings that are on the ground level. There are currently no prescribed solutions for glazing and carpentry.

In terms of climatic zoning, the benign climate zone disappears, leaving the country divided into a zone I, coinciding with the previous "group I" and zone II which includes the previous "group II" and the benign climate zone.

With the approval of the Basic Building Standard. Thermal conditions in buildings, NBE-CT-79 (RD 2429, of July 8, 1979, three substantial changes occur. In the first place, it is the first Spanish standard dedicated specifically to the conditioning and thermal insulation in residential buildings, applicable to all types of housing, whether free rent or protected housing. Note that, until now, for free rental housing there had been no other regulation than the ambiguous Order of 1944 [11]. Secondly, it is an eminently practical regulation providing values and tables of conductivities of the different materials, as well as, for the first time, classifying the carpentry according to its permeability and air tightness (A-1, A-2, A-3) along with forcing the use of one or another type depending on the climatic zone and, finally, it devotes an annexe to the definition of key concepts, as well as units of measurement. It is also relevant the inclusion of basic prescriptions to be met by insulating materials and that the manufacturer must reflect as well as recommendations for the control of reception and testing of insulating materials, an aspect with very little development in Spain until the near future [37]. It is worth highlighting that approximately 67% of the housing built in Spain was built under this regulation [38].

In general, the primary objective of the standard is the adoption of practical solutions that reduce energy use in the face of growing energy prices, which coincides with target 11.1 of SDG 11 described above. Additionally recommended are concrete construction methods and calculating techniques to enhance the hygrothermal behaviour of buildings. As a result, it became necessary to determine a global thermal transmission coefficient, or "K_G," for the whole building enclosure, which includes all vertical and horizontal elements in contact with the outside, other structures, or the ground.

Regarding the climatic zones, it introduces greater detail of zoning expanding the casuistry and divides the country into 6 zones: from A (more benign climates) to E (more severe climates) leaving the Canary Islands apart. In turn, it establishes another zoning map for the calculation of condensations, where it divides the country into 5 other zones depending on the minimum average temperatures of January and, also based on the areas delimited in this second map, the temperature of the land is established for calculation of walls in contact. According to the type of energy used for heating or in buildings without heating, two cases are also distinguished. This aspect was not taken into account by any previous regulations and, according to the analysis, is consistent with the fact that homes despite being situated in regions with extreme climates rarely have any heating. Finally, a form factor of the building is established that is obtained from the quotient between the total surface of all the walls that make up the thermal envelope and the volume of the building. The maximum allowable transmittance values continue with the downward trend observed in the previous standards.

As thermal insulating materials, it gathers expanded clay, cork chipboard, elastomeric foam, fiberglass, mineral wool, expanded perlite, expanded polystyrene, extruded polystyrene, cross-linked polyethylene, polyisocyanurate foam, formed polyurethane foam, polyurethane foam applied "in situ" and urea formalin foam. Except for cork, all materials are of organic or inorganic synthetic origin. The first of them involves a complex production system in addition to having high entropy values [39].

Of the most widely used inorganics: rock wool, glass wool, expanded clay, perlite, or aerated concrete, in addition to non-combustible, are also recyclable [40].

Finally, more than 25 years later, in 2006 the Technical Building Code was approved (RD 314/2006 of March 17) which describes the housing stock built in Spain during the second half of the twentieth century as "reasonable satisfaction to the basic needs of the majority of the Spanish population". However, what motivates the Royal Decree is a greater demand for quality by citizens. Regarding the two previously examined rules, it is necessary to adopt a different approach: although they prescribed certain technical solutions, which severely restricted both the designer and the technical evolution, the Technical Code recommends the achievement of objectives while leaving open the means to do so, giving the designer flexibility and allowing for the incorporation of a diversity of solutions. It does not apply to the homes under study, but it establishes the reference that has allowed us to conclude the degree of adaptability of the homes analysed, in use in a percentage of 89% [9], to the current requirements determined by the Sustainable Development Goals (SDGs) of the 2030 Agenda.

In essence, the basic requirements regarding energy saving are practically specified in the basic document DB HE, on energy saving. What is intended is a rational use by reducing consumption and achieving the partial contribution of renewable energy sources, objectives in line with the aforementioned SDGs.

