Energy & Buildings 352 (2026) 116858

Contents lists available at ScienceDirect

Energy & Buildings

journal homepage: www.elsevier.com/locate/enb

Evaluating the effectiveness of public subsidies for energy-efficient retrofit: a comparative study of two next-generation programs with standard market interventions in Catalonia

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A R T I C L E I N F O

Keywords:
Energy Retrofit
Residential Building Renovation
Energy Efficiency
Retrofitting Strategies
Spain Residential Retrofitting
Next-Generation Subsidies

A B S T R A C T

Assessing the impact of past and current renovation efforts is essential for refining decarbonisation mechanisms and ensuring the effective use of public resources. In this context, this paper examines the effectiveness of two Next Generation subsidy schemes implemented in Catalonia between 2021 and 2024. It evaluates their impact on energy demand, non-renewable energy use, and CO_2 emissions, while also assessing the associated investment costs. In addition, the analysis compares subsidised interventions with a reference sample of standard market interventions carried out without financial support. The analysis revealed that the subsidies reached 35% of the region and 15% of low-income municipalities, with a scope comparable to that of standard interventions. The study also emphasises that the impact of the samples remained broadly similar, noting only a few minor differences when more restrictive conditions were introduced. Furthermore, the study shows that although in some cases there is a clear improvement in the Energy Performance Certificates, in many others the impact is significantly lower, with some even remaining in conditions clearly below the decarbonisation objectives. The assessment also identifies a lower effect on energy demand compared to overall energy consumption and emissions, as well as a correlation between energy savings and climate, with colder climates yielding greater results. Finally, territorial urban–rural disparities in terms of investment costs are revealed. These findings underscore the need to redesign the instruments to consider geographic and social aspects, effectively engage more of the population, particularly the vulnerable groups, and facilitate integral interventions that surpass conventional market practices.

1. Introduction

The path towards climate neutrality requires not only the improvement of energy efficiency standards in new constructions, but also the acceleration of the large-scale renovation of the existing building stock, as 85 % of EU buildings were built before 2000 and will still be in use in 2050, and 75 % have poor energy performance [1,2]. Buildings are responsible for approximately 40 % of final energy consumption and 36 % of greenhouse gas emissions in the EU [3]. In Spain, in 2022, buildings were responsible for 30.6 % of energy consumption and 11 % of emissions.

Nevertheless, despite its recognised importance, the current renovation rate remains insufficient to meet the ambitious targets set by the European Green Deal and the Renovation Wave Strategy. According to a study conducted in the same year as the launch of the initiative, the annual rate of energy renovations for residential buildings is 1.0 %, while the rate for deep renovations is considerably lower at approximately 0.2 % [8]. In Spain in particular, the renovation rate for residential buildings is 0.82 %, with deep renovations at 0.3 % [9], far from the 3 % renovation rate needed to achieve decarbonisation.

To enhance energy efficiency within the existing building stock and to improve living conditions while alleviating energy poverty, the European Union responded with an increasingly ambitious regulatory and financial framework. This included the Clean Energy for All Europeans package adopted in 2019 [10–12], the Green Deal and the Renovation Wave launched in 2020 [13,14] and the Fit for 55 package in 2021 [15], all of which have progressively outlined the pathway to decarbonise Europe. Furthermore, the approval of the EPBD recast in 2024 [16] set

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https://doi.org/10.1016/j.enbuild.2025.116858
Received 3 September 2025; Received in revised form 19 November 2025; Accepted 8 December 2025

another cornerstone in this path. The regulations establish a mandatory reduction of 16 % in emissions from residential buildings by 2030 and 20–22 % by 2035 compared to 2020, emphasising also the need to target the lowest-performing buildings. In addition, the new EPBD also highlighted the importance of accurately assessing local conditions, including climatic factors during both winter and summer periods.

Furthermore, to expedite the transition, the European Union has mobilised an unprecedented volume of financial resources. Among these is the Recovery and Resilience Facility (RRF) [17], the central mechanism of the Next Generation EU funds and other various EU funding sources, such as the Cohesion Policy Funds [18], the Just Transition Funds [19] and InvestEU [20], which have also played a vital role in supporting building renovation initiatives.

Given the plethora of financial instruments in place, understanding the concrete impact of past and ongoing initiatives is essential for effectively adapting decarbonisation pathways over the next few years. This involves collecting relevant data, which can be done through surveys, application forms, or other available resources such as Energy Performance Certificates (EPCs), or by systematically monitoring energy and emissions savings. As an example, the vast majority of funds in Spain have been linked to the use of energy performance certificates as a mechanism to ensure energy improvements and establish incentives.

In this evolving policy scenario, a growing amount of research has explored the effectiveness of subsidies in promoting retrofit measures and energy efficiency improvements employing a wide range of methodological approaches. Scientific papers can be found applying quantitative methods, such as ex-post metered data or theoretical estimations, to analyse the effects of financial incentives on energy savings or comfort conditions [21–25]. Other studies can be found analysing the number of users who would have conducted renovations even in the absence of subsidies, also called the free-ridership effect, the rebound or prebound effect or the effect of subsidies on improving the willingness to renovate [26–35]. Furthermore, some authors discuss the accuracy and efficacy of Energy Performance Certificates (EPCs) as primary instruments associated with retrofit programs and the discrepancies between theoretical estimations and real data and prebound effects [35–41].

The literature also reflects a tension between financial instruments and social equality; some authors emphasise the critical role of subsidies to address energy poverty, avoid disparities and counterproductive effects [24,29,42–46]. Additionally, several papers aim to consolidate the fragmented landscape, outlining barriers and key lessons for improving policy effectiveness and efficiently integrating diverse instruments, providing guidance for policy design [21,47–53].

Nevertheless, despite the increasing interest in the topic, it is worth mentioning that, up to the point of this publication, no specific paper has been found in the Web of Science database using the keyword Next-generation that quantitatively assesses the impact on building rehabilitation of the Next Generation EU funds, one of the most significant financial instruments introduced in recent years. This gap becomes particularly critical considering its relevance for reviewing and updating long-term decarbonisation strategies in the upcoming years.

In this scenario, this paper aims to provide some evidence on the impact of two subsidies implemented in Spain as a part of the next-generation funds mechanism. The study focuses on analysing the geographic and socioeconomic coverage of the funds, the costs associated with the rehabilitations, as well as the energy demand, consumption, and emissions savings associated with two specific funding programmes. The analysis relies on data derived from the official EPC required by the mechanism, as well as information registration information facilitated by the Catalan Institute for Energy (ICAEN). The geographic scope and socioeconomic impact have been assessed using data available from the Spanish National Statistics Institute (INE).

The paper is structured as follows. The Spanish policy context, the characteristics of the building stock, and Spanish funds and subsidies related to rehabilitation are presented in Section 2. Section 3 presents the methodological approach to the analysis, and Section 4 presents the analysis and results. The discussion and conclusions are presented in the final section.

2. Catalan context under the Spanish regulation

In Spain, buildings account for 30.6 % of final energy consumption and 11 % of emissions [54], slightly below the EU average of 40 % with households accounting for 66 % of the total building stock, with 25.92 million homes [55]. In 2022, buildings accounted for 41.9 % of the total emissions in the subcategory of commercial, institutional, residential, agricultural, forestry, and fishing, representing a 110 % increase compared to 1990 [56], highlighting the need to implement further actions. The high energy consumption of the sector is not only the result of economic dynamics, such as income growth [56], but also the reflection of the characteristics of the existing stock, much of which was constructed before the introduction of thermal regulations.

In this scenario, the clustering of residential building stock has gained significant attention in various projects at the national or local level [57–62] as a basis for properly designing decarbonisation pathways. Following Initiatives such as TABULA at the international level [59], at the Spanish level, the most commonly used clusterisation was developed by the Long-Term Strategy for Energy Renovation in the Building Sector in Spain (ERESEE) [55]. In addition, other regional and local entities, such as the clusterisation presented in the Barcelona Energy Improvement Plan presented in 2002 [63] or the one developed by the Catalonian Housing Agency (AHC) [64], have also made attempts to cluster the existing park.

According to the ERESEE, 68.9 % of Spanish homes are located in urban environments, with 67.9 % of these being multifamily buildings, and nearly 54 % of Spanish residential buildings were built before the enactment of the first energy performance regulation, NBE-CT, in 1979. Moreover, according to the Recovery, Transformation and Resilience Plan, 81.0 % of currently standing buildings are classified as E, F, or G regarding emissions, while this figure increases to 84.5 % for energy consumption [65]. This situation is even more pronounced in the Catalan region, with 62 % of residential buildings constructed before 1979 and more than 23 % before the enactment of the first Building Technical Code (CTE), 70 % of which are single-family houses [6,66]. Out of those, the most significant volume of houses was constructed between the period of 1961 and 1980, representing almost 40 % of the existing building stock, with approximately 3.863.381 houses in the region [67]. Concerning the emission, 81 % of the existing buildings in Catalonia have a classification of E, F or G [68].

In this context, several steps were taken to encourage the adoption of retrofit measures. First, with the transposition of the EPBD, which led to the development of the CTE, initially established in 2006 and subsequently revised in 2013, 2019 and 2022 [69–72] and the Regulation on Thermal Installations in Buildings (RITE) in 2007, revised in 2013 and 2021 [73–75]. The CTE provided a comprehensive framework that limited the energy performance of buildings and the renewable contribution to be integrated, including the requirements for interventions that retrofit more than 25 % of the envelope, while the RITE established the requirements of thermal systems and renewable sources. Moreover, in 2021, the Royal Decree (RD) 390/2021 [76] related to Energy Performance Certificates was amended to extend its focus beyond new constructions.

In addition to fostering the improvement of energy performance in integral renovations, several strategies, policy instruments, and financing mechanisms were established to guide and support the renovation efforts. Among them are the ERESSE [55,77,78], the National Energy Efficiency Action Plan (NEEAP) [79–81], the Climate Change and Energy Transition Law (CCETL) [82] and the National Integrated Energy and Climate Plan (NIECP, also known as PNIEC in Spanish) [54,83]. Being the ERESEE, the main relevant instruments in terms of rehabilitation policy.

The ERESSE, presented in 2014 and its subsequent versions in 2017 and 2020, established a roadmap with intervention scenarios, measures, and progress indicators for the energy rehabilitation of the building stock. The strategy evaluated the existing building stock and its potential for renovation, setting progressive targets aimed at achieving decarbonization, with a strong emphasis on renovating heating and domestic hot water systems.

The PNIEC, revised in 2023, established 110 measures aimed at reducing greenhouse gas emissions by 32 % compared to 1990 levels [54,83]. The 2023 revision underscored the necessity of retrofitting the existing building stock and increased the targets for rehabilitation efforts to 1,377,000 households, prioritising investments for improving thermal envelopes and establishing mechanisms to foster the renovation of 3 % of the air-conditioned floor area within public administration.

In addition to the cited laws, between 1981 and 2025, twelve National Housing Plans were implemented, with the first one spanning from 1981 to 1983 and the last one from 2022 to 2025 [84–96]. Although the main objective of the plans was the promotion of social housing, rehabilitation aspects were also included over the years, particularly after 2008, such as specific support lines for improving energy efficiency and addressing vulnerable areas and housing buildings.

The foundations established by all these policies were subsequently operationalised and scaled up through the 2022 Recovery, Transformation and Resilience Plan (PRTR) [97], the main instrument for deploying the EU Next Generation Funds. The instrument included one specific component that channelled significant investments into the renovation of the built environment. This included mobilising specific funding and the development of the Spanish Urban Agenda [63].

