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Identification of cost-optimal levels for energy refurbishment of a residential building stock under different scenarios: Application at the urban scale

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ABSTRACT

The low replacement rate of existing residential buildings, together with their high share in the final energy consumption, has put energy refurbishment of the current stock in the centre of the agenda. Nevertheless, due to the high up-front investment and long payback period that it usually implies, deep energy retrofitting is not yet widely applied. In this context, the cost-optimal methodology introduced by Directive 2010/31/EU created a framework to identify the energy efficiency measures that would maximize the economic return. However, the analysis of cost-optimality has often been limited to a single building or type of building, which cannot be extrapolated to an existing building stock. In other cases, the limited number of reference buildings hinders the capture of the great heterogeneity of an existing building stock into sufficiently homogeneous building typologies for a reliable extrapolation of the assessment results. To address such a challenge, this research proposes the application of the cost-optimal method on an urban scale, aiming to identify the suitable range of energy performance that is reasonable to promote in different types of buildings, keeping in mind their specific characteristics. The methodology is applied to the residential building stock of the city of Bilbao, northern Spain, through a comprehensive approach that also incorporates deeper interventions pointing at nearly zero-energy building levels. The results aim to support decision-makers in outlining the most suitable energy efficiency policy and determining the priority targets that demand the mobilisation of investment.

1. Introduction

1.1. Context

In the European Union (EU), buildings are responsible for 40% of the final energy (FE) consumption and cause 36% of the greenhouse gas (GHG) emissions [1], which turns them into a sector of strategic importance within the ambitious European energy policy towards 2050 [2,3]. In Spain, 18.3% of the final energy demand corresponds to residential buildings [4].

The low replacement rate of existing buildings – about 1–3% per year in EU countries [5] – means that most buildings in existence in 2050 have already been built. In this context, the energy refurbishment of existing buildings becomes imperative to reduce energy consumption and related GHG emissions, and has thus been put in the centre of the political agenda.

Numerous methods and tools have been proposed to assess and compare different energy saving measures. [6–9] provide comprehensive reviews of the extensive research in the field of building energy retrofitting. Nevertheless, the energy retrofit rate remains scarce, leading to a slow diffusion of energy efficient technologies. Furthermore, this refurbishment is often limited to a single element retrofit measure, either because of its quick investment return, as in the case of lighting replacement, or due to the expiry of an element's lifetime, such as the replacement of the heating system.

Yet, a significant investment gap exists in deep energy retrofitting, beyond the minimum indispensable maintenance repairs, mainly due to the high up-front investment and long payback period (PBP) that it usually implies. The practice has proven that these two are the most relevant parameters in the evaluation of a major building energy refurbishment [10,11]. Also, in Spain, financing is identified as the main barrier faced by refurbishment projects, in a framework of lower solvency of households due to the effects of the economic crisis [12]. A reasonable investment PBP, through trusted energy cost savings, is indispensable to motivate owners to

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carry out such a great financial effort. It is therefore crucial to reliably identify the retrofit measures that would maximize the economic return.

In this context, Directive 2010/31/EU (EPBD recast) [13] aimed to create a framework for long-term improvements in the energy performance of buildings, by promoting cost-effective energy refurbishments. For the first time, the EPBD recast introduced the cost-optimal methodology: an assessment that allows different levels of energy intervention to be compared under distinct macroeconomic scenarios, aiming to identify the long-term cost-optimal energy performance level, i.e. the level that leads to the lowest cost during the estimated economic lifecycle (hereinafter cost-optimal level).

Supplementing the EPBD recast, the Commission Delegated Regulation No. 244/2012 [14] and the Guidelines that accompany it [15] were published in 2012. This further developed the harmonized methodology for calculating buildings' cost-optimal levels. The methodology is based on the net present value approach. The term global cost (GC), taken from the standard EN 15459, corresponds to what in the literature is generally called lifecycle cost. Therefore, it includes not only the up-front investment, but also additional such costs as operational, maintenance, disposal and energy saving costs. Thus, the framework incorporates a holistic lifecycle approach, and is not limited to short-term optimizations. Nevertheless, unlike the life cycle assessment (LCA), it excludes the environmental impacts of grey energy.

The starting point of the methodology is the set of reference buildings (RBs) that should faithfully represent an entire building stock. At the beginning of the process, some energy efficiency measures (EEMs) are defined, and then combined in packages of measures (variants) to be applied to the RBs. Afterwards, the calculation splits into two parts: the calculation of the energy performance and that of the economic performance of the different combinations of RBs and variants. The objective of the former is to determine the annual overall energy use in terms of primary energy (PE). That of the latter is fed by the results of the former. Thus, a cost curve could be derived showing the assessed scenarios of energy performance (PE consumption, in the x-axis) and financial performance (GC, in the y-axis). The best retrofit solutions can be found in the lower part of the curve.

On the other hand, the EPBD recast also introduced the nearly-zero energy building (nZEB) concept, which refers to a building with a very high energy performance that uses renewable sources to largely cover the low amount of required energy. The EPBD recast required the Member States to determine a national indicator of primary energy use for nZEBs and to guarantee all new buildings are erected in those terms by December 31, 2020. In Spain, the applicable definition of nZEB is included in the Building Technical Code regulation (CTE DB HE), which was updated in December 2019 [16].

1.2. Literature review

The EPBD recast requests the EU Member States (MS) to periodically calculate and report national cost-optimal levels, in order to compare them with the minimum energy performance requirements set in national building regulations. Since it is not possible to assess the cost-optimality for every single building, EPBD recast demands MS to define at least two RBs for each category of existing buildings. Accordingly, Spain defined two single-family RBs and two multi-family RBs [17]. Besides these reports, delivered by all the European governments, there are also many additional studies which focused on the cost-optimal retrofits of national building stocks [18–21].

Nevertheless, like other national building stocks, the Spanish one is very diverse in terms of building styles and usage. For instance, construction technologies are substantially influenced by local climatic conditions, which also determine the distribution of the final energy consumption into different end-uses. Considering the great heterogeneity of the existing residential buildings, the question is straightforward: is such a small number of RBs actually representative of a national building stock? An elementary assumption for the usefulness of the methodology is the consideration that the results achieved for certain RBs could be reliably extended to the rest of the buildings of the same typology. If the number of RBs is not enough to classify a large building stock into sufficiently uniform and homogeneous building typologies, no extrapolation of the assessment results is possible at the entire building stock level. Thus, some authors have wondered whether the cost-optimal procedure ensures credible results for all the buildings within a specific category [22]. A suitable identification of RBs is therefore fundamental to faithfully reflect an existing building stock and ensure the representativeness of the analysis results.

On the other hand, a substantial number of studies consider only one specific building typology among all the stock. Kuusk et al. assessed 1960–1990 Estonian brick apartment buildings [23]. Corrado et al. analysed an Italian 1946–1960 apartment block [24]. Saglam et al. focused on Turkish high-rise apartment blocks [25]. Niemela et al. addressed 1960–1990 large panel-structured apartment buildings in Finland [26]. Carpino et al. identified cost-optimal energy interventions in Italian social housing of the 1960s–1970s [27]. In addition, many analyses have been performed at a single building level, as a specific case study in which a high quantity of data is available. Kumbaroglu and Madlener assessed an existing building in Aachen [28]. Becchio et al. examined a building in Turin [29]. De Angelis et al. analysed a social housing apartment block in Brescia [30]. Ferrara et al. applied the cost-optimal method to a two-floor residential building in Ambérieu-en-Bugey [31]. Guardigli et al. studied three real buildings in Bologna [11]. La Fleur et al. evaluated a multifamily building in Linköping [32]. However, although the targeted buildings are usually emblematic, none of these approaches permits the entire building stock to be handled as a whole, allowing the economic costs associated with the renovation of each building typology over long-time horizons to be estimated and compared. The latter is fundamental to help decision making in energy policy planning.

Looking at city level, few comprehensive analyses have still been presented from an urban perspective. A limited number of studies assess the urban scale from the perspective of commercial buildings [33], but methods which focus on city-level residential building stocks' retrofitting are scanty. Delmastro et al. described a novel methodology to identify cost-optimal energy retrofits for residential buildings at city level, although the presented case study was limited to a district of Torino [34]. Likewise, Liu et al. investigated the cost-optimal refurbishment strategies for a medieval district in Visby (Sweden) [35]. More recently, Martinez-Garriga et al. presented an interesting case study in Barcelona [36], but it focused on the achievement of carbon neutrality through the implementation of renewable energies, not on cost-optimal levels, and it relied on only three prototypical residential buildings. Ali et al. described a worthwhile method to optimize urban-scale energy refurbishment decision for residential buildings and applied it to the residential building stock in Dublin [37]. Nevertheless, the study relies on the energy consumption data from the Energy Performance Certificates database, which often involves a large gap with the actual energy use, and classifies the different buildings into groups on the basis of their respective energy ratings using simple aggregation, thus limiting the number of building characteristics that can be represented by each building archetype. All in all, there is still a need for further cost-optimal energy refurbishment investigation, from a sufficiently close perspective as to allow the great heterogeneity of an existing large building stock to be entirely captured.