Regarding the transmittance of the different constructive elements, there is generally a significant reduction in addition to contemplating more constructive elements. The following table (Table 2) shows the evolution of this throughout the study period, through the four analysed norms of those constructive elements comparable between the different norms analysed. The Technical Code introduces, apart from greater differentiation of climatic zones, other constructive elements such as carpentry, glass or party walls not contemplated in the previous regulations, of a more generic nature. It is worth mentioning the tendency towards increasingly restrictive values (shaded in yellow) which complicates the rehabilitation of this type of housing.

Table 2. Comparative limit values transmittance (U) (W/m^2K).

Value limit transmittance/Constructive element	Mild climates (α, A, B)	Extreme climates (C, D, E)
Walls	2,5–1,8/1,6/0,8–0,56	1,4/1,2/0,49–0,37
Covered living space	3,0–2,5/1,8/0,90–0,75	1,4-/1,2/0,70–0,59
Non-living space covers	3,0–2,5/1,8/0,55–0,44	1,8/1,6/0,40–0,33

Source: Own elaboration from Order 1955, Order 1969 and CTE.

The Technical Code also addresses the issue of thermal bridges, which are areas of an enclosure that have lower thermal resistance than the rest and are therefore susceptible to producing condensation in that area during cold weather. This issue has not yet been addressed, and it affects the houses that were under study. The Figure 5 shows the analysis of thermal bridges carried out in the analysed homes. In both cases, RENFE homes and cooperative homes, despite the time elapsed between the construction of one and the other, no constructive solutions are detected that minimize or avoid the existence of thermal bridges.