Derived from the various strategies and plans implemented, a range of financial mechanisms have been introduced over the years to support the renovation of its building stock, particularly in the residential sector. The instruments include public subsidies, tax incentives, soft loans, awareness campaigns, and improvements to the regulatory framework to address barriers, stimulate investments, and optimise energy efficiency while considering social and environmental factors.

Among these initiatives, it is possible to highlight the National Housing and Rehabilitation Plans, such as the 2008 plan [92] and several other instruments, such as the Energy Renovation of Existing Buildings in the Residential Sector (PAREER) [98], the PAREER-CRECE [64] and the PAREER II [99].

The PAREER, with an original budget of € 125 million, focused on improving the building's envelope and the upgrade of heating, cooling, and lighting systems. To obtain the aid, users were required to demonstrate at least one letter improvement in the EPC rating. Following this initial scheme, the PAREER-CRECE program, approved in 2015 with a budget of €75 million, and the PAREER II, approved in 2017 with a budget of €78 million, continued to provide funding for rehabilitation efforts.

More recently, seven additional mechanisms were established to promote the rehabilitation of both private and public households as a part of the Recovery, Transformation, and Resilience Plan [100,101]. With a budget of €9.520 million, the mechanisms promoted renovations of individual homes, entire buildings, and concrete neighbourhoods and also supported the development of building logs and rehabilitation programs. In addition to direct subsidies, the Spanish government introduced complementary financial and tax incentives to accelerate the renovations done under the Recovery Plan [102–105]. These include personal income tax deductions of up to 60 % for homeowners, depending on the level of interventions and savings achieved, as well as secured loans to cover upfront costs through the Official Credit Institution (ICO).

Furthermore, as a part of the Next-Generation funds, two additional funds were created to foster rehabilitation actions, the PREE [106] and PREE5000 [107]. The PREE, approved in 2020 and extended in 2021, with a total budget of €402.5 million, aimed to accelerate energy renovations in existing buildings across all sectors and regions. Similar to previous mechanisms, applicants were required to achieve at least one-letter improvement in emissions in the EPC rating and a 10 % reduction in final energy consumption. The PREE5000, on the other hand, with a total budget of €201.5 million, focused specifically on small municipalities (up to 5,000 inhabitants) facing demographic decline. The eligible actions were similar to the PREE, but with a more restrictive requirement in terms of energy savings. In order to qualify for funding, users needed to reduce at least 30 % the non-renewable primary energy consumption.

Regarding the evolution of rehabilitation efforts, the ERESEE reported that a total of 80,304 dwellings underwent refurbishment or restoration between 2017 and 2019, marking a 9.1 % increase during that period [55]. Furthermore, according to the Higher Council of Architects' Associations of Spain, this initial trend of increase has continued in recent years, with a reported 117 % rise between 2019 and 2024, representing a total of 55,473 houses intervened during that timeframe [108]. Nevertheless, even though the number of rehabilitations conducted during 2024 surpasses the objective of 45,000 interventions specified in the ERESEE 2020, a significant effort still needs to be made to achieve the goal of conducting 300,000 annual renovations by 2030, as the renovation rate is still far from the 3 % required [9]. Regarding the types of interventions supported to date, a notable inclination toward heating strategies has been observed among various funding programs, with most strategies focusing on improving envelope insulation and upgrading heating systems and installations [57].

3. Methodology approach

The study provides a detailed analysis of interventions conducted under the Next Generation PREE and the PREE5000 programs in Catalonia and a comparative evaluation with standard market interventions, hereafter SMI, implemented in the region during the same period and without public financial support. The period of analysis was marked by the validity period of the aid programs provided by the competent authority, during which 6,800 EPCs were issued.

Information on the subsidised sample was provided by the Catalan Institute for Energy (ICAEN), the authority responsible for managing the two funds at the Catalan level, which included a total of 674 applications received for both programs. In the case of SMI, the ICAEN EPC open database [7] was used to collect the interventions. To differentiate interventions that implemented measures without the use of public funds, two end-user mandatory declaration fields were used, firstly the field "reason for certifying" to eliminate those that indicated that they were applying for aids, sales or rents and secondly the "rehabilitation actions" field to retain only those that stated that they had undertaken energy retrofit measures. It is worth noting that no specific restrictions were implemented besides the period of implementation; therefore, all renovations were considered, regardless of the energy savings or the type of intervention undertaken. The assessment yielded a total of 327 SMI interventions, of which 305 were retained after verifying the availability of pre- and post-intervention energy and emissions savings.

From these 979 subsidised and SMI registers and interventions, a cross-reference analysis based on the cadastral data was conducted to eliminate duplicates. As a result, 23 references were discarded, leaving a final sample of 956 cases. This includes 432 PREE cases, 234 PREE5000 registers, and 290 SMI interventions.

Applicant's information, facilitated by the ICAEN, provided characterisation data for the building, including its typology, use, climatic zone and year of construction. The files also included details about the user and encompassed declared energy and emissions savings, as well as emissions ratings (EPC labelling), both before and after the interventions, along with information related to the measures taken and their associated costs. As for SMI, the EPCs' open database provided information on declared energy consumption and emissions, along with

EPC labelling. However, since this database is solely linked to EPC compliance, there was no data available regarding costs.

Complementary data, including Catalonia's building stock, postal codes, and municipal information, were collected from the Catalan Institute of Statistics' (Idescat) database [109] to assess the geographical impact on the territory and the existing building stock. Municipalities were then classified according to the degree of urbanisation [110] to differentiate large, medium and small populations. Six distinct clusters were identified based on population size: small towns with fewer than 5,000 inhabitants, populations ranging from 5,000 to 20,000 inhabitants, populations between 20,000 and 50,000 inhabitants, populations from 50,000 to 100,000 inhabitants, populations between 100,000 and 1,000,000 inhabitants, and populations exceeding 1,000,000 inhabitants.

As for the impact on the building stock, the analysis was conducted employing a set of clusters derived from the harmonisation of various national and local sources, conducted under the RETABIT project [111], which aimed to improve the characterisation of the Catalonian building stock. Two typologies were identified, single-family and multi-family houses and seven different archetypes: Archetype 1 (pre-1900), Archetype 2 (1901–1940), Archetype 3 (1941–1960), Archetype 4 (1961–1980), Archetype 5 (1981–2007), Archetype 6 (2008–2014) and Archetype 7 (post-2014) that represented the different constructions periods and the influence of the changes in the CTE. Additionally, the CTE climatic classification was used to evaluate the energy performance of various archetypes under diverse conditions. This classification system categorises climates based on the severity of winter and summer conditions. For winter, it employs letters ranging from A to E, with E denoting the coldest regions, and for summer, the classification employs numbers from 1 to 4, with 4 representing the hottest regions.

Furthermore, an analysis was also undertaken to evaluate the social impact of the subsidies, particularly to determine whether the mechanisms effectively target municipalities with lower economic capacity. To achieve this, data on gross household income by municipality were obtained from the INE to comprehend the socioeconomic characteristics of the region [112]. Gross household income data for 2022, published in 2024, was used. The median gross household income for the Catalan region was calculated, and the OECD methodology [113] was employed to establish the income categories of low, medium, and high earnings. Low-income households were defined as those earning below 75 % of the median regional income, while middle-income households as those with earnings ranging from 75 % to 200 % and high-income households as those with earnings exceeding 200 % of the median household income.

In addition to the geographical, social and architectural study, an environmental and economic analysis was conducted to assess the energy and emissions savings and the investments associated with the interventions. The analysis was limited to energy and emissions estimates derived from EPC information, as EPCs were the only instruments used for compliance and monitoring within the schemes and were therefore the only information listed in the application forms and the only information available for SMI as well. Nevertheless, since the objective of the study was to determine not only the overall emission reductions but also the effects on energy demand, historical data from pre-intervention EPCs were retrieved. As information on energy demand was not available in the application forms, information was retrieved from the EPC's open database or facilitated by ICAEN, as in some cases, pre-intervention EPCs were no longer available in the public database. To ensure data consistency and prevent erroneous conclusions that might arise from the manual entry of information by users in applications, EPC labels, along with emissions, consumption, and energy demand, were sourced from the EPC database.

To isolate the influence of subsidised mechanisms vs non-subsidised interventions from other relevant characteristics of the buildings, a statistical control through sample restriction was implemented. The environmental analysis was conducted using a single typology, single-family houses, from a single construction period, 1960 to 1980 (archetype 4), ensuring typological and temporal homogeneity across the analysed sample. Arquetype 4 was selected as it was the most representative archetype in the region, accounting for 41 % of the Catalan building stock [67] and having the most significant number of applications in the overall subsidy sample. Climatic variability, on the other hand, was explicitly considered in the analysis by disaggregating the variables according to the Spanish climatic zones. Only interventions that had all pre- and post-intervention values were considered, leaving a total sample of 114 cases. Cost details and specifications related to measures, on the other hand, were obtained from the summary of the PRE and PRE5000 application forms. In terms of cost, the application forms of the programs included the total costs associated with different intervention packages. Specifically, Type 1 interventions corresponded to passive measures, while Type 2 interventions referred to air conditioning (HVAC) and domestic hot water (DHW) systems. For Type 2, costs were further disaggregated by the type of HVAC and DHW system selected, including biomass, geothermal, solar thermal, or others such as heat pumps. Nevertheless, it should be noted that these figures represent only the total cost; no detailed information was available regarding the breakdown of materials, labour, or other associated expenses, such as permits or taxes. Furthermore, as mentioned, cost data were not available in the EPC database; thus, the comparisons on investment costs were made solely for the subsidised interventions.

Regarding the type of interventions conducted, in the case of PREE and PREE5000, the information while HVAC and DWH systems (Type 2) were distinguished in different fields of the application form, the passive interventions (Type 1) were not differentiated in sub-items; therefore, the details related to passive measures were recovered from the descriptive section included in the subsidy application form. As for the SMI, the information on both passive and active measures was obtained from the descriptive field in the energy performance certificates database. These provided insight into the type and scope of the interventions in most cases. However, the descriptive fields did not always offer detailed information, especially regarding envelope improvements. As a result, the analysis was constrained to the information available in those fields. Regarding the cost, the study was conducted solely for subsidised interventions based on the mandatory investments field of the application form. Absolute values were standardised using the declared square meters of the interventions to enable comparison of investment costs among the two samples.

It is worth noting that although the measures that the PREE and PREE5000 were similar, the scope and requirements of the two subsidies differ; while interventions under the PREE scheme needed to achieve a 10 % reduction in final energy consumption and a minimum one-letter improvement to qualify for funding, the requirements for PREE5000 stipulated a reduction of at least 30 % in primary energy consumption. In terms of actions supported, both programs focused on three main categories of interventions. The first was the improvement of the thermal envelope, including the insulation of the façade or the renovation of windows. The second involved upgrading the energy efficiency of thermal installations, which could include replacing conventional systems with solar thermal, geothermal, or biomass solutions, or improving generation systems with aerothermal or heat pump solutions. In addition, the PREE5000 subsidy also comprised the improvement of distribution, regulation and control of HVAC subsystems. On the other side, in the case of PREE, a third eligible category was included: the improvement of lighting installations. However, this aspect is not reflected in the EPC, as the EPC for residential buildings only accounts for heating and cooling, DWH, and ventilation consumption. Moreover, under the PREE specifically, one of the thermal or lighting interventions could alternatively be replaced by the installation of a solar photovoltaic system or another renewable energy generation technology, provided that the installed capacity was at least 10 % of the building's contracted electrical power.

Table 1 summarises the different indicators used and the sources of

Table 1
Indicators used in the analysis.