Among the research studies on the energy retrofitting of existing residential buildings, passive strategies are the most commonly addressed measures [7], and there are only a limited number of studies which combine passive strategies, intervention on a building's active systems and renewable energy technologies at the same time [38–40]. Nevertheless, nZEB targets would only be reached by adding renewable energy systems that could, beyond the savings achievable through conventional retrofits, partially cover the remaining energy consumption. Although the current practice is still far from a large-scale transformation of existing buildings into nZEBs, nZEB targets should also be included in the analysis, which allows an assessment of the distance between a cost-optimal performance and the nZEB level, addresses the economic viability of the latter and evaluates suitable measures that could encourage the long-term transition to nZEBs. Therefore, it is clear that a comprehensive approach requires the consideration of the whole energy efficiency range, from minor measures up to major renovations pointing to nZEB levels.

Looking at the whole workflow adopted in different studies [18], identified two main different methods when applying the cost-optimal methodology: simplified and complex. On the one hand, simplified methods [24,41] propose a simple way to approximate the energy demand, such as the Degree Days approach, and assume a certain level of uncertainty in the results. On the other hand, complex methods are based on simulations that account for the dynamics of a building to more accurately estimate its energy needs [42,43].

1.3. Approach

In summary, the authors believe that cost-optimality has scarcely been analysed on a scale which could allow an extensive consideration of the climatic conditions, energy usage and constructive features distinctive to a specific building stock. It demands combining a scale lower than a national stock with an adequate number of RBs. Attempting to address this aspect, this research proposes the application of the cost-optimal methodology at the urban scale, in order to provide a set of tailored technical solutions and identify the suitable range of energy performance that can reasonably be promoted, keeping in mind the specific characteristics of the different types of residential buildings.

The paper describes a comprehensive approach that goes beyond identifying the cost-optimal interventions and also incorporates deeper energy efficiency measures that could allow nZEB levels to be reached. In addition, energy performance assessments are carried out with a dynamic simulation software. The analysis is performed for the city of Bilbao, investigating the most effective energy efficiency measures that could be applied to the existing residential building stock under different scenarios. Nevertheless, similar data are often available, so the approach is easily replicable for any other urban context.

This work aims to support urban energy planning decision-makers in identifying the most suitable long-term policy for the retrofitting of the existing residential stock. The conducted research helps, through the exploration of multiple refurbishment scenarios, to evaluate the cost-effective range of interventions that could be promoted by policy makers.

The outputs of the study allow different types of analyses:

- Diagnosis of the set of optimal technical solutions for the energy retrofitting of the existing building stock.
- Quantification of energy saving and CO_2 emission reduction potential.
- Assessment of the current distance between the cost-optimal performance and nZEB targets.
- Evaluation of the level at which fiscal policies or incentives can be targeted in each building type.

Ultimately, this knowledge will support the implementation of an energy efficiency policy through the identification of energy refurbishments that should be prioritized by economic support schemes, aiming to ensure an optimal exploitation of the public financial resources.

2. Methodology

The comprehensive approach developed in this study is based on the adaptation of the cost-optimal methodology to local conditions. It focuses on space heating and domestic hot water (DHW) end-uses, which represent the greatest share of the residential energy consumption in the climatic zone where the city of Bilbao is located [44]. On the one hand, the cooling demand in such climatic area is negligible. On the other hand, the study excludes the energy savings related to the improvement in domestic appliances and lights, as it is assumed that their replacement would inevitably occur in the coming years.

The PE consumption calculation of the cost-optimal methodology, which is based on [15], excludes the renewable energy produced by a building and only considers the PE associated with the delivered energy. Nevertheless, the maximum PE consumption set by the CTE DB HE does include the PE related to the renewable energy generated on-site. Due to this mismatch, these values are not comparable. Therefore, in order to compare the outputs from the cost-optimal methodology with the PE thresholds set by the Spanish regulation in force, the non-renewable PE (nr-PE) consumption must be used within the calculation of the cost-optimal levels, for which the CTE also defines specific limit values. For the climatic zone where Bilbao is located, the CTE DB HE establishes a nr-PE limit of 32 $kWh/m^2{\cdot}year$ for new – nZEB – buildings.

A flowchart representing the whole process is provided in Fig. 1. The analysed RBs are conformed by the 17 building archetypes constructed by [45]. For each building archetype, two RBs are defined, each one with a different space heating and DHW production system. Thus, the cost-optimal methodology is applied to a total of 34 RBs. The detailed dynamic simulation software Design Builder v.6 [46] is used to calculate the space heating energy demands of the different retrofitted scenarios of RBs. The energy demand calculations are made referring to the same reference occupant behaviour. The computation of final energy use is obtained by applying the mean seasonal efficiency of the corresponding system. Likewise, calculations for renewable energy systems are carried out using System Advisor Model (SAM) v2020.2.29 software [47], whose outcome is subtracted from the final energy consumption before applying the corresponding conversion factors to nr-PE and CO_2 emissions. Finally, GC calculations are performed in an Excel environment, for both end-user's private (microeconomic) and macroeconomic perspectives. In addition, the discounted PBP parameter is also calculated for each package of measures, using the energy savings as a cashflow to recover the initial investment.

Although energy and CO_2 savings, together with associated economic advantages, constitute the core of an energy efficiency policy, energy refurbishment also involves further benefits. Some of them, such as increased thermal comfort and associated human health, could be difficult to monetise. There are also social targets such as the eradication of fuel poverty that can be achieved through energy retrofitting. Furthermore, although in some

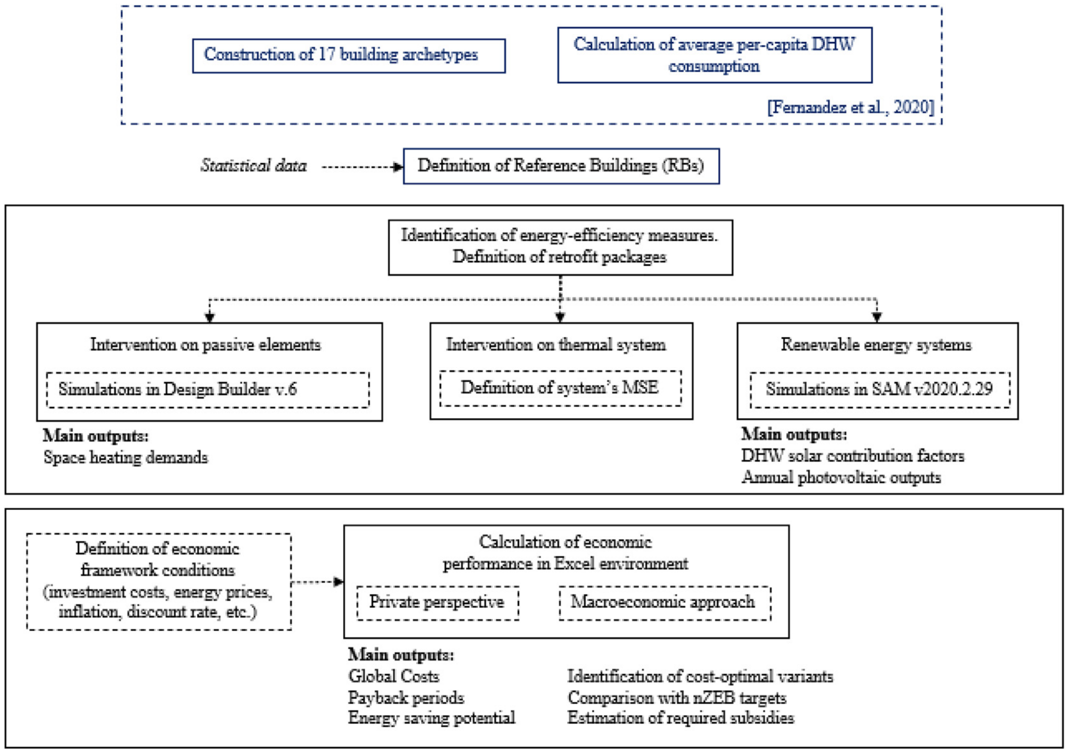

Fig. 1. Summary flowchart of the process.

locations there is not sufficient evidence yet to precisely quantify it, the market value of an energy efficient house undoubtedly increases. Therefore, it must be borne in mind that the present cost-optimal method does not entirely comprise all the benefits of energy retrofitting.