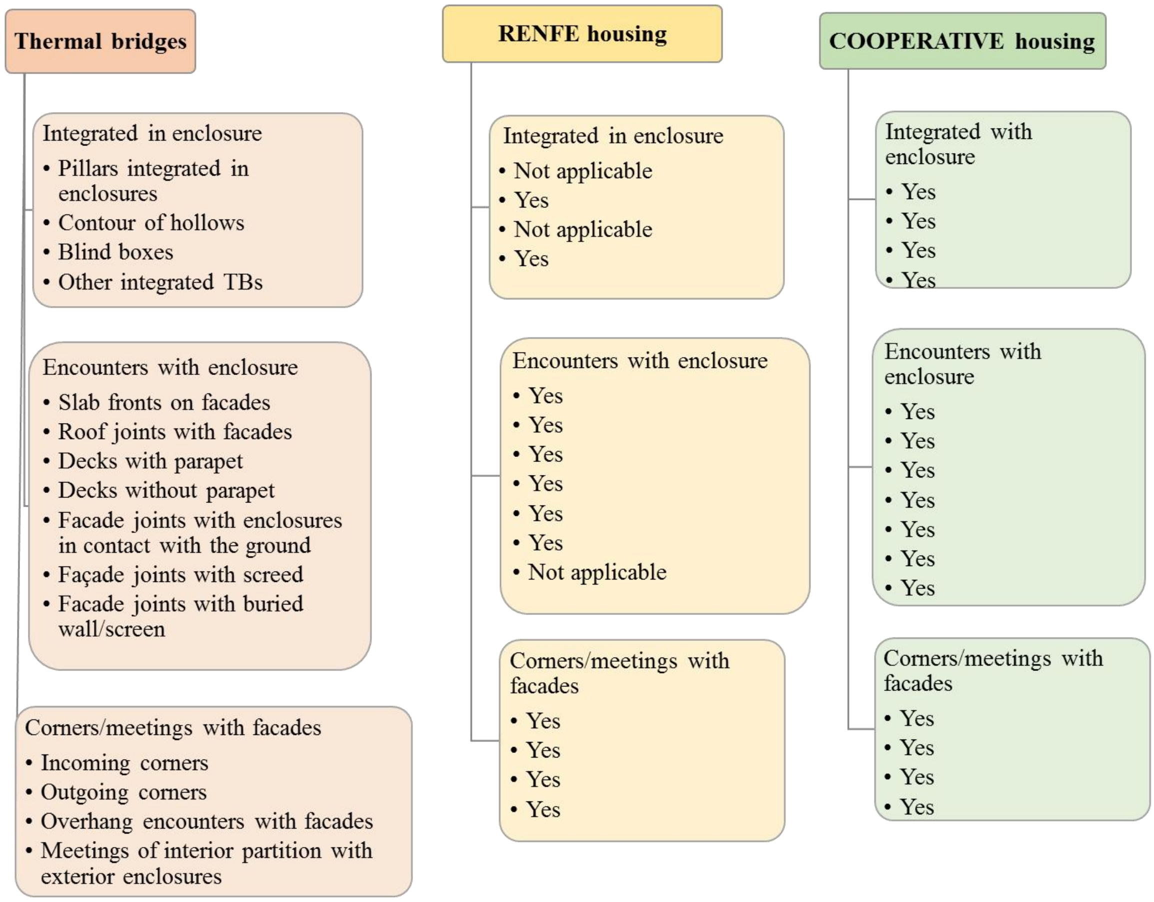


Figure 5. Analysis of the presence of thermal bridges in railway housing in Spain. Own elaboration.

Although a specific analysis in this regard has not been found, it has been discovered from the studies and research that have been examined on a global scale and detailed in the introduction, that the construction characteristics themselves are prone to the existence of thermal bridges, as is the case in Spain. This is one of the key areas on which to act in order to improve energy efficiency, though it is also more difficult technically and more expensive economically.

Finally, as a summary, the following table (Table 3) shows the main features of the different regulations applicable to the study period:

Table 3. Technical regulatory framework insulation and energy efficiency in protected housing in Spain.

Technical regulatory framework on energy efficiency in protected housing		
Period	Regulations	Prescriptions
1944–1955	Order 1944	• Generic: ventilation • Climate zone: no • Transmittance limit values: no • Calculation method: no • Constructive prescriptions: no
1955–1969	Order 1955 viv. RL	• Generic: ventilation/dimensions/orientation • Climate zone: yes (groups I, II, benign zone) • Transmittance limit values: yes • Calculation method: no • Constructive prescriptions: no
1969–1979	Order 1969 VPO	• Generic: ventilation/dimensions/orientation • Climate zone: yes (groups I, II) • Transmittance limit values: yes • Calculation method: no • Constructive prescriptions: sanitary slab
1962–1977	MV rules	• Nothing about thermal isolation or energy efficiency
1977	Approval of Basic Building Standards (NBE) General Directorate of Architecture (DGA): approval of construction solutions that meet the minimum standards	
1979–2006	NBE-CT-79	• Specific determinations • Climate zone: yes (maps 1 and 2) • Transmittance limit values: yes • Calculation method: yes • Constructive prescriptions: yes
2006-	CTE (Technical Building Code)	• Specific determinations • Climate zone: yes (maps 1 and 2) • Transmittance limit values: yes • Calculation method: yes • Constructive prescriptions: yes

Source: own elaboration.

3. Results

Regarding the homes analysed, the following table (Table 4), presents the percentage of homes in relation to the applicable regulations, being able to conclude that more than half of the homes analysed were made under the rule of law of 1969, specific regulations for protected housing and still with a marked ambiguous character as shown above.

Table 4. Percentage of dwellings in relation to the applicable regulations regarding thermal insulation.

Period	Length (year)	Regulatory framework	% Housing over total
1942–1955	13	Order 1944	11%
1955–1969	14	Order 1955	24%
1969–1979	10	Order 1969	56%
1979–2006	27	NBE-CT-79	9%

Source: own elaboration.

Regarding the calculation of the envelope, it is required to identify a number of factors that change the envelope during the course of the research, including the presence of basements, homes with first floors, and "cambra" or roof attics. The following graphs (Figure 6) show the changes observed in these aspects, noting the almost disappearance of ground floor housing by commercial premises from the 60s, matching with the self-promotion of housing by railway workers and, therefore, with the need to obtain resources through the rental of premises. Although there are only a few developments among those examined with the presence of basements, these also appear from the time when the houses are constructed by cooperatives. Regarding the attics or chambers, where the generalization of the flat crossable roof also dates from the 1960s and was typically the *Catalan Roof*, which was not ventilated and without insulation between partitions.

Additionally, during the studied time, modifications were made to the indirect problems associated with the structural typology and with the design of the building and its degree of compactness, which in turn affected how many and what kind of open spaces were present. These modifications affected how the structure responded to heat. Specifically, more than 80% of the houses are designed with structures based on a load-bearing wall, double-bay by regulatory requirement in a good number of cases, which guaranteed the direct ventilation of the houses (Figure 7). The block type shown in Figure 4 shows the double-framed block described, whose structural composition (load-bearing walls on the façade and central pillar line) and distribution of parts, favours the existence of cross ventilation, improving the energy efficiency of the dwelling in a natural way.