Aspect	Indicator	Description	Source
Geographical scope	Size and number of municipalities	Total number of municipalities disaggregated by county council and province, and according to five clusters based on their size.	Census (IDESCAT from INE census) [4]
Socioeconomic impact	Median gross household income (€/household)	Median gross household income of each municipality. The OECD methodology was employed to establish thresholds for low, medium, and high-income levels.	Census (INE) [5]
Impact on the building park	Archetype coverage (n° of buildings)	Number of buildings disaggregated by year of construction. The RETABIT archetype definition was followed to aggregate buildings and evaluate the impact over each period.	Census (IDESCAT based on INE) [6]
Environmental impact	EPC emissions label (letters G to A)	The emission label obtained in the EPC which is classified on a letter scale ranging from G, representing the worst energy performance, to A, indicating the best performance.	EPC database (ICAEN) [7]
	CO2 emissions (KgCO$_2$/ m^2 year)	Kg of CO$_2$ emissions normalised by the project area.	EPC database (ICAEN) [7]
Energy consumption	EPC emissions label (letters G to A)	The non-renewable primary energy consumption label obtained in the EPC, classified from G to A, before and after the intervention.	EPC database (ICAEN) [7]
	NRPE (kWh/ m^2/year)	Primary energy consumption coming from non-renewable sources normalised by the project area.	EPC database (ICAEN) [7]
Energy demand	EPC heating demand label (letters G to A)	The heating demand labels before and after the intervention classified from G to A, before and after the intervention.	EPC database (ICAEN) [7]
	EPC cooling demand label (letters G to A)	The cooling demand labels before and after the intervention classified from G to A, before and after the intervention.	EPC database (ICAEN) [7]
	Heating demand (kWh/m^2/year)	Heating demand normalised by the project area.	EPC database (ICAEN) [7]
	Cooling demand (kWh/m^2/year)	Cooling demand normalised by the project area.	EPC database (ICAEN) [7]
Cost	Investments cost (€/m^2)	Investment cost associated with the different interventions normalised by the project area.	Subsidy request form (ICAEN)
Measures	Measure type	Description of the actions undertaken: Type 1, envelope, Type 2 systems, Type 4 lighting and Type 4 renewable sources. Descriptive fields were used to further refine the type of interventions.	Subsidy request form (ICAEN) for subsidised interventions, EPC database (ICAEN) for SMI

information.

4. Analysis and results

4.1. Geographic coverage

A first analysis was conducted on all three samples to assess the scope of interventions within the territory, specifically focusing on the percentage of municipalities that adopted retrofitting measures across all four provinces of Catalonia: Barcelona, Girona, Lleida, and Tarragona. The province of Barcelona has the highest population, with an estimated 5,949,249 residents and 311 municipalities. In comparison, Girona and Tarragona have populations of approximately 830,994 and 874,682, respectively, with 221 and 231 towns each. Lleida, on the other hand, has a population of around 458,565 and comprises a total of 184 municipalities. Moreover, it is important to highlight that in the case of PREE5000, as previously mentioned, the call included only those municipalities with populations of up to 5.000 inhabitants, as well as non-urban municipalities with populations of up to 20.000 inhabitants, provided that all individual population entities within those municipalities have populations of 5.000 or fewer, therefore only 747 municipalities on the region were eligible.

Overall, between 23 % and 24 % of the total number of municipalities were covered with the funding schemes, while 17 % of the total territory was covered in the case of SMI. As shown in Fig. 1, in all three samples, most interventions were located in the province of Barcelona, followed by the provinces of Girona, Tarragona, and Lleida, the latter representing the province with the fewest interventions in all three samples. Furthermore, despite the incentive of partial investment coverage through subsidies, the distribution of interventions in the PREE, which shares the same territorial scope as SMI, remains quite similar; in both cases, over 60 % of the interventions originated from the province of Barcelona. The interventions under the umbrella of the PREE5000, on the other hand, are more evenly distributed, although Lleida significantly differs from the other provinces with a much lower coverage.

As for the number of municipalities covered in each province, as seen in Fig. 2 the province with the most territorial coverage is Barcelona in all three samples, although a difference can be perceived between the coverage of SMI and the territorial coverage of the funds; the scope of the interventions increased from 25 % to up to 40 % in the case of the

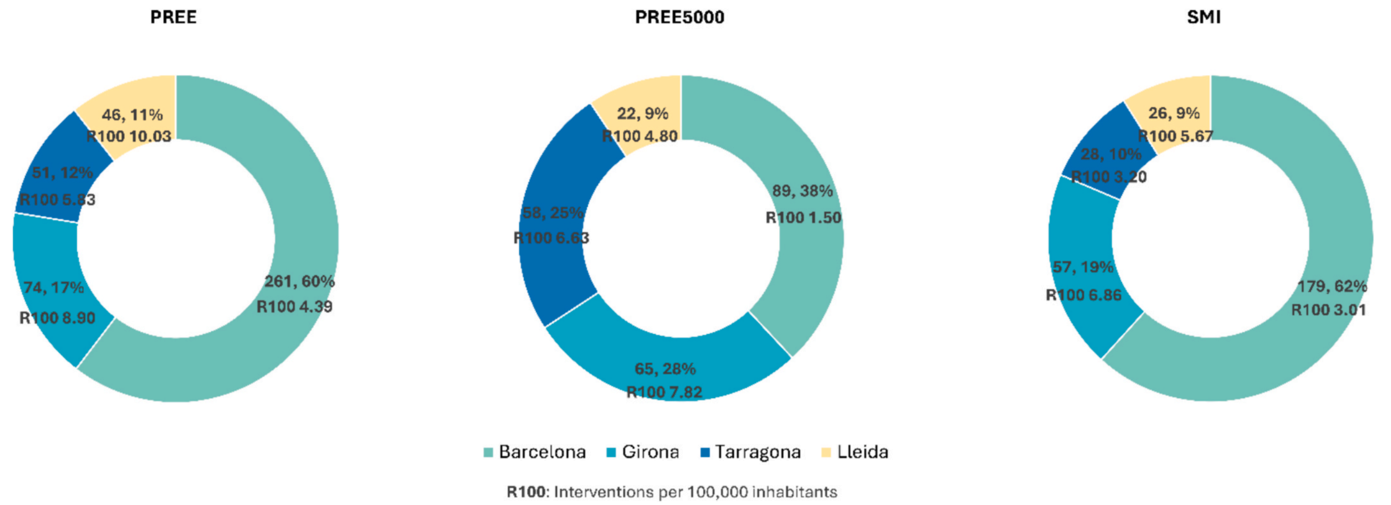


Fig. 1. Distribution of interventions by province. Source: own elaboration.

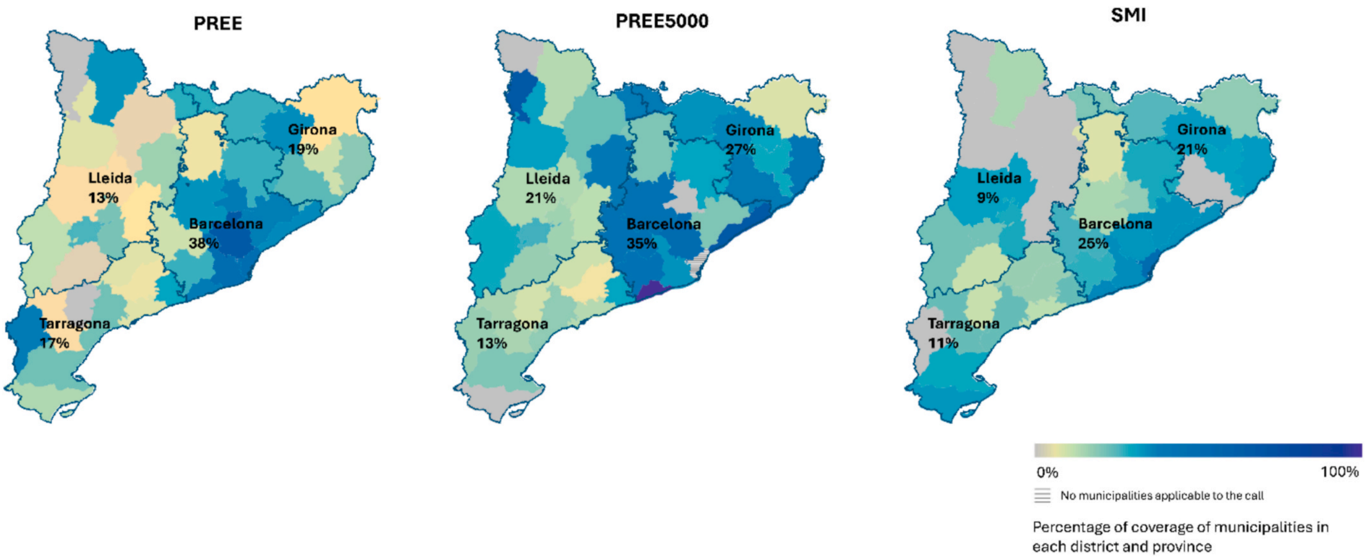


Fig. 2. Geographical coverage of interventions by county council and province. Source: own elaboration.

PREE, nevertheless an absence of applications from one of the county councils was identified in the case of PREE5000. Regarding Girona, the coverage appears quite similar across all three samples, although slightly more coverage is noted in the PREE5000 and PREE schemes. The first shows a higher overall percentage, and both schemes encompass all county councils in the province. Tarragona and Lleida have the least territorial coverage; however, a significant increase in coverage is observed in Lleida in both funding schemes. It is worth noting that while no SMI were identified in five county councils of Lleida, in the PREE and PREE5000, nearly all territories are covered, except for one county council in both schemes.

In terms of municipal size, and considering that the PREE

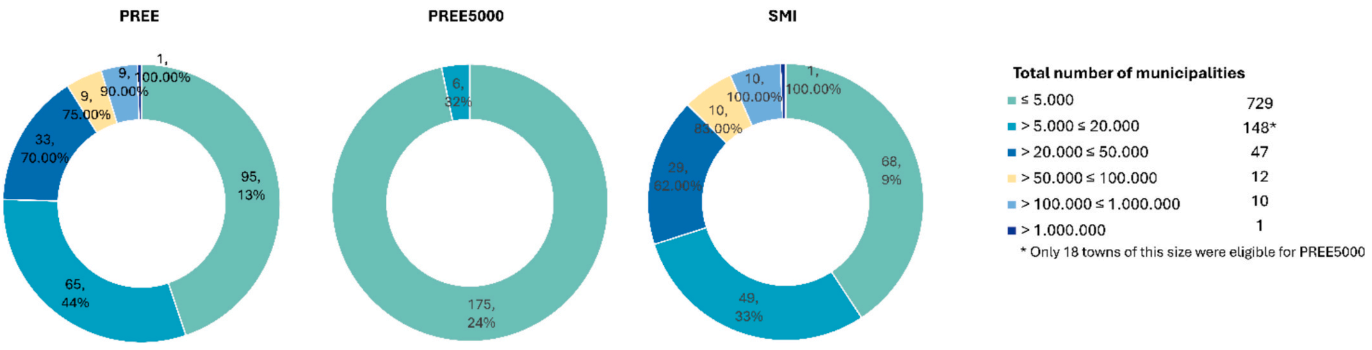


Fig. 3. Geographical coverage of interventions by the size of the municipality. Source: own elaboration.

interventions had no limitations on the magnitude of the municipality, a similar coverage to standard retrofit initiatives is evidenced, as seen in Fig. 3, with differences remaining below 10 %; therefore, no significant variance is identified due to the presence of the funds in terms of total scope.