2.1. Definition of reference buildings

2.1.1. Building archetypes

The geometries of RBs are based on the 17 building archetypes constructed in a previous work [45], whose relevant features are summarized in Table 1. Those building archetypes represent 87.90% of the total residential stock of Bilbao. Each building archetype is constituted by a representative dwelling (RD) with specific features, for which Spanish INE statistics are available.

Nevertheless, no active system was defined for each building archetype. Therefore, a specific thermal system must be defined for each building to which the cost-optimal methodology is applied. According to the Basque Energy Agency (EVE) [48], in the Basque Country, it is usual for the DHW system to be associated with the space heating system, so dwellings with either collective or individual heating systems usually use the same scheme to supply DHW. A similar conclusion can be derived from the results of the SPAHOUSEC II project [49] for the Atlantic climatic zone. Thus, the present study assumes that the DHW production system is the same as the heating system in all simulated homes, so it is determined according to the available statistics on the distribution of the latter. On the one hand, the 2011 Population and Housing Census provided the distribution of the heating systems of Bilbao's dwellings into collective systems, individual systems and independent heating devices [50], but did not contain the fuel distribution of such systems anymore. To get it, the previous Census, from 2001, must be explored [51], which distributes space heating fuels as natural gas (hereinafter NG), electricity and oil derivatives (hereinafter gasoil), among other residual fuels such as wood.

By cross-referencing both data, it can be verified that individual NG heating systems are the most usual ones, accounting for 40.9% of the total RDs, followed by electrical systems, which account for another 34.8%, including both heating devices and individual systems. By contrast, collective systems are only substantive in a few representative dwellings, such as RD 6, RD 11, RD 13, RD 14 and RD 17, with a relevant share of gasoil. Based on these results, two RBs, with thermal systems of different mean seasonal efficiencies (MSE), are defined for each of the 17 building archetypes (Fig. 2).

Thus, the cost-optimal methodology is applied to a total of 34 RBs, which account for 76% of the dwellings classified within the building archetypes or, what is the same, 67% of the total residential stock of Bilbao (which is made up of 147,655 dwellings). The representativeness of every RB is provided in Table 2, in which it can be verified that the analysed RBs cover more than half of the RDs in all cases, except for RD 11, RD 14 and RD 17. Hereinafter reported weighted values are based on the representativeness of every RB shown in Table 2.The base cases for RBs are defined as the current "as-built" status of the building, without any maintenance repair. Therefore, no baseline retrofitting level, representing a minimum indispensable level of renovation, is considered.

2.2. DHW base consumption

The DHW demand per inhabitant is estimated based on [45], which described the fuel consumption survey carried out to obtain additional real data for the validation of the models of building archetypes. Besides the information that such survey provided in terms of annual heating energy consumption, it also allows the average per-capita DHW consumption of dwellings in Bilbao to be estimated.

Table 1
Summary of main characteristics of the building archetypes used to define the RBs.

Building archetype	RD	Urban Form	Facade length (m)	Building width (m)	Dwellings area (m^2)	Occupants per dwelling	Dwellings per floor	Over ground floors (excl. ground floor)	Facade U (W/m^2K)	Orientation
Arch. 1	RD 1	Linear block	14.0	10.0	60	2	2	4	1.77	South-west
Arch. 2	RD 2	Linear block	17.0	10.0	75	2	2	4	1.77	South-west
Arch. 3	RD 3	Solid block	10.0	14.0	60	2	2	7	2.04	West
Arch. 4	RD 4	Solid block	14.0	12.1	75	2	2	7	1.77	West
Arch. 5	RD 5	Solid block	17.0	13.5	105	3	2	7	1.77	West
Arch. 6	RD 6	Solid block	20.0	13.0	120	3	2	7	1.77	West
Arch. 7	RD 7	Linear block	20.0	10.0	60	2	3	4	1.26	South-west
Arch. 8	RD 8	Linear block	24.5	10.0	75	2	3	4	1.26	South-west
Arch. 9	RD 9	Linear block	9.1	22.0	60	2	3	6	1.26	South-west
Arch. 10	RD 10	Linear block	11.1	22.0	75	2	3	6	1.38	South-west
Arch. 11	RD 11	Solid block	17.0	19.7	105	2	3	6	1.26	West
Arch. 12	RD 12	Linear block	20.0	10.0	60	2	3	12	1.38	South-west
Arch. 13	RD 13	Linear block	9.4	26.0	75	2	3	12	1.38	South-west
Arch. 14	RD 14	Detached building	18.3	18.3	105	3	3	12	1.38	South
Arch. 15	RD 15	Linear block	20.4	12.0	75	3	3	4	0.63	South-west
Arch. 16	RD 16	Linear block	13.6	18.1	75	3	3	6	0.93	South-west
Arch. 17	RD 17	Linear block	18.0	13.6	75	3	3	13	0.75	South-west

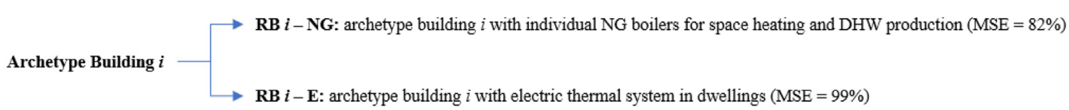

Fig. 2. Scheme of the partition of each building archetype into two different RBs.

Table 2
Representativeness of the defined RBs.

Building archetype	RD	Total number of RDs	RB	Share of RDs covered	RB	Share of RDs covered	Total share of RDs included in RBs
Arch. 1	RD 1	8,642	RB 1 – NG	36.0%	RB 1 – E	59.2%	95.2%
Arch. 2	RD 2	9,402	RB 2 – NG	47.3%	RB 2 – E	47.4%	94.7%
Arch. 3	RD 3	5,496	RB 3 – NG	39.7%	RB 3 – E	53.0%	92.7%
Arch. 4	RD 4	12,371	RB 4 – NG	52.8%	RB 4 – E	38.5%	91.4%
Arch. 5	RD 5	5,054	RB 5 – NG	55.2%	RB 5 – E	24.9%	80.2%
Arch. 6	RD 6	3,551	RB 6 – NG	43.4%	RB 6 – E	11.4%	54.8%
Arch. 7	RD 7	7,080	RB 7 – NG	41.3%	RB 7 – E	55.8%	97.1%
Arch. 8	RD 8	8,206	RB 8 – NG	46.3%	RB 8 – E	40.6%	86.9%
Arch. 9	RD 9	7,527	RB 9 – NG	51.7%	RB 9 – E	38.5%	90.2%
Arch. 10	RD 10	19,089	RB 10 – NG	36.1%	RB 10 – E	33.8%	69.8%
Arch. 11	RD 11	4,165	RB 11 – NG	8.4%	RB 11 – E	14.5%	22.9%
Arch. 12	RD 12	4,278	RB 12 – NG	20.5%	RB 12 – E	68.3%	88.9%
Arch. 13	RD 13	13,486	RB 13 – NG	33.5%	RB 13 – E	19.8%	53.3%
Arch. 14	RD 14	5,296	RB 14 – NG	13.4%	RB 14 – E	11.4%	24.8%
Arch. 15	RD 15	5,894	RB 15 – NG	64.8%	RB 15 – E	20.8%	85.6%
Arch. 16	RD 16	7,284	RB 16 – NG	55.5%	RB 16 – E	18.4%	73.9%
Arch. 17	RD 17	2,969	RB 17 – NG	21.9%	RB 17 – E	10.2%	32.1%

The output of the survey provided a daily average DHW consumption of 40 L at 60 °C per person, which is 44% higher than the per-capita consumption set by the CTE DB HE (28 L). Nevertheless, there are few studies in the literature which collect information on DHW use in households, so it is fair to wonder whether the current national standard is outdated or does not rightly represent the real DHW consumption. In this sense, the results obtained from the conducted survey lie within the order of magnitude of the outcomes from other field studies. For example, [52] provides a per-capita DHW use of 45 L per day at 52 °C in Canada. In Australia,

[53] estimates a 40 °C DHW daily consumption of 62 L per habitant, while [54] provides a mean household daily use of 122 L at 52 °C in the UK. For an average household size of 2.5 occupants, the latter corresponds to 49 L of per-capita consumption.