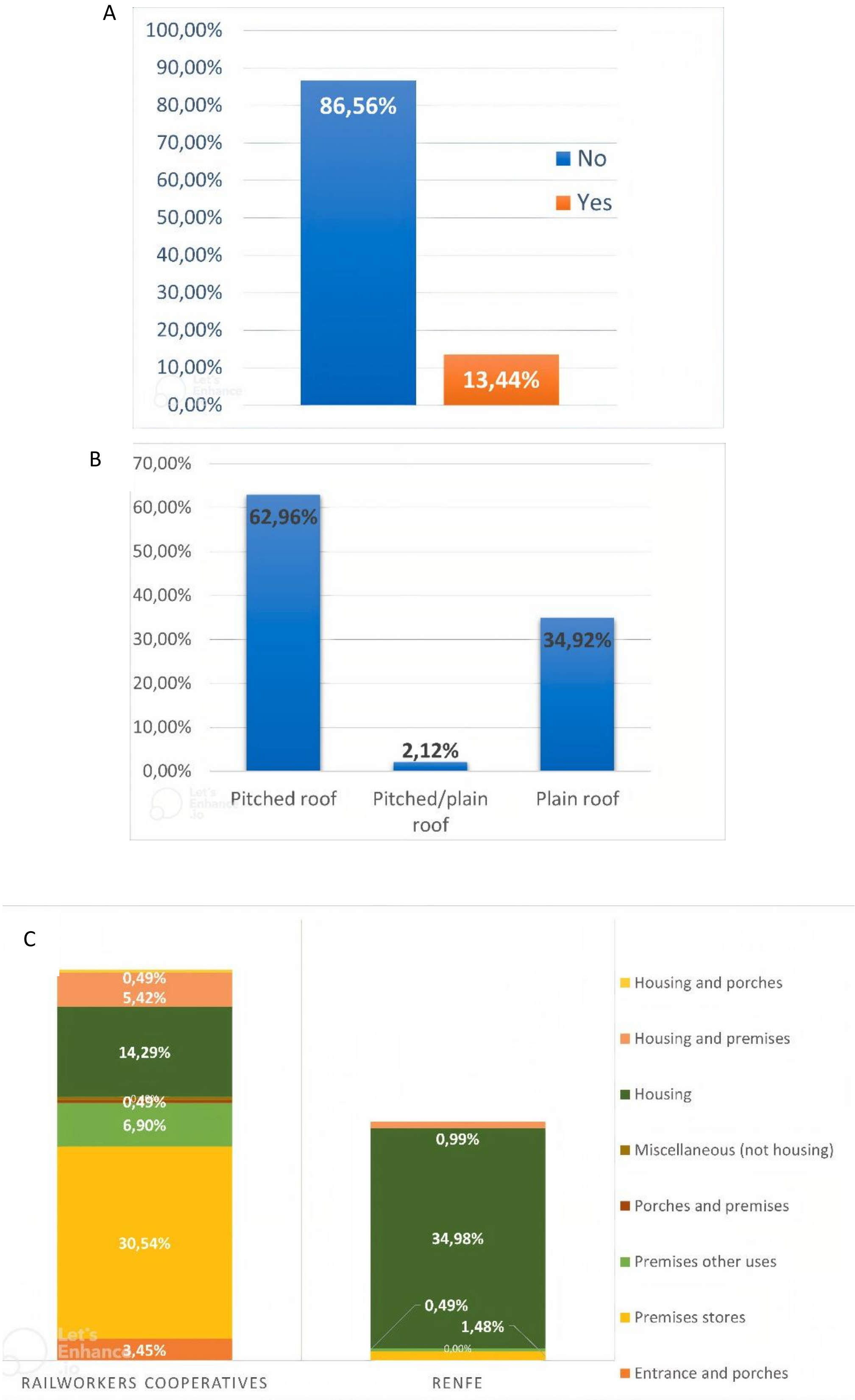


Figure 6. A) Existence of basements. B) Existence of "cambra" on deck. C) Use of ground floor. Own elaboration from analysed projects (primary sources).