Furthermore, the analysis of interventions linked to the PREE5000 scheme reveals an increase in coverage, particularly in smaller towns, where 24 % of the region's eligible municipalities have been identified, compared to 9 % and 13 % observed for the PRE and SMI samples. This suggests that the availability of funds has effectively stimulated intervention efforts across a wider geographical area. It's important to point out that, while small municipalities are relatively evenly distributed across the provinces—each province hosting between 151 and 215 towns with fewer than 5,000 inhabitants—the applications themselves are not evenly spread. Barcelona has the highest percentage of applications, accounting for 36 % of the total. This is followed by Girona and Lleida, which have 28 % and 24 % of the total applications, respectively. In contrast, Tarragona is the least impacted area, as it only accounts for 12 % of the total, despite having 151 municipalities, a number that is quite close to Barcelona's 178 municipalities.

Moreover, most of the interventions came from towns of 5.000 or fewer inhabitants, except for Barcelona's province in the PREE scheme and standard interventions, where the higher value corresponds to municipalities between 5.000 and 20.000 inhabitants. Moreover, the distribution of applications between the PREE and standard market intervention samples is quite comparable, with the exception of the province of Lleida, where a greater percentage of interventions is observed in the sample that undergoes rehabilitation without relying on public funds. In addition, it is worth noting that a higher percentage of interventions is observed in larger municipalities within the PREE funding scheme. For instance, Barcelona, the only municipality with a population exceeding 1.000.000, shows an increase in applications from 7 % in standard interventions to 23 % under the PREE framework. Similarly, two municipalities in Tarragona province, each with over 100,000 inhabitants, exhibit an application rate nearly double that of standard interventions. This underscores the significance of effective communication campaigns for such funding opportunities and highlights the need to identify suitable communication channels to better reach smaller county councils and a wider range of potential users.

4.2. Socioeconomic profile and beneficiaries

An additional territorial analysis was conducted to examine the socioeconomic characteristics of the beneficiaries. Given that the median gross household income in Catalonia for that year was €45,781, households with gross incomes below €34,335 were classified as low-income. Those earning more than €34,335 but less than €91,562 were categorised as middle-income, while high-income households included those with earnings over €91,562. Of the 947 municipalities analysed, 93 % were classified as middle-class, and 5 % as low-income households. Almost all low-income households were situated in small towns with fewer than 5,000 residents, with the exception of two municipalities that had between 5,000 and 20,000 inhabitants.

Although the household income data in this study refers to gross income per household, which means it is measured before taxes and social contributions, the values can still be qualitatively compared with at-risk-of-poverty threshold estimations. These estimations are based on equivalised disposable income after social transfers and are defined by EUROSTAT as households with less than 60 % of the national median equivalised disposable income. In Spain, the thresholds in 2022 were €10,088 for single-person households and €21,185 for two-adult households with two children [114]. After accounting for a deduction of taxes and social transfers of 25 %, the net income could be around €25,751. Therefore, although it would be necessary to explore net income and household size further to determine which of the municipalities would fall under a poverty classification, the value is quite close to the value established for large families.

Nearly all interventions were concentrated in municipalities with middle-income households, accounting for 96 % of the total interventions. Only 2 % of the interventions originated from low-income municipalities, while 4 % came from high-income municipalities. Nevertheless, although low-income municipalities constitute a minor segment of the region, they are in fact the most critical target users, as vulnerable families need assistance to overcome financial and knowledge-related barriers. In that sense, only 10 out of the 47 low-income municipalities were identified among the different samples.

As shown in Fig. 4, each sample included interventions in only four low-income municipalities; thus, only 9 % of the total municipalities facing socioeconomic difficulties were represented, with no significant differences resulting from the implementation of the funds. In the case of the PREE scheme, five applications emerged from four towns in the province of Tarragona, three from populations under 5.000, along with two applications from a municipality with fewer than 20,000 inhabitants. Regarding PREE5000, there were also five applications, all of which have populations under 5,000 and are situated in Lleida. Furthermore, within the SMI, five additional interventions were recorded, with the first three located in Tarragona and the latter in Lleida.

4.3. Impact on the building stock by the construction period

Assessing the impact of financial support mechanisms on the renovation of the residential building stock is particularly important not only to determine the proportion of the stock that has been effectively upgraded, but also to identify the types of buildings that have benefited from these schemes. This is especially relevant in light of the new Energy Performance of Buildings Directive (EPBD) requirements, which stipulate that at least 55 % of renovation efforts must focus on the worst-performing buildings in the stock. As a result, an analysis was conducted, specifically focused on residential households, since they represented 89 % of the subsidised interventions, and they embody the most significant volume of the existing building stock [67]. As illustrated in Fig. 5, Archetype 5 (1981–2007) and Archetype 4 (1961–1980) were the two typologies with the highest number of interventions, followed by Archetype 1 (< 1900). This pattern suggests that interventions were implemented in one typology prior to the introduction of the CTE in 2006, as well as in the older typologies constructed before the implementation of the first thermal regulations, NBE-CT-79, in Spain. In contrast, Archetype 6 (2008–2011) was exclusively found in non-subsidised interventions, as the financial mechanisms primarily targeted buildings constructed before 2007. Furthermore, the distribution among the samples was notably similar, with Archetypes 5 (1981–2007), Archetype 4 (1961–1980), and Archetype 2 (1901–1940) each representing between 20 % and 30 % of the total. However, as evidenced by the overall number of interventions, a greater number of renovations were carried out under the PREE framework during this period, particularly in Archetypes 1 and 4, when compared with standard market interventions.

Nevertheless, although Archetypes 5 (1981–2007) and Archetype 4 (1961–1980) were the typologies with the most significant number of interventions, considering the total number of buildings of each typology in the Catalan region, the most significant impact was on the Archetype 2 building stock (0.09 %), followed by Archetype 1 (0.04 %); hence, the two older archetypes as shown in Table 2.

4.4. Analysis of environmental and financial impacts in buildings from 1961 to 1980

To gain a better understanding of the energy behaviour of buildings before and after the retrofit process, a comprehensive analysis of the energy improvements made during renovations was conducted. This analysis aimed to identify the actions implemented, their associated costs, and their effects on energy demand, consumption, and emissions.

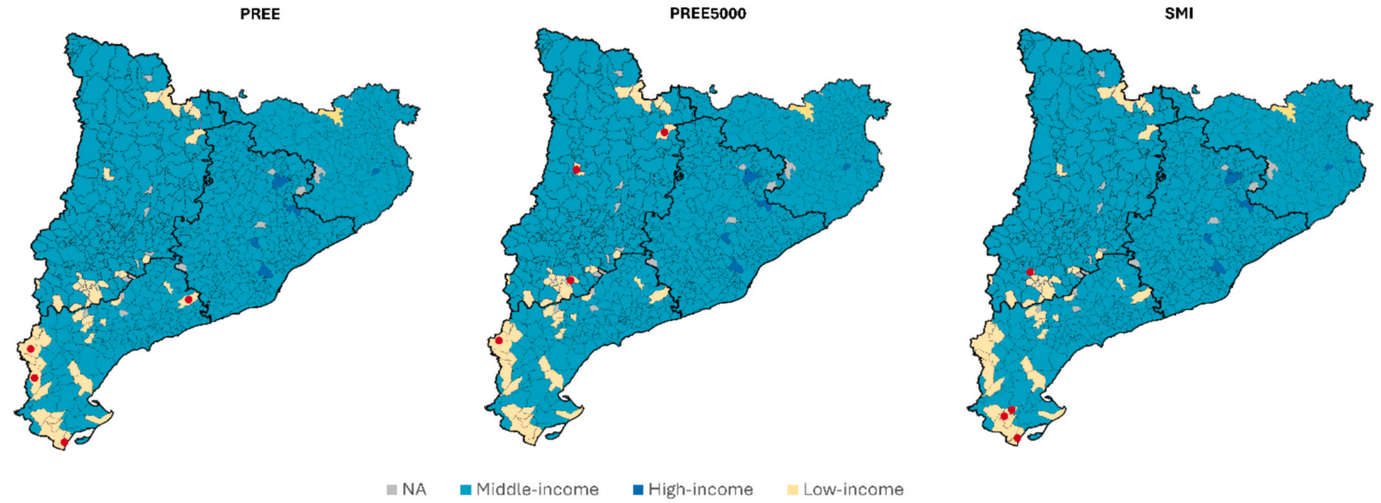


Fig. 4. Location of interventions in low-income municipalities. Source: own elaboration.

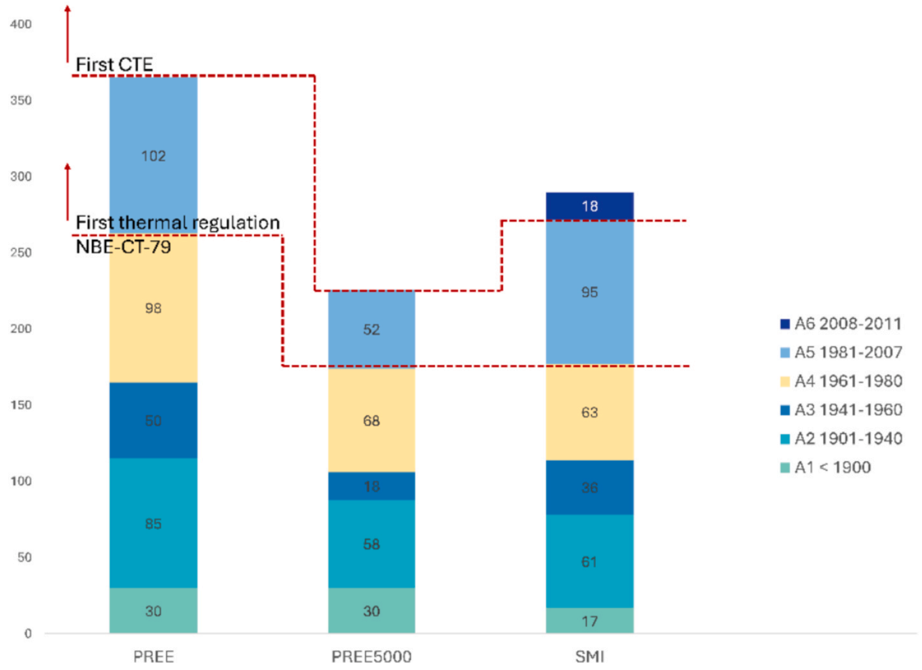


Fig. 5. Number of interventions by archetype and mechanism. Source: own elaboration.

Table 2

Proportion of subsidised interventions in housing according to year of construction.

Aspect	Total households in buildings intended primarily for residential use in Catalonia	Total number of households rehabilitated under aids (PREE + PREE5000)	Percentage over the total
A1 < 1900	204,859	77	0.038 %
A2 1901–1940	260,360	223	0.086 %
A3 1941–1960	399,788	141	0.035 %
A4 1960–1980	1,520,899	384	0.025 %
A5-6 1981–2011	1,360,621	234	0.017 %

Additionally, and for the purpose of the energy analysis, the Archetype constructed between 1961 and 1980 was chosen as it represented the largest sample with sufficient information and constituted the largest proportion of the Catalan building stock. The analysis focused on the single-family typology, which represented the largest sample size, comprising 114 interventions, and enabled a more detailed examination under varying conditions, such as climate.