Furthermore, the outcomes from the survey show an interesting trend of a decreasing per-capita consumption as the dwelling's occupancy increases from 1 to 4 habitants (Fig. 3). This is likely due to an economy of scale effect with DHW conservation from shared dishwasher and cleaning demands. In consequence, the less occupied dwellings show a significantly higher DHW consumption per-capita than the value given by the national standard, as occurs in other studies [55]. On the contrary, as occupancy increases, the mean DHW consumption comes very near to the standard value. Therefore, all the above-stated fits with the obtained average daily DHW consumption of 40 L per person (at 60 °C), which is set for the RBs' base cases. The resulting total daily DHW consumption of each RB is provided in Table 7.

2.3. Energy efficiency measures

There are multiple technical solutions which permit reductions in space heating and DHW energy consumption to be achieved, so the combination of retrofitting alternatives could be very extensive. The EEMs considered in the present analysis do not intend to be exhaustive and neither are they closed, they simply cover a reasonable range of possible EEMs. The selected EEMs are based on currently extended practices, which have been demonstrated to be technically feasible and widely implementable for a large number of buildings.

The chosen EEMs and their abbreviated names are presented in Table 3. In summary, the set of interventions pursues three different objectives: to reduce space heating demand, to supply the required energy more efficiently and to increase the share of the renewable energies in the energy use of the building.

Four outdoor and three indoor thermal insulation levels are evaluated, ranging between preceding CTE DB HE [56] compliance and EnerPHit levels [57]. These insulation levels are applied to the facade and the roof at the same time, ensuring a coherent envelope insulation. Table 4 shows the applied insulation thicknesses for each RB, which differ depending on the original façade type. Since post-1981 buildings are already slightly insulated, only three outdoor insulation levels are evaluated on them. Due to its continuity, the external insulation allows the effect of several thermal bridges to be significantly reduced. After-intervention values of linear transmittance considered in the analysis are obtained from [58].

It has been considered that the benefits of window replacement also include increased airtightness, which is also a common assumption in the literature [39,59]. Therefore, the infiltration rate decreases when window replacement is included within a package of measures. Considering that even the performance of very tight windows could be reduced due to errors in the work execution (e.g., improper mounting of the frame), and aiming to be on the safe side in the calculation of achievable energy savings, a conservative 25% infiltration rate reduction is contemplated in the present analysis, which is in the lower range of the outcomes of several studies performed in the Iberian peninsula [60–63].

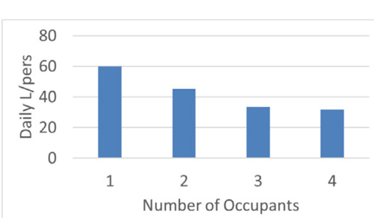

Fig. 3. Mean daily DHW per-capita consumption (60 °C) according to the occupancy of a dwelling.

In order to constitute a package of measures, combinations of passive EEMs were analysed in the first stage. Design Builder v.6 energy simulation software was used to calculate improved space heating energy demands. Table 5 summarizes the simulated combinations of measures, which were reproduced for each façade insulation level $IL_i - x$.

Energy demand outputs were later combined with interventions on the thermal system or the installation of renewable energies, according to Table 6. The effect of the new NG condensing boiler over the existing systems is calculated through the MSE. In total, 464 packages of measures were applied to each RB.

The sizing of the solar water system was defined for specific solar contribution factors, i.e. the fraction of the DHW demand covered by solar thermal energy over the total annual DHW energy demand. The last update of the CTE DB HE regulation increased the minimum solar contribution percentage which is applicable in the climatic zone of Bilbao from 30% to 60%. Both levels of solar contribution factors are defined for each RB. The dimensioning of the system is initially carried out using the F-Chart method [64], which is a semi-empirical method developed to estimate the annual fraction of the total heating load that can be supplied by a solar energy system. Table 7 summarizes the total daily DHW consumption of each RB, as well as the number of collectors and storage tank capacity needed to approximate each solar contribution factor. The orientation of the collectors was assumed to be the buildings' orientation (Table 1).

Calculations are then carried out in hourly time steps using SAM's Solar Water Heating module [65], which models a closed-loop flat plate collector that transfers solar energy from the working fluid to the water storage tank, shaped as a dual-mode model, by a heat exchanger. The DHW draw profile introduced in the simulations, shown in Fig. 4, accommodates common DHW consumption patterns that have been investigated in the literature [66,67] to a real working schedule in the analysed location. The y-axis indicates the share of the daily DHW consumption that is used every hour. There is often an intensive early morning peak, which presumably coincides with the morning showers, and a smaller evening peak, whose timing and width could depend on cultural habits. Thus, showers represent the major DHW consumption [68], which lessens during the mid-afternoon hours. At weekends, the consumption pattern may temporally differ from workdays, and the lower water mains temperature during the winter could drive the occupants to use hot water for some tasks which generally only need cold water, such as hand washing [69]. Nevertheless, no weekly or seasonal variations are introduced in the simulations. Table 7 also summarizes the solar contribution factors obtained with each solar system.

Concerning photovoltaic systems, the CTE DB HE establishes a minimum power of renewable electricity generation that must be installed in certain buildings, depending on their total floor area. In addition, a limit is also set for such minimum installable power, according to the building's roof area. The present study used these calculation methods as the sizing criteria of the analysed photovoltaic systems, which are simulated with SAM's Detailed Photovoltaic Model [70]. Solar energy to electricity conversion efficiencies of the modules are calculated by the CEC Performance Model. Table 7 provides the number of fixed modules and inverter powers modelled, as well as the results of the simulations. A DC/AC ratio of 1.15 is considered. The modules' orientation and tilt match with those for solar thermal collectors in each RB. For both solar thermal collectors and photovoltaic modules, the maximum available space on the roof of each building is assumed to be 50% of the

Table 3
Selected EEMs.

EEM	Description	Name	Main technical features	Investment Cost
Facade thermal insulation	Addition of 4 different levels of external insulation (ETICS), with mineral wool panels fixed by means of mortar to the existing façade and an external waterproof decorative mortar. It includes the required scaffolding.	IL_i – E	Mineral wool (λ = 0.038 W/mK)	59 – 78 €/m²
	Addition of 3 different levels of internal mineral wool insulation comprised of a direct plasterboard cladding. It includes the final painting.	IL_i – I	Mineral wool (λ = 0.038 W/mK)	30 – 56 €/m²
Roof thermal insulation	Dismantling of the existing ceramic tiles layer, installation of the mineral wool panel insulation between wooden strips and placing the waterproofing and the new ceramic tile covering. The insulation thickness is assimilated to the façade's insulation.	RI_i	Mineral wool (λ = 0.038 W/mK)	83 – 98 €/m²
Internal partitions thermal insulation	Addition of 1 cm insulation to the walls in contact with non-heated areas of the building.	PI	EPS (λ = 0.038 W/mK)	30 €/m²
Windows replacement	Installation of 4/6/4 double-glazed windows, PVC frame.	W1	U_{glass} = 3.3 W/m²K ; g = 0.76	267 €/m²
	Installation of 6/16/4 Low-E double-glazed windows, PVC frame.	W2	U_{glass} = 1.4 W/m²K ; g = 0.63	307 €/m²
Heating system improvement	Installation of a new condensing boiler.	CB	25 kW MSE = 86% (HHV basis)	2,000 €
	Installation of a new NG supply line, NG meters, risers, dwellings' NG installation, thermostats, hot water distribution piping and radiators.		–	41 – 52 €/m² *
Solar thermal collectors	Installation of flat plate collectors for DHW production, including support structures, hydraulic connections, heat exchanger, pumps and DHW storage tank, as well as DHW distribution piping that reaches each dwelling. Sized to cover 30% of DHW demand.	DHW 30%	Collector area = 2.3 m²F_R $(\tau\alpha)_n$ = 0.76$F_R U_L$ = 4 W/m²K	1,046 – 1,419 €/m² *
	Installation of flat plate collectors for DHW production, including support structures, hydraulic connections, heat exchanger, pumps and DHW storage tank, as well as DHW distribution piping that reaches each dwelling. Sized to cover 60% of DHW demand.	DHW 60%		688 – 844 €/m² *
Photovoltaic	Installation of a PV system on a sloping roof, constituted by multi-c-Si panels, their supporting structure and inverters The costs also include erection certificates and technical reports needed to legalize the facility.	PV	330 W_p panels (1,95 m²) Panel nominal eff. = 17% Inverter weighted eff. = 97% Degradation = 0.8%/year	205 – 220 €/m² *

Table 4
Applied insulation thicknesses and resulting façade U values per RB.