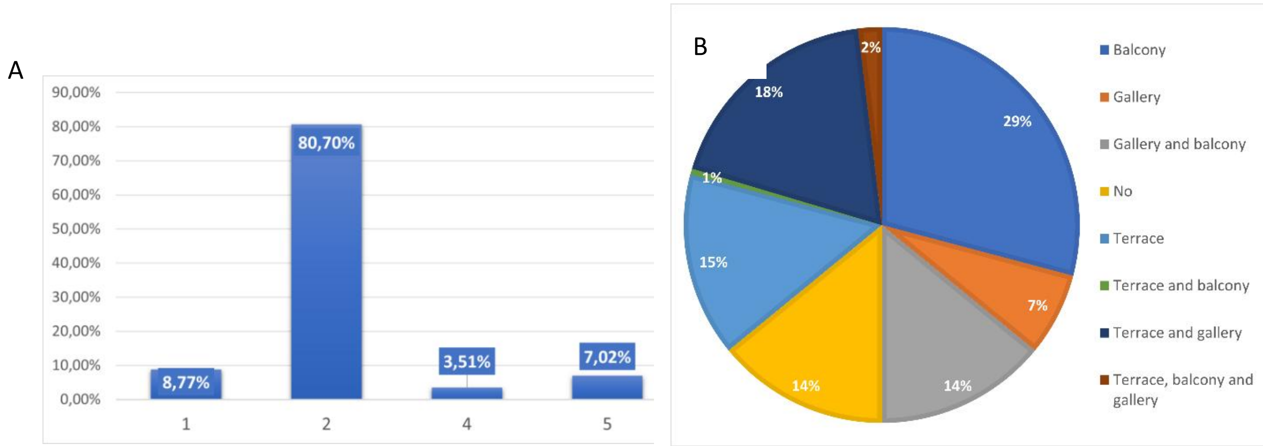


Figure 7. A) Structural bays blocks analysed. B) Free spaces in housing. Own elaboration from analysed projects.

According to the analysis of the CTE-DB-HE, the global coefficient of heat transmission through the thermal envelope of the building (K) [W/m²K] calculable in a simplified way from the transmittances (U), the length of the thermal bridges and the area of the enclosure, which links us with the K_G of the previous regulation (NBE-CT-79) establishes a limit value K_{lim} for reforms of more than 25% of the thermal envelope of the building, in private residential use, for V/A compactness ≥ 4 and more favourable climatic zone in winter, of 1.07. From the 18 developments currently analysed where the basic standard is applicable, the K_G value ranges from 1.087 (CA01CO) to 1.03 (MF02C0) (ZA08CO) with similar compactness. That is, substantial interventions are required to enforce the homes under study with current requirements.

About the type of hollow, carpentry and glazing (Figure 8), in almost half of the houses analysed, solid wood folding carpentry is observed. Later from the 60s and in the period of cooperatives, the first use of folding carpentry based on iron profiles and then sliding aluminium carpentry is generalized. In practically all the cases analysed, the glazing is simple.

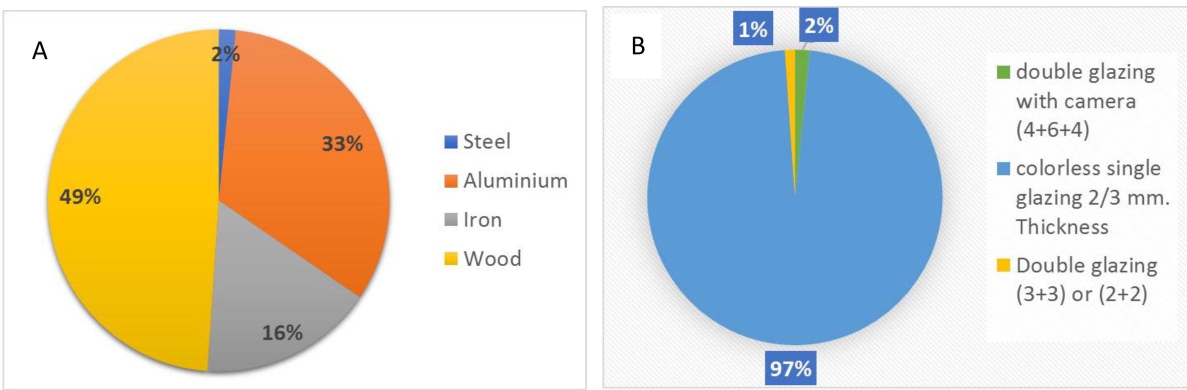
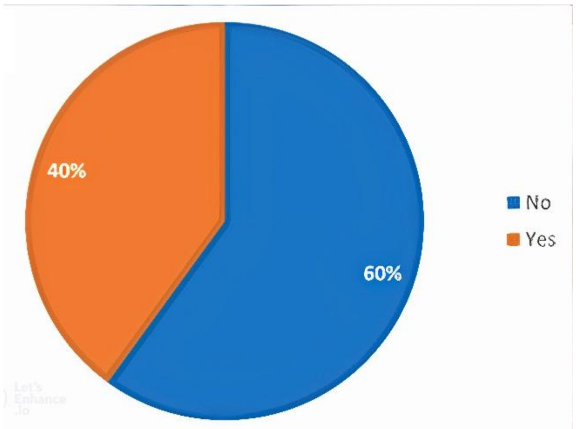