4.4.1. *Measures*

In terms of the typologies of interventions carried out, as shown in Fig. 6 up to 79 % of the PREE5000 interventions and 52 % of the PREE interventions involved executing renovations on various elements of the

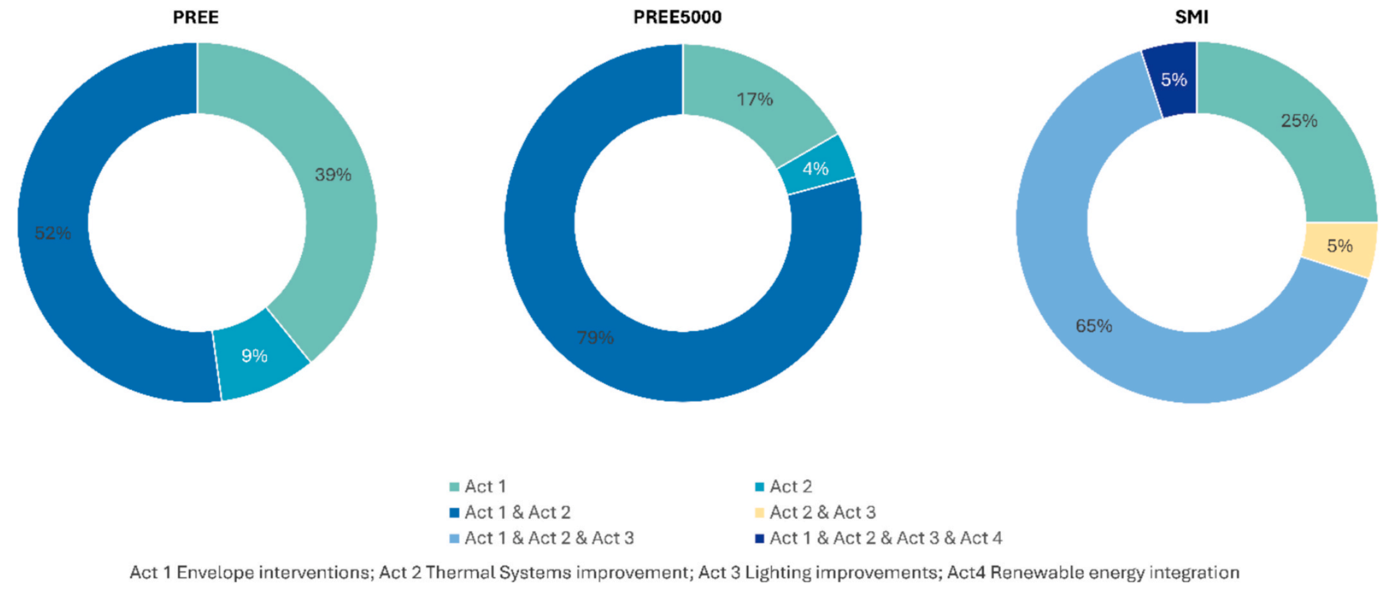


Fig. 6. Distribution of interventions by measure. Source: own elaboration.

envelope, along with enhancements to the thermal systems. In contrast, interventions affecting only a single element represented between 4 % and 39 % of the samples. For the SMI, 65 % of the interventions consisted of combined actions on the envelope and system improvements, which included both thermal and lighting systems; additionally, 5 % of the interventions incorporated photovoltaic panels during the renovations. Interventions involving only one element comprised 25 % of the overall sample considering the three schemes; nevertheless, despite the fact that combined renovations constituted a larger percentage across all three samples, a significant disparity was observed between the PREE and the other two samples, while the rate of combined renovations in the PREE5000 and the SMI was quite comparable. The proportion of combined renovations fell from 70 % to 52 % within the PREE framework; concurrently, the percentage of interventions focusing solely on the envelope rose to 39 %. Several factors could explain this difference, including the varying requirements associated with the funding, with the PREE5000 funds imposing stricter criteria regarding energy savings.

The most common passive measures financed were window replacements and façade improvements, which comprised 32 % of the cases under both the PREE and PREE5000 schemes. Nevertheless, a more substantial renovation effort was observed in the PREE5000 program, where improvements to windows, roofs, and façades ranked as the second most frequent interventions, accounting for 24 % of the sample, while within the PREE framework, the second most prevalent intervention was façade improvements, also accounting for 24 % of the total passive interventions. Furthermore, the percentage of integral renovation of three or more envelope elements increased from 19 % in the PREE scheme to 32 % in the intervention under the PREE5000. In standard market interventions, 83 % involved improvements of façades or roofs, combined with window renovations. It is important to note that, since many fields in SMI were not highly specific, it was not possible to verify whether the interventions focused on all three elements or just two of them. Additionally, it is noteworthy that a significantly lower percentage of interventions focusing solely on one element was observed, accounting for only 5.5 % of the total SMI sample, in contrast to the 35 % seen in the PREE funds.

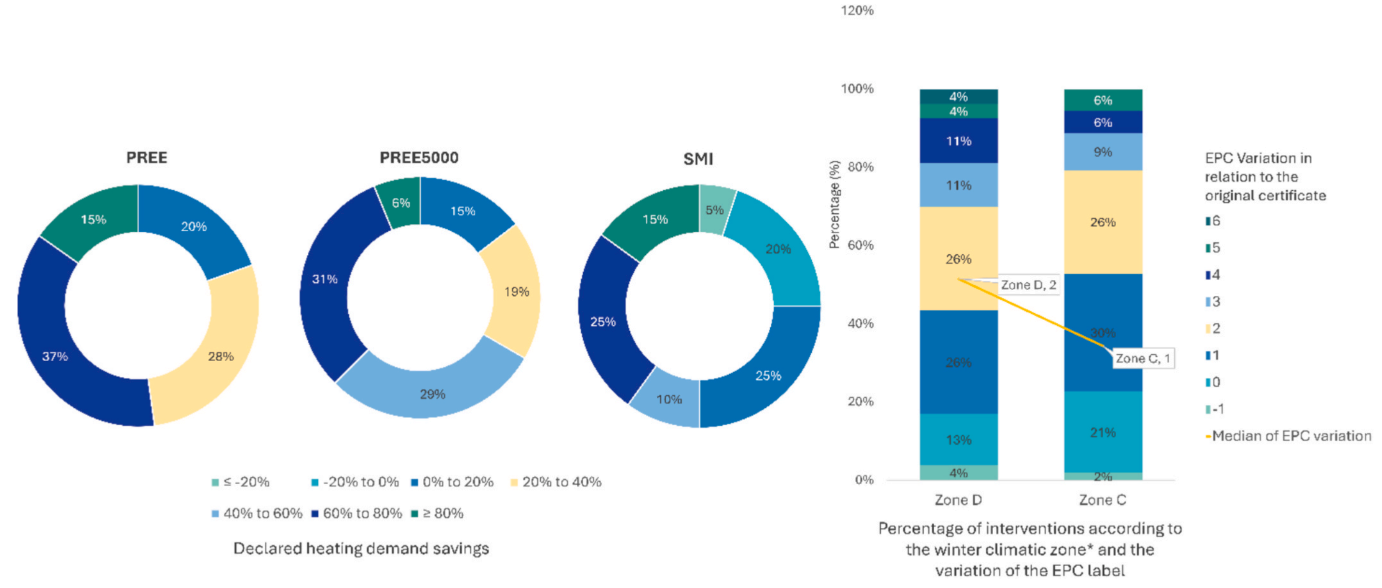
Regarding the active systems, 75 % of the interventions of all three samples replaced conventional systems with heat pumps or aerothermal units, while 15 % chose biomass as the primary thermal system, and 5 % opted for geothermal units. Some smaller percentages incorporated combinations of more than one system, such as biomass for heating and heat pumps for cooling. In addition, 27.5 % of the interventions also included improvements in the system's distribution, regulation or control. As for the PREE scheme, all the improvements made under the funds involved replacing conventional systems with heat pumps or aerothermal units. In only one instance, a heat pump was combined with a solar thermal installation. In the context of SMI, while the vast majority implemented system improvements, only one intervention detailed the specific type of energy system selected in the descriptive panel, which in this instance was a heat pump. Furthermore, 10 % of the interventions conducted for this archetype incorporated the integration of photovoltaic panels.

It is important to note that the renovations carried out in low-income zones, financed by the PREE and PREE5000 schemes related to this archetype, focused solely on insulating the façade. This passive measure was complemented by enhancements to thermal systems, with two out of the three interventions involving the installation of a heat pump, and one incorporating a geothermal system.

4.4.2. Energy demand

Assessing the impact of renovations on energy demand can yield valuable insights into how implemented measures have not only fostered the replacement of fossil fuels and improved system efficiencies but also helped effectively reduce energy requirements during both summer and winter by improving various elements of the building envelope.

A first exercise was conducted to evaluate the starting point and the improvements in heating demand. As shown in Fig. 7, the proportion of households with the worst-performing labels (EPC letters G and F) was higher in the samples corresponding to the subsidy frameworks, representing 59 % and 75 % of the applications for the PREE and PREE5000, respectively. In comparison, in the standard market interventions, the worst-performing buildings accounted for only 35 % of the sample; therefore, a significantly lower percentage. This difference could indicate that the subsidies were effectively promoting renovation actions for building users in that context, thereby increasing the proportion of renovations conducted for those typologies. In terms of improvements, 45 % of the interventions carried out under the PREE5000 and PREE frameworks demonstrated savings exceeding 60 %, with median savings reported at 48 % for PREE5000 and 41 % for PREE. Conversely, the results were somewhat lower for SMI, where 40 % of interventions achieved savings greater than 60 %, resulting in a median energy demand savings of 33 %. Regarding EPC heating demand labelling, measures that received subsidies experienced a median improvement of two



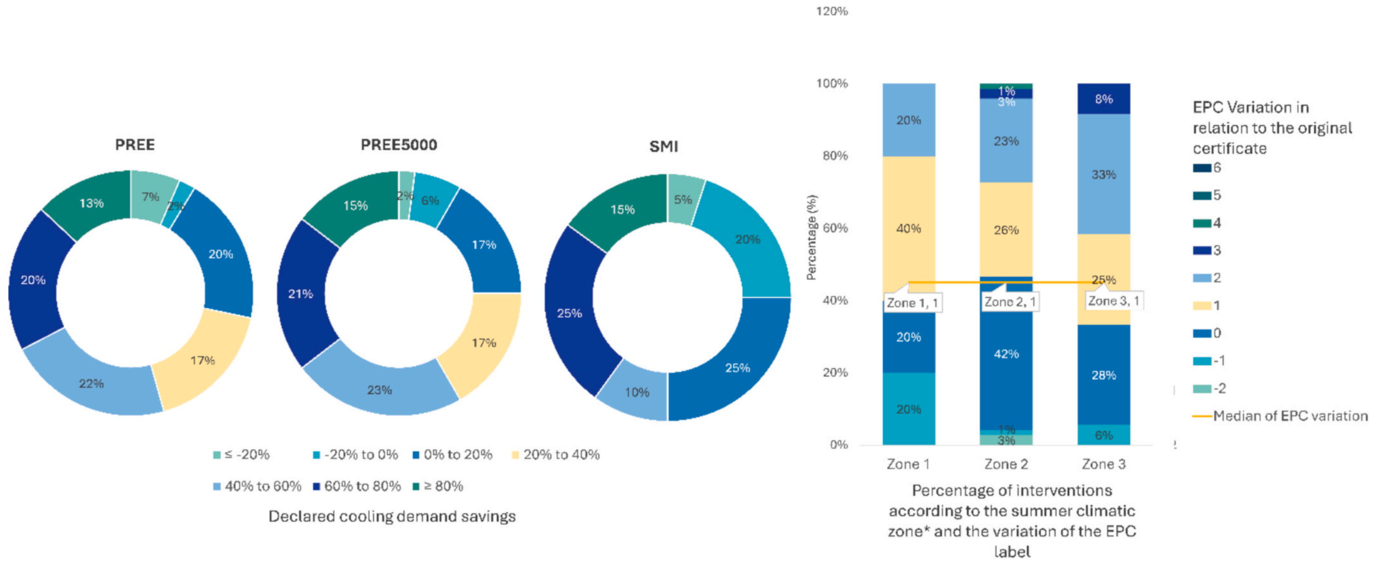
* There are 5 Spanish winter climate zones, being A = warmest, E = coldest.