		RB	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
	Base case	Facade U (W/m²K)	1.77	1.77	2.09	1.77	1.77	1.77	1.26	1.26	1.26	1.38	1.26	1.38	1.38	1.38	0.63	0.93	0.75
External insulation	IL1 – E	Added insul. thick. (cm)	3	3	3	3	3	3	2	2	2	2	2	2	2	2	2	3	2
		Retrofit. facade U (W/m²K)	0.74	0.74	0.78	0.74	0.74	0.74	0.76	0.76	0.76	0.8	0.76	0.8	0.8	0.8	0.47	0.54	0.54
	IL2 – E	Added insul. thick. (cm)	5	5	6	5	5	5	4	4	4	4	4	4	4	4	4	6	5
		Retrofit. facade U (W/m²K)	0.47	0.47	0.48	0.47	0.47	0.47	0.54	0.54	0.54	0.56	0.54	0.56	0.56	0.56	0.38	0.38	0.38
	IL3 – E	Added insul. thick. (cm)	7	7	8	7	7	7	7	7	7	7	7	7	7	7	7	9	8
		Retrofit. facade U (W/m²K)	0.37	0.37	0.38	0.37	0.37	0.37	0.38	0.38	0.38	0.39	0.38	0.39	0.39	0.39	0.29	0.29	0.29
	IL4 – E	Added insul. thick. (cm)	11	11	11	11	11	11	10	10	10	10	10	10	10	10			
		Retrofit. facade U (W/m²K)	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.3	0.29	0.3	0.3	0.3			
Internal insulation	IL1 – I	Added insul. thick. (cm)	3	3	3	3	3	3	2	2	2	2	2	2	2	2			
		Retrofit. facade U (W/m²K)	0.74	0.74	0.78	0.74	0.74	0.74	0.76	0.76	0.76	0.8	0.76	0.8	0.8	0.8			
	IL2 – I	Added insul. thick. (cm)	4	4	4	4	4	4	3	3	3	3	3	3	3	3			
		Retrofit. facade U (W/m²K)	0.62	0.62	0.65	0.62	0.62	0.62	0.63	0.63	0.63	0.66	0.63	0.66	0.66	0.66			
	IL3 – I	Added insul. thick. (cm)	6	6	6	6	6	6	5	5	5	5	5	5	5	5			
		Retrofit. facade U (W/m²K)	0.47	0.47	0.48	0.47	0.47	0.47	0.47	0.47	0.47	0.49	0.47	0.49	0.49	0.49			

total roof area. That this constraint is satisfied is verified in each case.

Finally, the national factors used to convert the calculated final energy consumptions into nr-PE and equivalent CO_2 emissions are presented in Table 8.

2.4. Global cost calculation

The defined calculation period of the present approach is 28 years, as it assumes a timeframe which starts in the year

Table 5
Combinations of passive measures simulated for each insulation level $IL_i - x$.

n°	Facade Insulation	Windows	Roof Insulation	Internal partition Insulation
1		W1		
2		W2		
3	$IL_i - x$			
4	$IL_i - x$	W1		
5	$IL_i - x$	W2		
6	$IL_i - x$		RI_i	
7	$IL_i - x$	W1	RI_i	
8	$IL_i - x$	W2	RI_i	
9	$IL_i - x$	W1	RI_i	PI
10	$IL_i - x$	W2	RI_i	PI

Table 6
Combination of EEMs considered in the packages of measures.

n°	Combinations of interventions
1	Passive measures (P) only
2	P + CB
3	P + DHW 30%
4	P + DHW 60%
5	P + PV
6	P + CB + DHW 30%
7	P + CB + DHW 60%
8	P + CB + PV

2022 and ends in the year 2050, when the European target for the decarbonisation of the economy should have been achieved.

Investment costs of the different EEMs, which can be seen in Table 3, are based on market prices. To this end, the Spanish CYPE database [71] and the Basque Government's *Construction and Urbanization Prices Database* [72] were used, which include material costs and labour costs. On top of that, an additional 5% of overhead costs and another 8% of constructor's profit have been considered. In the private perspective, a reduced VAT of 10% and a municipal tax of 2.5% were also included, with a 60% tax rebate on the latter for the solar systems.

Annual costs considered in this study include maintenance, replacement, and energy costs. In addition, the calculations from the macroeconomic perspective include carbon cost as well. The maintenance cost is estimated as a percentage of the investment cost, according to the values shown in Table 9. No maintenance cost is considered for the new condensing boiler as it is assumed that it would be similar to the cost faced with the current system, so no relevant variation would exist. Table 9 also shows the lifespan considered for each retrofit measure. For elements that have a shorter lifetime than the calculation period, the succeeding replacement cost is assumed to be the same, in real terms, as the investment cost. On the other hand, residual values are taken into consideration, discounted to the beginning of the calculation period, for components whose lifetime exceeds the latter. The residual value is determined by a straight-line depreciation of the initial investment (or replacement cost). No disposal costs are considered.

Focusing on the future development of electricity prices, the authors believe that the grid access fees, necessary to finance the maintenance of the electrical system, will not vary substantially, remaining stable. In addition, considering that the income from electricity taxation represents an essential governmental resource, it is not likely to be reduced either. The price uncertainty range would therefore be subject to the wholesale market price variations, which represents around 30% of the electric bill paid by final consumers [73]. It can be expected that the gradual introduction of renewable energy technologies, as well as the planned improvement of cross-border electrical interconnections, will tend to reduce the influence of NG and coal on the wholesale market clearing prices. Although these investments, required for the decarbonisation of the electrical system, could temporarily increase the price of electricity [74], in the longer term the fuel cost savings, as well renewable technologies costs reduction due to learning

Table 7
Sizing and results of the modelled renewable systems (although summarized in the same table, please note that DHW 30%, DHW 60% and PV EEMs were applied separately, never combined, according to Table 8).

			DHW 30% system			DHW 60% system			PV system			
	Daily DHW use (L)	Tilt (°)	no. of collectors	Storage (L)	Solar contribution factor	No. of collectors	Storage (L)	Solar contribution factor	no. of modules	Inverter (kW)	Annual output (kWh/kW)	PR
RB 1	640	30	3	1,000	0.36	7	1,000	0.62	14	1 × 4.2 kW	1,105	0.78
RB 2	640	30	3	1,000	0.36	7	1,000	0.62	18	1 × 5.2 kW	1,105	0.78
RB 3	1,120	20	5	1,500	0.31	14	1,700	0.58	24	1 × 6.5 kW	985	0.79
RB 4	1,120	20	5	1,500	0.31	14	1,700	0.58	27	1 × 7.9 kW	985	0.79
RB 5	1,680	20	8	2,000	0.33	22	2,600	0.60	36	2 × 5.3 kW	983	0.78
RB 6	1,680	20	8	2,000	0.33	22	2,600	0.60	40	2 × 6 kW	982	0.78
RB 7	960	30	4	1,200	0.33	10	1,200	0.60	22	1 × 6.3 kW	1,105	0.78
RB 8	960	30	4	1,200	0.33	10	1,200	0.60	27	1 × 7.8 kW	1,096	0.77
RB 9	1,440	30	6	1,600	0.33	15	1,800	0.60	32	2 × 4.6 kW	1,092	0.77
RB 10	1,440	30	6	1,600	0.33	15	1,800	0.60	40	2 × 5.6 kW	1,092	0.77
RB 11	1,440	20	6	1,800	0.30	18	2,100	0.58	54	2 × 7.7 kW	981	0.78
RB 12	2,880	30	11	3,000	0.32	30	3,500	0.61	32	2 × 4.6 kW	1,092	0.77
RB 13	2,880	30	11	3,000	0.32	30	3,500	0.61	39	2 × 5.6 kW	1,090	0.77
RB 14	4,320	30	16	4,500	0.32	42	5,000	0.62	54	2 × 7.7 kW	1,166	0.79
RB 15	1,440	30	6	1,600	0.34	15	1,800	0.61	27	1 × 7.8 kW	1,096	0.77
RB 16	2,160	30	9	2,400	0.34	23	2,700	0.62	40	2 × 5.7 kW	1,092	0.77
RB 17	4,680	30	18	5,000	0.32	42	5,200	0.57	40	2 × 5.6 kW	1,092	0.77

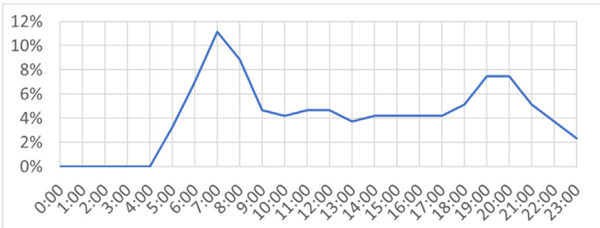

Fig. 4. DHW draw profile introduced in the simulations.

Table 8
National conversion factors.

	kWh_{nr-PE} /kWh_{FE}	kg_{CO2}/ kWh_{FE}
Natural gas	1.19	0.252
Electricity	1.954	0.331

Table 9
Lifespan and maintenance cost of the different EEMs.