Figure 8. A) Types of carpentry used. B) Type of glazing used. Own elaboration from the analysed projects (primary sources).

Other structural and material characteristics include the replacement of load-bearing walls coinciding with enclosure by reticular structures from the mid-sixties, as well as progressive abandonment of the double bay block and direct ventilation by the progressive incorporation of the patios of lights. Thus, the load-bearing walls of one layer usually become composite enclosures with or without an intermediate air chamber. According to the analysis of the construction details and memories of the projects analysed, they were generally, unventilated air chambers. Regarding the insulating materials used, the most used according to the analysis carried out, are the projected polyurethane and the fiberglass or rock wool sheets in thicknesses between 2.5–3 cm.

Although the examination of thermal facilities has not been taken into account, questions about the availability of heating and the kind of system to produce it are directly related to how dwellings conduct themselves thermally. The following graphs show a preliminary analysis of this (Figure 9).

A



B

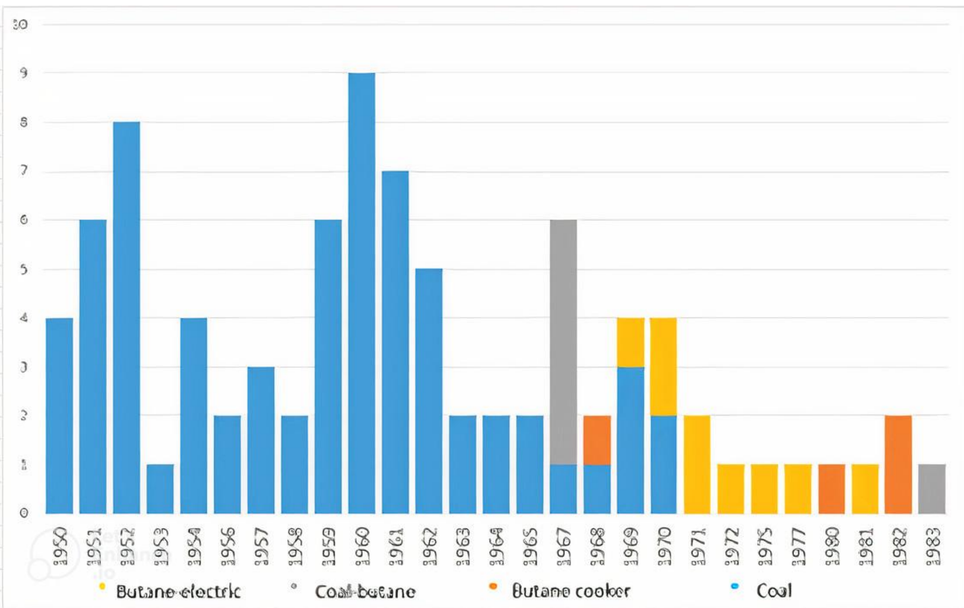


Figure 9. A) Existence of heating in housing. B) Heating energy system used throughout the study period. Own elaboration from the analysed projects consulted.

This is related to energy consumption where the homes analysed are far from the limit values established in the current regulations. In this sense, with respect to the consumption of non-renewable primary energy established in the modification of the CTE of 2022, none of the four model projects complies, being very far from the current limitations for the climatic zone under study (Table 5). Regarding energy efficiency, the four model projects have a value of E, which requires global interventions.