Fig. 7. Renovation impact on heating demand. Source: own elaboration.

letter grades, whereas this figure decreased to one letter grade for SMI. Additionally, a supplementary analysis was conducted to visualise potential differences across climatic zones, particularly in zones D and C, which accounted for the majority of the samples. This analysis revealed a notable divergence between the two climates; specifically, houses located in climate D, with colder conditions, were able to improve their energy efficiency by two ratings and achieve greater savings compared to those in zone C, which has warmer conditions. This suggests that colder climates may offer the potential for higher energy savings compared to warmer climate zones, at least considering the EPC labelling methodology.

Nevertheless, although improvements were made across the different climates and typologies, between 17 % and 13 % of the worst-performing houses either maintained the letter or improved only one letter and still exhibit deficient behaviour. This percentage increased to 30 % for standard market interventions, demonstrating that, in general, the scope of the interventions in terms of heating demand was higher under the funding programs.

A similar exercise was carried out to analyse cooling demands. In this instance, the proportion of houses with poor performance was significantly lower than that of heating demand. Only 4 % of the interventions under the PREE scheme registered labels classified as G or F, whereas the other two PRE5000 and SMI samples had initial EPC labels starting with either E or D letters, as illustrated in Fig. 8. In terms of improvements, only 32 % of the subsidised interventions reported savings exceeding 60 %, indicating a lower improvement compared to the one noted for heating demand. The median energy savings associated with subsidised interventions were observed to be slightly higher than those from standard market interventions, reporting values of 47 % and 34 % respectively. However, it is important to note that although a difference



* There are 5 Spanish summer climate zones, being 4 = warmest, 1 = coldest.

Fig. 8. Renovation impact on cooling demand. Source: own elaboration.

was observed, the difference was not statistically significant. Regarding the labelling of EPC cooling demand, all three samples showed a median improvement of only one letter grade. Furthermore, no distinctions were found among the various summer climates, as the median EPC improvement remained consistent at one across all conditions. Thus, although there was a slight enhancement in the declared savings across the samples, the implementation of funds did not yield any significant differences.

Moreover, a disaggregated analysis was conducted to understand the relationship between specific envelope interventions and heating and cooling demand savings. In that sense, integral renovations where more than two elements were upgraded resulted in a 40 % improvement in energy savings for heating demand and a 30 % improvement for cooling demand compared to those that focused on one or two elements. Furthermore, in some cases, counterproductive effects on cooling were observed, as 10 % of the interventions resulted in an increase in cooling demand. This was particularly accentuated in warmer zones with more severe summer conditions, where the median cooling savings decreased from 70 % in zone 1 to 45 % in zone 3. Futhermore, negative impacts were identified in strategies such as integral interventions that included the insulation of the floor, which increased the energy demand up to 50 %, or interventions of single elements such as windows or façades that despite achieving a positive outcome for heating demand, neglected the potential interactions associated with the summer season and resulted in an increased cooling demand of up to 50 % in zone 2 and 3. These findings are particularly relevant, considering the climate projections associated with Mediterranean climates, where heatwave episodes are expected to increase over the coming years. Some studies showed up to five times more frequent events [115] and a change in intensity of 104 % on average for the near future, 2021–2050 [116]. The issue could be further emphasised by the underestimation of cooling demands at the Spanish level, with public mechanisms such as the Long-term Strategy for Energy Rehabilitation in the Building Sector in Spain (ERESEE) [77] exclusively focused on strategies for reducing heating demand and historical mechanisms, both public and private, often solely linked to winter strategies, the improvement of systems or the introduction of renewable energy [57].

Additionally, the variations in Energy Performance Certificates (EPC) concerning temperatures and cooling demand further emphasise the need to address this aspect properly. Also, as highlighted by a Spanish study 80 % of Spanish cities already have a different climate zone to the one used by the EPCs, and that the forecasts recorded in the RCP 4.5 and RCP 8.5 scenarios, practically 100 % of the cities in mainland Spain will change their climate zone to warmer ones, being the warner zone A4 and B4 the predominants in the region [117]. Aligning with this fact, a study comparing historical weather with EPC values showed that real climatic records would nearly triple the estimated cooling demand of the EPCs, highlighting the overheating risk and critical underestimations in current certification methodologies [118].

4.4.3. Emissions and consumption performance

Beyond assessing energy demand, the evaluation also involved quantifying reductions in greenhouse gas emissions and non-renewable primary energy consumption (NRPE), as these are the main indicators for the Energy Performance Certificate (EPC) rating. These indicators provide a basis for understanding the overall environmental impact of renovations and their effectiveness in decarbonising the residential building sector.

Taking into.

The analysis of the three samples showed a median emission reduction of 77.5 % and a median of 72 % savings in NRPE, enabling up to 70 % of renovated houses to achieve an EPC rating of A or B. Interestingly, this share was greater among SMI cases, representing 70 % of the total, of which 45 % obtained an A in the emissions EPC label. In contrast, the percentage of A or B EPC emission labels in subsidised ranged between 50 % and 55 %, with A labels reaching up to 35 % of the total. The different starting points can partially explain this apparent contradiction, since the percentage of the worst CO_2 labels varied among the samples. As observed in Fig. 10, only 30 % of the houses had G and F emission labels in standard market interventions. In contrast, this percentage was significantly higher in the PREE5000, exceeding the SMI rate by more than double. Conversely, the variance observed between the PREE and SMI samples was approximately 10 %.

In terms of label improvement, a significant upgrading in emissions and NRPE labels was observed in the PREE5000, indicating a median upgrade of four letters in the emission EPC label, with up to 75 % of the interventions reporting savings exceeding 60 %. In contrast, the PREE and SMI showed improvements of up to three letters, with primary energy savings being 68 % and 55 % respectively. This differential behaviour was also confirmed by a statistical analysis of variance (ANOVA), which showed a significant difference in non-renewable energy savings between the three samples of interventions ($F = 18.4$; $p < 0.001$). Tukey's post hoc test indicated that the most marked differences occurred between the PREE5000 and the other two samples, while the results of the PREE and SMI did not have a significant statistical difference. As shown in Fig. 9, the PREE5000 scheme derived higher average savings values and less dispersion, reflecting more homogeneous behaviour as a consequence of the higher level of energy savings required by the scheme. In contrast, the less strict requirements of the PREE sample resulted in a significantly greater range of values, showing a tendency to carry out interventions which comply solely with the minimum savings thresholds established by the program. As a consequence, many financed projects under the PREE scheme achieved either lower or comparable levels of improvements to those observed in SMI.

Furthermore, in line with the energy demand assessment, a correlation was observed between climate and the number of letter jumps. The most significant jumps were noted in colder region D, as well as in the milder summer conditions, zone 1, where the median improvement was four letters, compared to the three-letter improvements recorded in the other zones. Nevertheless, despite the significant advancements noted, as much as 4 % of the subsidised interventions continued to be classified in one of the lowest EPC label categories, an F, showing only a single-letter improvement; thus, still in need of energy upgrades to attain optimal energy performance. In contrast to this, none of the standard market interventions remained in the lowest emission and NRPE labels; the lowest EPC labels were D and E for emissions and

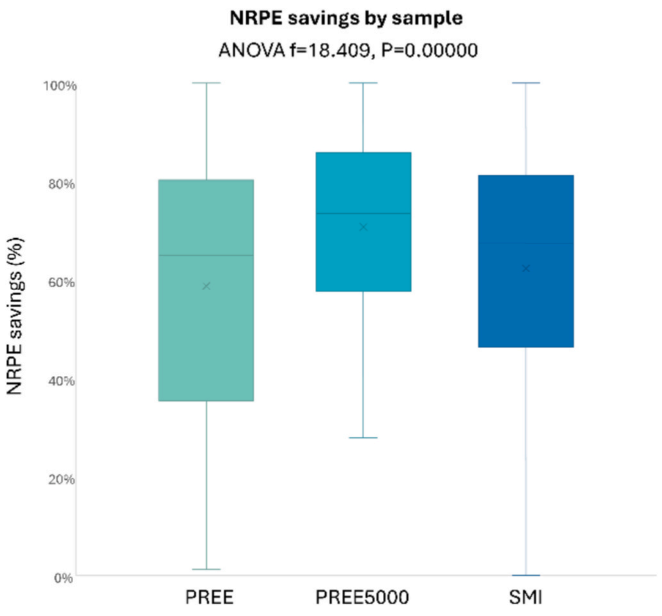


Fig. 9. Statistical comparison of NRPE across samples. Source: own elaboration.

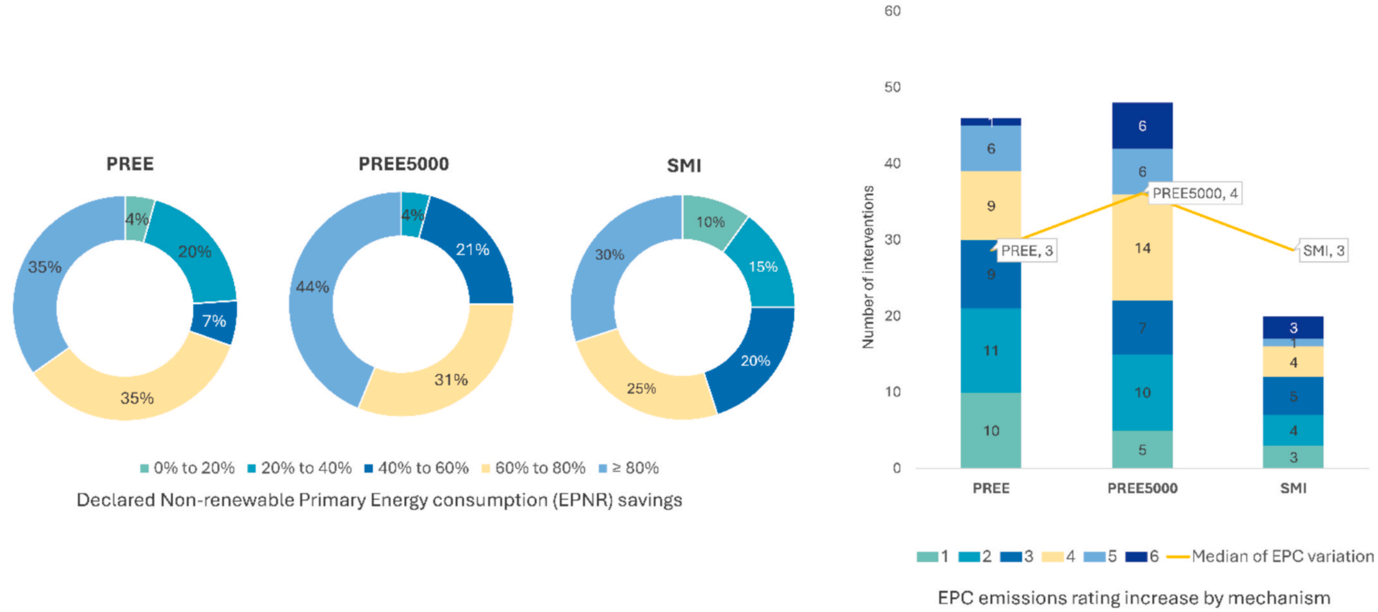


Fig. 10. Emissions and non-renewable impact by scheme. Source: own elaboration.

NRPE, respectively.