	Lifespan	Annual Maintenance Cost
Opaque envelope elements	50	0.0%
Windows	30	0.0%
Condensing boiler	20	0.0%
Cu piping, radiators	30	0.0%
Solar Thermal System	25	0.5%
Photovoltaic system	25	0.5%

curves and the consequent elimination of any subsidy, could lead to an equilibrium of the average electricity price (despite the higher hourly variability) [75,76]. These trends are compiled in the EU 2016 Reference Scenario [77], which is probably the most comprehensive report on EU energy for a time horizon up to 2050. Its findings include that mean electricity prices will increase up to 2030 and remain broadly stable beyond 2030, which is also considered in [17].

Thus, a similar trend in electricity prices is assumed in the present study, which is depicted (in nominal terms) in Fig. 5. It can be observed how the largest share of the price increment belongs to the expected inflation (which is presented below). Such an evolution is applied to an initial energy price of 10c€/kWh in 2022, while the fixed term of the electric bill, which refers to the contracted power in a dwelling, is excluded from the analysis. It is considered that this fixed term will be paid anyhow by every dwelling, as it is necessary for other end-uses such as lighting and domestic appliances regardless of the fuel used for space heating and DHW. In addition to the 21% VAT, the Spanish electrical tax of 5.11% is also included in the microeconomic calculations.

Additionally, the Spanish legal framework that regulates self-consumption energy installations in the residential building sector has recently been updated. A relevant novelty introduced by the Decree 15/2018 [78], which was supplemented by the Decree 244/2019 [79], is the so-called *net balance*, allowing some remuneration for the surplus photovoltaic production exported to the electrical grid. In the free market, the electricity injected to the grid is valued at an hourly price to be agreed between the trading company and the consumer, while in the regulated market it is derived from the hourly results of the daily and intraday wholesale markets, deducting the cost of the network deviations [80]. Based on the wholesale market historical evolution and considering that the network deviations costs are negligible, a price of 5c€/kWh is set for the photovoltaic surplus, which will develop according to the variation of electricity prices.

In each billing period, the financial compensation is made on an hourly basis, balancing the energy consumed from the grid with the injected photovoltaic surpluses. Thus, at the end of every billing period each hour could reflect either a net surplus or a net consumption. Due to the lower photovoltaic surplus selling price in comparison with the electrical energy price borne by households, the more the domestic consumption is accommodated to the timing of the generated energy, the greater the savings would be. In the present study, it is assumed that 30% of the photovoltaic production contributes to decrease the electricity consumed from the grid by the occupants, while the remaining 70% constitutes a surplus injected to the grid at different moments. Nevertheless, the economic benefits from the photovoltaic installation would be further optimised when the self-consumption of the generated photovoltaic production is maximised.

On the other hand, NG prices often show a cyclical pattern, varying significantly on a seasonal basis. During the last decade, the variable term of the Spanish NG bill has fluctuated around a pretty stable average value, without showing a notable increasing trend [81]. At the same time, the fixed term has remained almost flat. In the long-term, a similar price stability is expected: according to [82], NG prices will not follow the strong upward trend of oil price, by decoupling from them and staying at a certain level in real terms. This could be aligned with the existing change of paradigm on the NG pricing mechanism and the decline in importance of oil-indexed prices [74]. Other relevant forecasts provide a very similar NG price trend in the medium-term [83,84]. This price stability could probably be supported by the new liquefied natural gas (LNG) supply [85,86], from which Spain could benefit thanks to its leadership status in LNG infrastructures, as well as through the outcomes of the recent union of the French TRS and PEG gas markets into a single French market, whose greater liquidity and integration with the northern European hubs could also contribute to an increased convergence of the novel Spanish market with the rest of the European hubs [87]. This should compensate for the

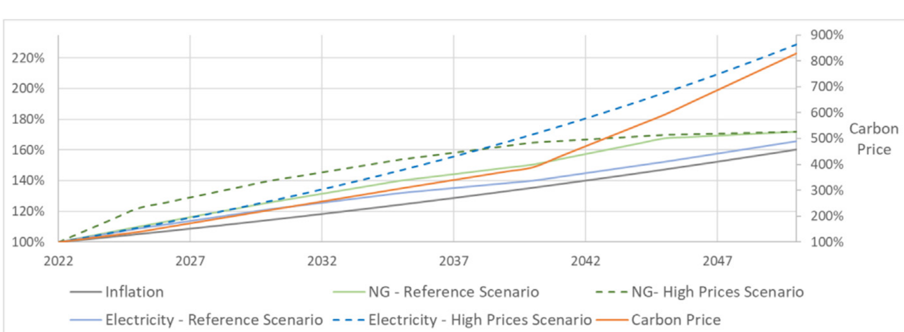

Fig. 5. Defined long-term nominal prices evolution.

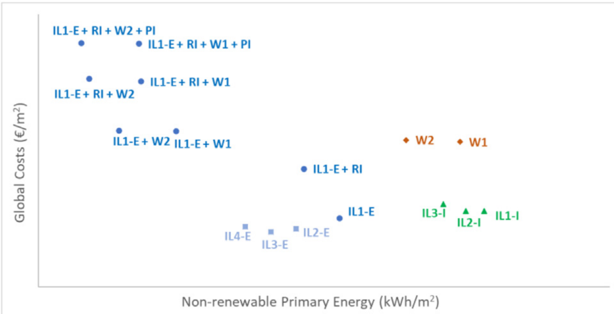

Fig. 6. nr-PE consumption and GC map of the different passive renovation packages.

foreseeable increase of NG consumption for electricity production, which may be driven by the closure of the existing coal plants.

Accordingly, a rather stable NG price increase is assumed, based on the actual prices provided by [82] and applying the estimated inflation rate. Fig. 5 shows the nominal price increase implemented on an initial energy price of 5.3c€/kWh in 2022. The fixed term of the NG bill is kept constant at 0.28 €/day. As with electricity, 21% VAT is also considered in the microeconomic calculations, as well as the Spanish hydrocarbon tax of 0.234c€/kWh.

In order to estimate the future development of the inflation rate, economic data provided by EUROSTAT and the Bank of Spain (BdE) were reviewed. According to the Harmonised Indices of Consumer Prices (HICP) data published in EUROSTAT [88], during the last decade, European inflation was most of the time well below 2%, and the eurozone long-term forecast is that it will remain likewise. It is reasonable to expect that the European Central Bank's (ECB) mandate of controlling the inflation below, but close to, 2% will contribute to keeping the rate around 2% [89]. Nothing seems to foresee an inflationist trend for the next decades in Spain either. The consumer price index has remained below 2% since 2013 [90] and the recent evolution of the industrial producer price index, which measures price changes from the seller's perspective and therefore can serve as an early indicator of inflationary pressures in the economy, does not indicate the latter either. For an expected framework of a low economic growth similar to the last decade, determined by the maturity of European economics and deepened by the shock resulting from the Covid-19 crisis, an average inflation rate of 1.7% is considered within the economic analysis.

Concerning the determination of the discount rate, the following assumptions have been taken: a) it is contextualised to the Spanish framework, b) inflation is included in the discount rate estimation and, c) no alternative investment comparison (opportunity cost or the value of the next best alternative foregone) has been considered. Thus, the cost of borrowing undertaken by Spanish households is analysed from the data published by the BdE [90]. With the help of the monetary policy deployed by the ECB, especially the Asset Purchase Programme (APP) since 2014, such cost of borrowing has experienced a clearly decreasing tendency. The 2019 interest rates, in terms of Narrowly Defined Effective Rate (NDER), reached 1.75% in the lending for house purchase (which also includes home refurbishments) and 7.25% in consumption loans, the 2015–2019 five-year average being 2.28% and 7.80%, respectively. Nevertheless, it should be considered that not every household would ask for finance when facing an investment, as this would depend on its wealth and savings capacity. Overall, an average cost of capital of 4% is finally considered in the private perspective.

From the macroeconomic perspective, the cost of capital undertaken by the Spanish Government is used. Recent data on debt instruments' tenders [91] show that the cost of financing remained at reasonably stable values, even though the Covid-19 crisis has already impacted the Spanish economy. Moreover, the perspective of the major rating agencies on the Spanish Government's credit quality is stable. Looking at Spanish payments for 30 years, it is verified reasonable to consider a macroeconomic discount rate of 1.7%.