Table 5. Results of non-renewable energy consumption (Reform of buildings. Zone B). Comparison with CTE limit values.

Project type	EPNR maximum limit consumption (kwh/m^2 year) (CTE 2022)	Actual consumption EPNR (Kwh/m^2 year)
PT I	55	121,73
PT II	55	121,19
PT III	55	93,41
PT IV	55	64,78

Own elaboration with CERMA V.5.11 (May 2022).

With the casuistry described regarding the envelope, the results applying the CERMA V.5.11 program (May 2022) and contrasting the results of energy efficiency with the unified Lider/Calener (HULC. Version Jun 2022) tool yield the following global thermal transmittance values for the four model projects (Table 6). Values far removed from the limit values set out in Table 2.

Table 6. Transmittance (U) (W/m^{2}K) envelope elements in project types (climatic zone B). Energy Efficiency (E).

Project type	Façades	Openings	Sloped roofs	Flat roofs	Ground contact/others	Energy Efficiency (E)
PT I	2,77	5,14 (*)	2,10	-	3,46	E
PT II	2,77	5,14 (*)	1,47	-	3,46	E
PT III	1,34	5,70	1,80	1,58	2,39	E
PT IV	0,79	5,70	-	0,73	1,95	E

Own elaboration using CERMA V.5.11, May 2022- HULC, Jun 2022.

Finally, concerning the rehabilitation or improvement actions with respect to energy efficiency, the following figure (Figure 10) shows the actions carried out on the thermal envelope for the adaptation of the houses to the new regulatory requirements. It is observed that the most complete actions include the closure of terraces, actions on the roof (insulation arrangement to a lesser extent than waterproofing), and, above all, changes in the exterior carpentry. Comprehensive actions that affect the entire thermal envelope have only been carried out in 3% of cases. Another characteristic observed, although not quantified, is the arrangement of independent air conditioning/heat pump devices with an outdoor unit on the façade as there is no specific place for it.

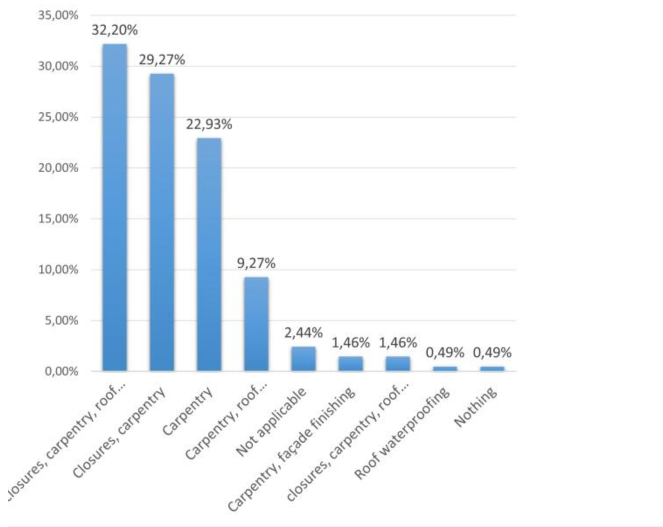


Figure 10. Improvements carried out in the thermal envelope of the houses. Own elaboration from the analysed projects [11].

4. Discussion and conclusions

The uniformity seen in type I and type II projects, where many project and technical characteristics were repeated regardless of location, orientation, and climate zone, cannot be assumed to presuppose extrapolated "type" improvement actions since, in addition to the three factors mentioned above that must be taken into account, it is also necessary to analyse the socio-economic evolution and the profile of the occupant in order to be able to propose solutions. It is therefore essential to carry out detailed and individualized audits and case studies that contemplate not only the technical-constructive factors [41] but also the economic and social ones [42,43].

Solutions that were somewhat ambiguously required by the rules in existence up to that point, are gradually being included until the fundamental standard NBE-CT-79 is approved are the result of a greater variety of promoters (RENFE projects are rigid, repetitive, and do not propose any type of improvement in the constructive solution for adaptation of the houses to the climate of the area) and of the overcoming of the critical period of autarky which favoured greater material diversity. More pronounced is this design and technical variety in the period of cooperatives where autarky has already been overcome and each cooperative independently hires its own architect.