The assessment was also disaggregated, considering the type of action implemented to evaluate the different upgrades obtained. As illustrated in Fig. 11, integral renovations encompassing both passive and active measures generated a CO_2 reduction of up to six levels, while passive measures alone achieved up to three-level improvements. System improvements, on the other hand, resulted in upgrades of up to five letters. Moreover, CO_2 savings increase from 40 % when only the building envelope is addressed to up to 86 % when actions are taken on the systems as well. As shown in Fig. 11, the percentage of renovations achieving more than 60 % of NRPE savings increased from 26 % in the case of passive measures only to 88 % of cases when combined interventions were implemented. The highest savings according to the EPC calculation were achieved in colder climates with a combination of integral interventions, including windows, roofs, façades and the replacement of the heating system with a biomass boiler, resulting in savings of up to nearly 100 %. On the other hand, aerothermal and heat pump integrations, along with comprehensive envelope renovations that included more than two elements, achieved significant emissions savings of between 70 % and 90 % across all climates. On the contrary, interventions that focused solely on integrating thermal solar panels had a lower impact as they influenced mainly domestic hot water production.

4.4.4. *Investment costs*

As the final element of the study, an additional analysis was performed to assess the reported costs associated with the interventions, aiming to visualise the investment required for each of the identified energy scenarios. This analysis was limited to the two subsidised schemes, as there was no available cost information for standard interventions.

The economic analysis is descriptive, as it is based solely on information available in the subsidy programme application forms. Neither the subsidies nor the EPC scheme require the monitoring of actual energy consumption, which limits the establishment of robust relationships between investment and energy savings. Furthermore, a cost-optimal analysis would require additional information not provided by the instruments, such as monitored consumption or energy bills, fuel prices, and socio-economic conditions of the users, including use patterns or access to social bonuses on the electricity bill. It is also worth noting that EPC consider only cooling, heating and DHW services under fixed-use conditions, which have been shown to differ significantly from actual energy performance. Therefore, although some initial conclusions are presented, the results must be taken with caution, as the emissions

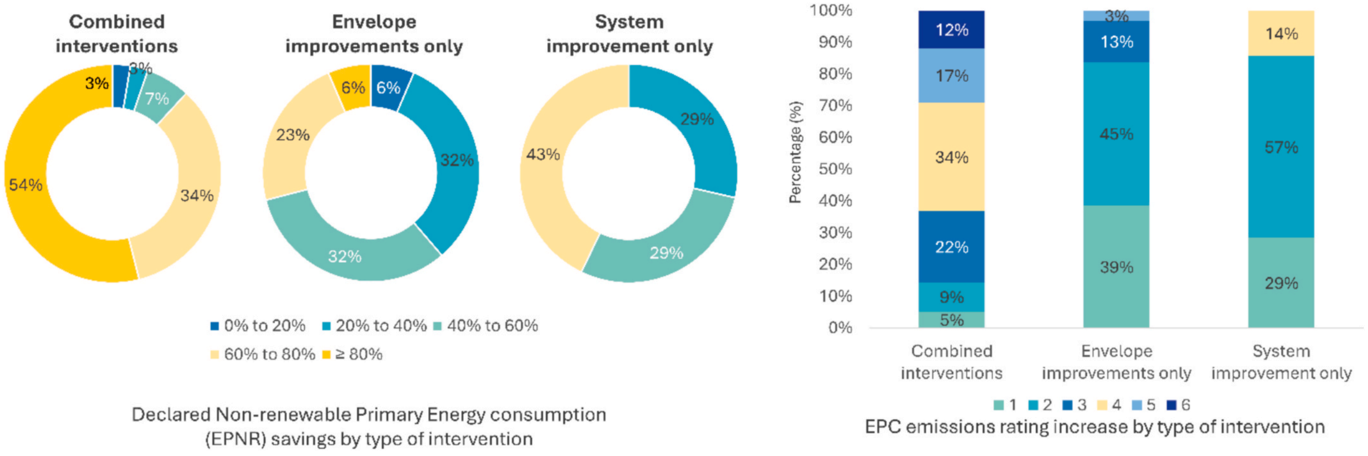


Fig. 11. Energy savings and emissions upgrades by type of measure. Source: own elaboration.

and energy savings reported in EPC may differ from the real savings in energy bills.

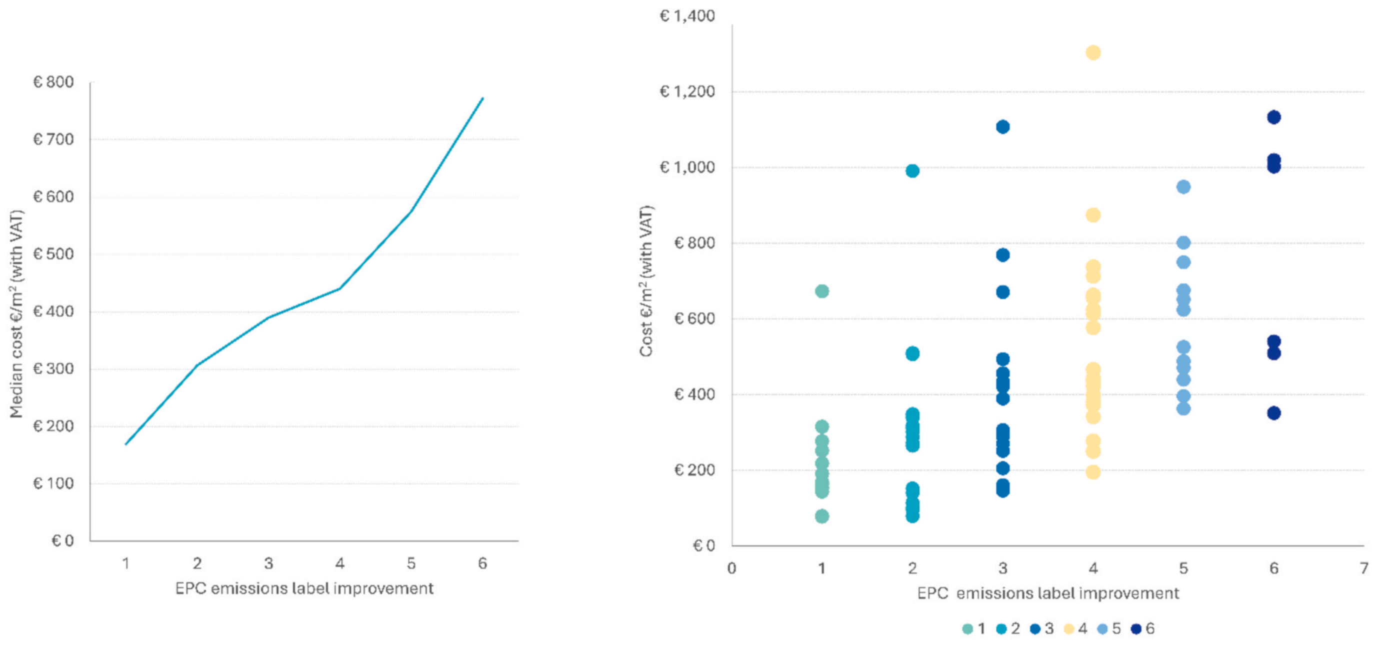
As shown in Fig. 12, the analysis showed that investments varied considerably among the samples, with values ranging from € 79/m^2 to € 1,300/m^2, depending on the implemented measures and the improvement achieved in the EPC level class. The median average cost of each EPC level improvement was € 130/m^2. Nevertheless, the cost of each EPC class improvement was relatively higher when only one or two rating levels were achieved, and decreased when improvements exceeded three levels. Moreover, more economic efforts were identified in the first and last sections, which are associated with achieving the first letter improvement and achieving improvements of 5 or 6 letters. The analysis revealed a significant difference in investment prices across the samples. Investments per square meter in PREE5000 were as much as 84 % higher compared to PREE. Nevertheless, it is important to note that, as mentioned in the previous section, the median EPC level improvement rose from three to four in the case of PREE5000, indicating that, in general, the scope of the interventions tended to be larger. Another relevant aspect identified was the higher investment cost registered in low-income locations, where prices increased by up to 30 % to achieve equivalent results. In contrast, capital cost tended to decrease in larger municipalities. Moreover, although there is no real data available to establish a direct relationship between investments associated with EPC class improvements and energy bill savings, some studies suggest that improving an energy rating from an E to an A could result in monthly savings of approximately €30 on bills [119] in a building in Barcelona, therefore, around €360 annual savings for the analysed latitude. Considering a median cost of €443 per square meter for improving a four-letter rating on the EPC scale, the payback period for an 80 m^2 improvement could exceed 90 years. This discrepancy highlights that the direct economic return from energy savings alone is limited and underscores the need to emphasise other benefits.

Finally, considering the various measures implemented, the analysis revealed that even integral renovations registered energy savings that were up to double those of partial interventions; the investments required for these integral renovations were significantly higher. Integral renovations required up to 380 % more capital compared to partial or individual measures. The median costs of interventions addressing façades, roofs, and windows, which resulted in NRPE savings of between 80 % and 99 % in combination with active systems, were €567/m^2 for PREE5000 and €304/m^2 for PREE. The combination of windows and façades with active systems, on the other hand, resulted in slightly lower energy savings with values between 67 % and 81 % while the cost dropped to €277/m^2 and €197/m^2, respectively; Therefore up to 65 % less investment needed, nevertheless the difference in the values registered between the two instruments showed a significant increase in investment values in smaller municipalities showing territorial disparities associated with the costs. In contrast, window improvement along with system replacement resulted in NRPE savings of up to 65 % with investments of €133/m^2 for PREE5000 and €79/m^2 for PREE. In the case of system replacements, although the costs among the two samples were closer, there were considerable variations among the different active systems. Although the median cost for system improvements was €165/m^2, geothermal installations were considerably more expensive than the other systems, with costs up to 200 % higher than those of heat pumps and four to six times the cost of biomass boilers and solar thermal integrations, which evidenced significantly higher costs that did not result in greater energy savings. The results show that although all systems are valid solutions, the associated cost of geothermal installations significantly increased the energy savings-investment cost ratio.

It should be noted that the lack of breakdown cost by materials, labour or other aspects hinders the ability to draw more granular conclusions. As a result, while differences in price between intervention types and programs, and therefore the size of municipalities, are reported, it was not possible to determine whether specific cost components drive these differences. Furthermore, the limited number of cases in low-income municipalities, combined with the high predominance of heat pumps over other system types, prevents a detailed analysis by climate zone or socio-economic context. Therefore, the study provides only a global assessment of cost, as more granular conclusions regarding the drivers cannot be drawn from the available data.

5. Discussion

The transition towards a decarbonised built environment requires significant collaboration between the public and private sectors and the



Median cost (€/m^2) of each EPC increase

Cost €/m^2 of the different interventions, according to the EPC label improvement

Fig. 12. Cost of interventions in relation to EPC improvement. Source: own elaboration.

inhabitants, alongside an acceleration of current renovation rates. Such a transformation depends on the collective efforts of various stakeholders, with public administration playing a pivotal role in not only easing the economic burdens associated with this transition but also in addressing the socioeconomic challenges faced by diverse citizens as well as the potential disparities across the territory. Furthermore, the proper design and implementation of support mechanisms is crucial not only to encourage the renovation of public infrastructure but also to promote actions within the private sector. In this respect, a thorough understanding of the characteristics of the building stock, the socioeconomic implications of renovations, and the regional context is essential for developing effective renovation strategies and ensuring the efficient allocation of public resources.

In this context, the analysis presented in this paper offers a detailed examination of two funding programs, evaluating emissions, energy consumption and demand, and comparing them with standard market interventions without public financial support. This assessment provides a foundation for understanding the potential impact of the implemented support mechanisms.