Finally, the carbon cost is also considered within the calculations from the macroeconomic perspective. Although Annex II of the Delegated Regulation 244/2012 [14] provided an estimation of long-term Emissions Trading System (ETS) carbon price development, the scene has significantly changed since then. Apart from the changes implemented for the 2013 – 2020 third trading period (a single EU-wide cap on emissions, the decrease of free allocation of allowances, etc.), the creation of the Market Stability Reserve (MSR) [92] and its subsequent strengthened capacity to more rapidly reduce the allowance surplus [93] will certainly contribute to enhancing the increasing trend in the carbon price. To this effect, by modelling the MSR together with a continuously decreasing number of available allowances, [77] provides the most comprehensive estimation of the ETS price. Thus, starting from a price of 18 €/t_{CO2} in 2022, the same price trend (shown in Fig. 5) is assumed within the present analysis.

3. Results

3.1. Energy renovation packages

Comparing the influence of the different passive renovation measures on space heating energy demand, insulating the exterior of the existing facades shows the highest energy saving effect. This effect increases with the façade area exposed to the outside, as well as with worse insulated (older) facades. Depending on the building, an externally insulated façade could reduce the current heating demand by 19–47%. The lower boundary refers to buildings located in solid blocks and constituted by facades with medium transmittance levels, in which achievable demand savings range between 13 and 19%, depending on the added insulation thickness. On the other hand, the upper limit refers to buildings with poorly insulated envelope situated in linear blocks (35–47%), as well as to detached buildings with medium transmittance levels (31–46%). In between, most recent (better insulated) buildings, usually located in linear blocks, show similar savings potential (22–37%) to older poorly insulated buildings placed in solid blocks (24–36%).

On the contrary, due to the associated increment of thermal bridges, the internal façade insulation shows much lower effectiveness, of about half the savings achievable with a similar insulation level placed externally. Nevertheless, the replacement of windows contributes significantly to reducing the space heating energy demand due to the high thermal transmittance and the improvement of air infiltration rate. Its effect ranges from the lowest demand saving of 20%, achieved by simple double-glazed windows in certain buildings, to 36% of saving achievable in some buildings with double-glazed low-E windows. On the other hand, the insulation of the roof and internal partitions shows no relevant impact on space heating demand.

These savings are smoothed in terms of nr-PE when the DHW consumption is also included within the calculation. Fig. 6 maps the change of nr-PE consumption and GC with different passive renovation packages. The comparable nr-PE and GC values of distinct packages of measures may differ depending on the building type, but the qualitative patterns shown in Fig. 6 are in general applicable to all the RBs, regardless of the fuel currently used for thermal uses. Optimum external façade insulation of 7–8 cm is generally observed. It is more pronounced in RBs with electric thermal systems, while the minimum GC area is broader in NG

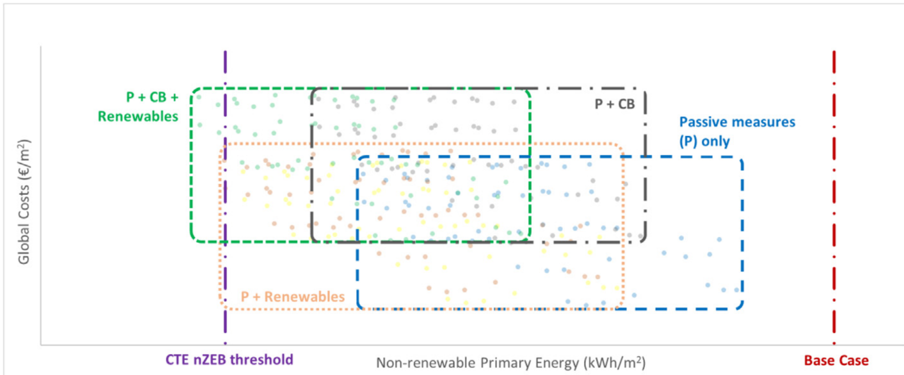

Fig. 7. Qualitative overview of nr-PE and GC private perspective benchmarks in RBs that consume NG.

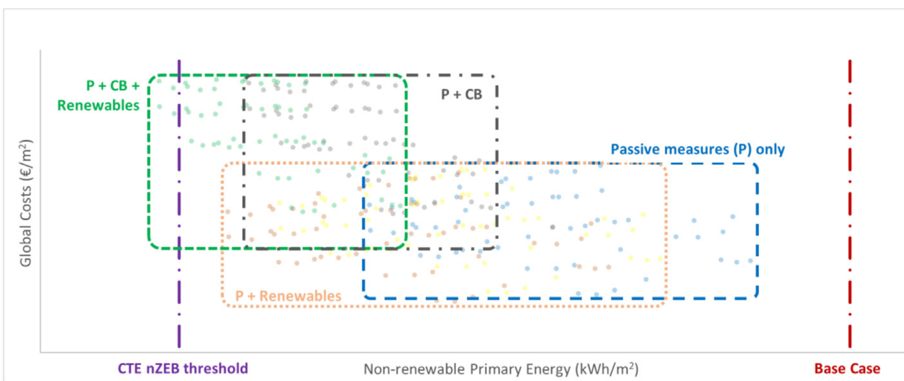

Fig. 8. Qualitative overview of nr-PE and GC private perspective benchmarks in RBs with electrical thermal systems.

consumers, with little GC difference for insulation levels slightly worse or slightly better than the optimum one. In addition, both window types show similar results in terms of GC, being slightly above one or the other depending on the RB. Nevertheless, low-E windows generally show remarkable additional PE savings over the simple double-glazed window. Furthermore, the combination of window replacement with external façade insulation could provide significant supplementary nr-PE savings; although the increment of their GC is also considerable. It would, in any case, be much more effective than the insulation of the roof and internal partitions, which show low improvement in terms of nr-PE with similar GC increments. Nevertheless, it should be noted that the simultaneous addition of double-glazed low-E windows, roof insulation and internal partition insulation to an externally insulated façade could derive in additional nr-PE savings of 28–39%, depending on the RB.

On the other hand, the effects of incorporating interventions on buildings' systems are summarized by Figs. 7 and 8, which provide a qualitative overview of achievable nr-PE and GC private perspective benchmarks in buildings that consume NG and electricity, respectively. It can be observed how the effect of incorporating an efficient condensing boiler reduces as a building is better insulated, in contrast with renewables that have a significant impact on the building nr-PE consumption even in a well-insulated building. Furthermore, it can be verified that, as long as renewable energy sources are not employed, the performance of all the interventions is, in all cases, far from reaching the nZEB performance levels. Moreover, it is worth noting that, in buildings which use electricity for thermal uses, the nZEB consumption levels could only be reached by, in addition to implementing renewable sources, also changing the thermal system to NG.

In general, in buildings which consume electricity for thermal uses, the cost-optimal levels appear to be characterized by a combination of passive measures and solar thermal collectors, which contribute to covering a relevant share of DHW demand that would otherwise have to be satisfied by an expensive electrical consumption. On the contrary, the cost-optimal benchmarks for buildings that are NG consumers are more heterogeneous. In some cases, they are constituted by the insulation of the building's façade only, while in others they are combinations of the latter with renewable systems. Within the latter, solar thermal collectors and photovoltaic systems show a very similar GC to the assumed PV self-utilization scenario. Nevertheless, as the exploitation of PV is optimized, by increasing the self-consumption share (and thus reducing the surplus injected to the grid), the benefits of such a system over the solar thermal collectors would accordingly

Table 10
Key economic assumptions of the GC calculation.

Economic parameters		Starting year prices	
Inflation rate	1.7%	Electrical energy price	10c€/kWh
Private discount rate	4%	Photovoltaic surplus selling price	5c€/kWh
Macroeconomic discount rate	1.7%	NG energy price	5.3c€/kWh
VAT – Residential refurbishment	10%	NG fixed term	0.28 €/day
Municipal tax	2.5%	Carbon price	18 €/t_{CO2}
VAT – Energy	21%		
Electrical tax	5.11%		
Hydrocarbon tax	0.234c€/kWh		

Table 11
Calculated cost-optimal levels in RBs that consume NG.