From 1965 another change of trend was observed, which, without modifying the constructive characteristics, introduced changes to the efficiency and thermal comfort. On the one hand, the gradual increase in the construction of semi-basements and basements for garage and in the disappearance of the houses on the ground floor replacing them with premises. It is worth noting that an effective solution for enhancing the envelope resulting from the lack of free height of the same that avoids acting on the wall in contact with the ground is practically impossible in developments where there is housing on the ground level. A major issue to be resolved in the adaptation of these dwellings to the new regulatory standards and sustainable development is the change in structural system, which results in new forms of thermal bridges not anticipated in any of the applicable rules. The significant number of thermal bridges detected makes it necessary to apply methodologies and analyse them in detail [44–46].

The increase in the average height of the buildings is substantial. Taking into account that the minimum side of the patio is maintained at 3 m., as well as the width of streets, this increase in height influences the conditions of sunlight and ventilation. One of the indirect advantages that the imposition of the double bay block introduced is the direct ventilation capacity of the houses, which improves their energy efficiency as a passive cooling technique strategy [47].

Regarding the climate zone, climate change makes it necessary to contemplate prospective climate scenarios [48]. The Intergovernmental Panel on Climate Change (IPCC) (UN body for the study of climate change science created in 1988) has developed different situations to predict future climate based on current data [49]. Similar to this, the National Plan for Adaptation to Climate Change (2021–2030) sets as objectives the development of specific climate tools or applications that are useful for the various areas of action as well as the ability of citizens to plan their actions using climate scenarios and projections. In this sense, in case of planning any action to improve energy efficiency in any of the homes analysed, it is essential to update the climate data as a starting point. Regarding possible financing lines, at least 10% of ERDF resources at the national level will have to be dedicated to sustainable urban development. Thus, within the specific objective 2 of these Funds, ('OP 2'), its paragraph (iv) is intended to promote adaptation to climate change, risk prevention, and resilience to disasters. For its part, the PREE 5000 program, approved by RD 691/2021, regulates the subsidies to be given to energy rehabilitation actions in existing buildings, in the execution of the Energy Rehabilitation Program for existing buildings in municipalities of demographic challenge included in the Regeneration and Demographic Challenge Program of the Urban Rehabilitation and Regeneration Plan of the Recovery Plan, Transformation and Resilience, as well as its direct concession [10]. This work is essential as a starting point since the improvement of the thermal envelope is one of the three types of subsidized actions, together with the improvement of energy efficiency [50,51] of thermal facilities and the improvement of lighting facilities, which the PREE 5000 program contemplates. In this sense, the rehabilitation of the buildings is an option since they represent a 60% saving with respect to the construction of a new equivalent building [48]. Two comprehensive actions of reference to the case study are found in the neighbourhood of San Martín de Porres in Córdoba [52] or in the post-war homes of vulnerable areas in Zaragoza [53,54].

Although focused on the analysis of construction characteristics, this study reflects the complexity that the adaptation of these homes has to meet current requirements [55]. Apart from the need for subsidies in a good number of cases because they are low-income occupants in a good number of cases [56] and in situations of energy poverty, we should also contemplate the changes in habits that are occurring (teleworking, reduction of occupants, etc.), the incorporation of technology (home automation) as well as the aging of occupants and buildings, so both the maintenance of the buildings and the improvement operations must be co-substantial to it. Shortly put, it is necessary to make a significant shift in routines and tactics for building and using energy [57], in addition to taking into account that it is a daily heritage with characteristics of study and consideration that are similar to those of other more recognized and valued heritages [58].

As future lines of research, we have detected the need to analyse thermal bridges in detail, as both the analysis of the construction characteristics of the dwellings analysed and the studies and research carried out at a global level show that this is one of the key points on which to act in order to improve the energy efficiency of dwellings. Given that these are low-income dwellings, analysing specific improvement solutions, such as those aimed at solving thermal bridges, could help to improve the energy efficiency of the dwellings.

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Conflict of interest

The authors declare no conflict of interest.

Author contributions

In this investigation, A.M-C and J.C-C. visited archives for primary sources. A.M.-C, F.C-F and J.K. reviewed and visited the sites; A.M.-C. and J.C-C conceived and designed the methodology; J.C.-C., and A.M-C. analysed the data and contributed materials/analysis tools; A.M.-C., J.C.-C., and J.K. wrote the paper. All authors have read and agreed to the published version of the manuscript.

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