Moreover, although the methodology developed in this study could be replicated across Europe, it is important to note that, even though Next Generation funds have been implemented throughout the European Union, eligibility requirements may vary significantly from country to country. As such, a case-by-case assessment will be essential to capture the differences among the various instruments used and to clearly illustrate the divergences in the EPC mechanisms and climatic conditions. In the Spanish context, while this research is specifically focused on Catalonia, the methodology and findings could be applicable to other Spanish regions as all fall under the same national regulation. It is worth mentioning that even though the implementation of the subsidies was delegated to the autonomous communities, their requirements were established at the national level, therefore the conditions were equivalent across all country. Furthermore, some of the conclusions could be extrapolated to other regions as similar climatic and socio-economic conditions are present across the territory. In terms of climate, eight of the fifteen official Spanish climatic zones were analysed during the study. Furthermore, according to the CTE [72] 17 of the province capitals, which represent almost 30 % of the reference capitals for climatic zone estimations, have zone D and C for winter conditions and zones 2 and 3 for summer conditions, four of the main climatic zones identified in the analysis. Nonetheless, although climatic conditions may be equivalent, territorial and economic disparities may develop across regions; therefore, to effectively evaluate the impact of the interventions, it would be necessary to reassess the associated costs and other pertinent factors.

Regarding the lessons learned, several conclusions can be drawn from the analysis and used as a guide to optimise future rehabilitation support programs.

While public financial support mechanisms had a positive impact on the territory, especially in the case of the PREE5000 framework, the coverage of the territory is limited, and therefore, more targeted efforts are needed to improve the territorial coverage, especially in less populated and centralised provinces such as Lleida and Tarragona, where a large number of small municipalities with lower incomes are located. The low engagement observed within low-income municipalities may be attributed to several interrelated factors. On one hand, the limited access to or awareness of the available programs, which were primarily communicated through the ICAEN website. On the other hand, several barriers may discourage individuals from applying, such as the perceived complexity of the process, lack of technical knowledge or support, or insufficient funds to cover the initial investment. As noted in previous local studies, the paperwork required to obtain public subsidies is extensive and challenging to navigate and often demands management skills and resources that vulnerable sectors might not have, further widening the gap [42,120,121]. Future analyses could delve deeper into the underlying reasons for this low engagement and the barriers that contribute to the underrepresentation of certain areas and identify potential mechanisms to overcome them, such as improving awareness and accessibility or offering technical or administrative support to prepare the associated documentation. This role can, for instance, be fulfilled by the one-stop shops (OSS) promoted in the revised EPBD, which are still to be deployed in the territory and could offer integrated assistance to homeowners. Analysis, such as dedicated surveys, could help gain a comprehensive understanding of the issue. Moreover, the territorial disparities observed in investment costs, both across different regions and among various measures, highlight the need to develop more targeted and adapted schemes that effectively assess aspects such as socioeconomic vulnerability and the unique realities of different territories. Recognising potential territorial disparities, such as those between rural and urban environments, which can affect accessibility or readiness of resources, is crucial to improving the efficacy of future instruments.

In addition, although the implementation of subsidies has had a considerable positive impact on the oldest typologies, the renovation rate remains very low compared to the total building stock, leaving a large part of the building park in need of renovation. Therefore, if the decarbonisation objectives are to be achieved, it is imperative to explore other complementary mechanisms and partnerships with the private sector further to encourage the renovation of the worst energy-behavioural buildings.

Another critical point to guarantee the real effectiveness of the funds and the proper allocation of resources is the improvement and optimisation of the assessment tools and mechanisms used to evaluate aids. While EPC labelling provides a normalised methodology for assessing energy behaviour, the shortcomings of the procedure, such as different temperature settings, simplified occupancy patterns and fixed schedules for cooling or heating that do not always reflect the actual needs, can lead to estimations that might differ substantially from real-life conditions. In this line, previous analyses reported deviations ranging from 17 % to 60 % between ex ante and ex post outcomes, depending on the measures implemented [32,35,122–124]. The differences can be attributed to behavioural factors, such as heightened expectations for thermal comfort, which may result in increased energy consumption, especially in low-income households. Additionally, variations in occupancy patterns, differing assessments of interior and exterior temperatures, interpretations by professionals, and an underestimation of cooling demand could also result in divergencies in energy savings [22,35,37–41,118,122–126]. Therefore, to effectively address the energy impact, it is essential to either improve existing methodologies to align them with real-world scenarios or consider adopting additional mechanisms for evaluating the energy impact of financial instruments. This could involve integrating metered or monitored data to enhance the accuracy of the calculations and gathering more information regarding use and socioeconomic factors. Improving the mechanisms used to monitor the subsidies could not only allow for a more robust analysis of impacts but enable more detailed analysis of costs and benefits associated with the interventions.

Furthermore, the results showed that the effect on demand was significantly less pronounced than on consumption, and in general, cooling demand remained an under-addressed issue. As temperatures in Mediterranean regions are projected to rise in the coming years, addressing cooling needs will become a critical issue for adapting houses to future conditions, as noted by other authors as well [117]. In this context, and considering the recommendations of the new EPBD recast, it is essential to develop policy instruments and methodologies that promote actions suitable for different climates and that enable a proper evaluation of the resulting impacts. While the improvement of the system's efficiency and the replacement of fossil fuels are relevant, it is worth noting that improving energy demand, which can be achieved by improving the envelope, is also an essential aspect for ensuring improved comfort conditions and alleviating energy poverty.

Moreover, to achieve the desired results, it would be essential to rethink the energy requirements of the mechanisms to promote deep renovations and minimum energy savings, ensure comfort conditions in both summer and winter, and prevent the need for further interventions in the near future. The disparities in savings associated with the different climates of the sample reinforce the need to analyse this aspect and define adequate strategies properly. Similar conclusions have been noted by several authors [32,122], who highlighted that retrofit impacts can vary seasonally, with higher energy savings typically associated with winter months, and that colder climates tend to yield greater energy savings, further underscoring the importance of exploring suitable solutions for both hot and cold climates. In addition, the similarity in scope and impact between some subsidised interventions and those already implemented in the market in certain climates highlights the need to further promote deep renovations. Although the decision to conduct deep renovation is influenced by several factors, such as income [33], there is still room to improve the effectiveness of the instruments. To reduce the percentage of free riding [26,27,33], hence users that would have pursued renovations even without the presence of subsidies and avoid favouring partial renovations instead of comprehensive structural changes [46], it is essential to design a diverse set of policy instruments. As highlighted by other authors [28,31,42,46,47], it is necessary to implement mechanisms that guarantee a greater impact than standard market interventions and that consider territorial realities, socioeconomic disparities and potential counterproductive effects. In that sense, mechanisms such as the PREE5000 have proven to be more effective, resulting in average savings that exceed not only standard market interventions but also the results of other aid programmes.

5.1. Conclusions

The objective of the research presented in this paper was to examine the estimated effects of renovation initiatives under both public subsidy and private initiative frameworks. This analysis aimed to provide a preliminary evaluation of the scope and the associated energy and socioeconomic implications of these renovation efforts, thereby establishing a foundation for rethinking the structure of future mechanisms.

In terms of scope, the analysis indicated that while there were no specific size restrictions for municipalities under one of the subsidy schemes, only 40 % of the territory was actually covered by both subsidy programs. Furthermore, only a small percentage of low-income municipalities submitted applications. Additionally, there was no significant difference in territorial coverage when compared to interventions without financial aid; in all cases, middle-income municipalities and those located in the most populated areas were the most represented.

Moreover, although the subsidies increased interventions in the worst performance buildings (letter G and F) and on three archetypes: Archetype 4 (1961–1980), Archetype 5 (1981–2007) and Archetype 2 (1901–1940), two of which were constructed before thermal regulations, the total impact was most pronounced in Archetypes 2 (1901–1940) and Archetype 1 (<1900). In contrast, despite being the most prevalent typologies in the park, and especially Archetype 4, with the poorest energy performance, both Archetypes 4 and 5 were the least impacted.

The subsidies led to substantial emission savings, particularly in colder climates, where they increased by nearly double the values registered in other climates. Conversely, in warmer climates, both the scope and the impact of the actions were similar to or less than those typically seen in standard market interventions. The improvements in the energy rating reinforced this trend as the EPC label was improved by as much as six levels when passive and active measures were combined. Notably, the interventions associated with the PREE5000 programs resulted in the most substantial improvements, achieving a median increase of four levels, although these preliminary results may be related to the stricter requirements of the aid. In contrast, the PREE scheme and standard market interventions yielded a lower certification impact. Additionally, although nearly half of the interventions received an EPC label of A or B, a non-negligible number of subsidy initiatives with the worst EPC label still denote a minimal impact, registering only a one-letter improvement and therefore still exhibiting a poor energy behaviour. In comparison, standard actions managed to surpass this threshold in terms of emissions ratings after interventions. Nevertheless, while significant improvements were achieved in emissions and consumption savings, the improvements in energy demand were significantly lower.

Furthermore, adverse effects were detected in warmer climates, with some measures having significantly less impact in warm areas, and in some cases resulting in counterproductive effects in cooling demand. These findings underscore the importance of taking both summer and winter conditions into account when planning interventions. In this sense, several studies can be found analysing the changes in climatic patterns, such as an increase in temperature, frequency, and intensity of heat waves [115–118,127,128] and the subsequent effects on mortality [129–131] and energy poverty [132,133].

Moreover, the study revealed that almost 70 % of the interventions executed combined building envelope measures with improvements of the thermal installations. The most frequent strategies included the renovation of windows and façades, while heat pumps were the predominantly chosen system, followed by biomass and geothermal energy. These approaches resulted in savings that were almost double those achieved through partial measures, and with energy demand savings up to 40 % higher than those achieved by partial interventions, emphasising the importance of undertaking integral renovations.

The study also emphasised the importance of the costs related to the interventions. The analysis showed that achieving the first letter improvement and implementing integral renovations involve higher expenses. Integral renovations required investments up to four times greater than those needed for partial or individual measures. The study also pointed out economic disparities across the regions. A significant difference was observed between medium-to-large municipalities and smaller ones, typically from rural areas, with prices sometimes up to twice as high as those registered in larger municipalities and even more pronounced in low-income areas. These facts are particularly relevant considering the goals of the new 2024 EPBD; both the higher costs associated with integral renovations and more cost-effective solutions should be explored and taken into account in future planning to ensure adequate scalability and replicability of results across the territory.

It is important to note that the economic analysis and cost-benefit assessment of the study were constrained by the availability of data, as they relied solely on estimated values derived from energy certificates. This limitation hindered a precise evaluation of the relationship between the scale of the interventions, their actual costs, and the energy savings achieved. Future research could delve deeper into this relationship by using monitoring data and user information, which could provide a more comprehensive understanding of the cost-effectiveness of these interventions.

The findings emphasise the importance of adapting rehabilitation instruments to guarantee that the energy transition is not only technically and economically feasible but also socially just. The various instruments developed in the coming years should be tailored to consider the diverse geographical and social differences within the country. This includes factors such as citizen vulnerability, income levels, cost, urban versus rural contexts, and climatic conditions. This multi-layered approach is essential for aligning these instruments with real market conditions, rather than just theoretical considerations.

Lastly, as this analysis is limited to two specific subsidy schemes implemented in Catalonia and the available information, the research could be broadened in the future to encompass additional Next Generation fund schemes, enabling a more thorough examination of the impact of these subsidies as well as a detailed assessment of potential vulnerabilities and disparities.

CRediT authorship contribution statement

N. Soledad Ibañez Iralde: Writing – original draft, Visualization, Investigation, Formal analysis, Conceptualization. **Jordi Pascual:** Writing – review & editing, Supervision, Conceptualization. **Núria Martí Audí:** Supervision.

Funding

All researchers from IREC have been partially supported by the Departament de Recerca i Universitats, Generalitat de Catalunya (2021 SGR 01403). The funding entities had no involvement in the writing of this paper.

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

This research was supported by the Catalan Institute for Energy (ICAEN). The funding entity had no involvement in the writing of this paper.

Data availability

Statistical data, such as EPC, geographical or socioeconomic information, is available in open databases. Subsidy form data is confidential. Specific data, however, may be shared upon request.

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