		REFERENCE SCENARIO				HIGH ENERGY PRICES SCENARIO				BRL BASE CASE SCENARIO			
		nr-PE (kWh/m^2)	nr-PE savings	ΔGC	PBP (years)	nr-PE (kWh/m^2)	nr-PE savings	ΔGC	PBP (years)	nr-PE (kWh/m^2)	nr-PE savings	ΔGC	PBP (years)
Private approach	RB 1-NG	70.56	48.7%	1.1%	–	70.56	48.7%	−2.0%	>28	70.56	48.7%	−13.9%	14.1
	RB 2-NG	62.43	51.5%	0.7%	–	62.43	51.5%	−2.6%	>28	62.43	51.5%	−15.0%	13.9
	RB 3-NG	56.80	40.6%	−3.3%	>28	56.80	40.6%	−5.5%	22.5	56.80	40.6%	−10.4%	21.3
	RB 4-NG	52.55	40.9%	−1.4%	>28	52.55	40.9%	−3.7%	>28	52.55	40.9%	−10.1%	22.2
	RB 5-NG	52.96	38.7%	−1.1%	>28	52.96	38.7%	−3.4%	>28	52.96	38.7%	−9.4%	>28
	RB 6-NG	51.03	39.2%	−0.7%	>28	51.03	39.2%	−3.2%	>28	51.03	39.2%	−9.6%	23.4
	RB 7-NG	66.97	45.0%	7.3%	–	66.97	45.0%	4.2%	–	66.97	45.0%	−9.3%	20.2
	RB 8-NG	60.98	46.9%	7.6%	–	60.98	46.9%	4.2%	–	60.98	46.9%	−10.0%	17.0
	RB 9-NG	54.13	40.4%	3.0%	–	54.13	40.4%	0.5%	–	54.13	40.4%	−6.5%	21.9
	RB 10-NG	47.65	44.1%	2.2%	–	47.65	44.1%	−0.5%	>28	47.65	44.1%	−7.8%	>28
	RB 11-NG	27.28	60.3%	1.3%	–	27.28	60.3%	−2.4%	>28	27.28	60.3%	−5.8%	22.4
	RB 12-NG	69.56	39.3%	3.9%	–	69.56	39.3%	1.4%	–	69.56	39.3%	−12.0%	18.5
	RB 13-NG	52.37	32.1%	0.9%	–	52.37	32.1%	−1.0%	>28	52.37	32.1%	−8.2%	>28
	RB 14-NG	55.68	50.5%	3.7%	–	55.68	50.5%	0.3%	–	55.68	50.5%	−14.1%	15.7
	RB 15-NG	50.07	46.6%	15.4%	–	50.07	46.6%	11.8%	>28	50.07	46.6%	−3.2%	21.4
	RB 16-NG	45.17	48.1%	8.2%	–	45.17	48.1%	5.0%	>28	45.17	48.1%	−4.3%	21.8
	RB 17-NG	44.47	47.7%	12.7%	–	44.47	47.7%	9.2%	>28	44.47	47.7%	−3.9%	16.5
Macro-economic approach	RB 1-NG	67.27	51.1%	−13.5%	23.2	67.27	51.1%	−15.4%	21.7	67.27	51.1%	−21.6%	11.9
	RB 2-NG	62.43	51.5%	−15.3%	22.3	62.43	51.5%	−17.3%	20.7	62.43	51.5%	−23.6%	11.8
	RB 3-NG	40.30	57.9%	−14.6%	20.7	40.30	57.9%	−16.9%	19.2	40.30	57.9%	−18.4%	16.3
	RB 4-NG	34.31	61.4%	−14.9%	21.7	34.31	61.4%	−17.4%	20.2	34.31	61.4%	−19.6%	16.8
	RB 5-NG	32.53	62.4%	−14.2%	22.4	32.53	62.4%	−16.6%	20.8	32.53	62.4%	−18.6%	18.7
	RB 6-NG	32.44	61.3%	−13.6%	22.8	32.44	61.3%	−16.0%	21.3	32.44	61.3%	−18.3%	17.5
	RB 7-NG	65.32	46.3%	−8.2%	>28	65.32	46.3%	−10.1%	24.7	65.32	46.3%	−17.2%	15.9
	RB 8-NG	60.98	46.9%	−8.9%	>28	60.98	46.9%	−11.0%	24.6	60.98	46.9%	−18.4%	13.8
	RB 9-NG	34.67	61.8%	−6.9%	>28	34.67	61.8%	−9.4%	24.4	34.67	61.8%	−12.2%	17.0
	RB 10-NG	30.59	64.1%	−11.6%	23.7	30.59	64.1%	−14.4%	22.0	30.59	64.1%	−17.0%	18.3
	RB 11-NG	27.28	60.3%	−13.8%	21.0	27.28	60.3%	−16.4%	19.5	27.28	60.3%	−17.5%	16.9
	RB 12-NG	53.29	53.5%	−10.2%	>28	53.29	53.5%	−12.3%	24.2	53.29	53.5%	−19.0%	14.9
	RB 13-NG	24.91	67.7%	−9.3%	>28	24.91	67.7%	−12.0%	24.2	24.91	67.7%	−14.3%	19.9
	RB 14-NG	52.88	53.0%	−13.6%	24.7	52.88	53.0%	−15.7%	23.2	52.88	53.0%	−23.1%	13.1
	RB 15-NG	50.07	46.6%	−3.6%	>28	50.07	46.6%	−5.7%	>28	50.07	46.6%	−13.5%	18.1
	RB 16-NG	45.17	48.1%	−7.9%	24.7	45.17	48.1%	−9.9%	23.1	45.17	48.1%	−14.6%	17.4
	RB 17-NG	44.47	47.7%	−5.2%	>28	44.47	47.7%	−7.3%	>28	44.47	47.7%	−14.1%	17.7

increase. The assumption that 30% of the photovoltaic production is self-consumed leaved room for further optimization.

3.2. Cost-Optimal levels

The outcomes of the calculation provide weighted cost-optimal levels of 59.01 kWh/m^2 and 50.34 kWh/m^2 in private and macroeconomic approaches respectively, which represent approximately half the current nr-PE consumption (116.10 kWh/m^2) for thermal end-uses. These outcomes do not deviate excessively from the results of the governmental calculations at national level [17] which, according to the multi-family buildings distribution shown in the report, average optimal nr-PE consumptions of 68.1 kWh/m^2 and 39.0 kWh/m^2 in private (with a 10% discount rate) and macro (with a 4% discount rate) perspectives.

Nevertheless, the results of this study reveal that the cost-optimal nr-PE consumption varies significantly between the different RBs (Tables 11 and 12). In the private perspective, it ranges widely from 27.28 kWh/m^2 to 70.56 kWh/m^2 in RBs which consume NG and from 38.99 kWh/m^2 to 91.49 kWh/m^2 in RBs with electric thermal systems. It is worth noting that in a few cases the cost-optimal level even corresponds or approximates to the nZEB range. Therefore, despite the same climatic conditions and similar constructive solutions, it is verified that the different geometrical features, the building's contiguity level and the fuel used for thermal uses can make the cost-optimal level deviate considerably, even in the same location. It ratifies the need for a close focus when determining the cost-optimal levels of existing building stocks.

Considering the number of existing dwellings within each RB, the private cost-optimal levels would constitute a total nr-PE saving of 48.4% over the current consumption of the stock (Table 13). Nevertheless, those savings differ depending on the economic perspective and the fuel that is currently used for space heating and DHW production. Fig. 9 shows the distribution of the nr-PE savings obtained with identified cost-optimal variants. From the private perspective, the average PE savings achievable with optimal variants range from 44% in RBs that currently use NG to 54% in RBs that consume electricity. In the macroeconomic perspective, on the other hand, the achievable nr-PE savings are similar for RBs that use NG and electricity (56% and 57%, respectively), being higher in both cases than the savings of the private perspective.

Thus, the gap between the cost optimal levels of private and macroeconomic approaches is noteworthy in the case of RBs that use NG, which indicates that financial support may be needed to make certain energy efficiency investments economically interesting for the users.

In fact, it should be noted that the GC of the private optimal variants in RBs that use NG are very similar to the GC of the base cases. In many RBs, almost all post-1960 buildings, the former is even slightly higher than the latter, which means that acting on energy efficiency could turn out to be counterproductive from an economic point of view. This means that the GC of private optimal variants can be, on average, 3.3% higher than the base cases of RBs that consume NG for thermal uses. On the other hand, in the case of RBs that consume electricity for space heating, this only occurs, exceptionally, with RB 15 (as a post-1981 building, it is among the best insulated ones in the existing stock, so it is reasonable to show

Table 12
Calculated cost-optimal levels in RBs with electrical thermal systems.

		REFERENCE SCENARIO				HIGH ENERGY PRICES SCENARIO				BRL BASE CASE SCENARIO			
		nr-PE (kWh/m^2)	nr-PE savings	ΔGC	PBP (years)	nr-PE (kWh/m^2)	nr-PE savings	ΔGC	PBP (years)	nr-PE (kWh/m^2)	nr-PE savings	ΔGC	PBP (years)
Private approach	RB 1-E	91.49	51.1%	−10.3%	22.7	91.49	51.1%	−15.2%	20.3	91.49	51.1%	−22.0%	12.0
	RB 2-E	87.80	49.9%	−10.5%	22.7	87.80	49.9%	−15.2%	20.3	87.80	49.9%	−22.5%	11.4
	RB 3-E	48.83	62.5%	−10.9%	21.9	48.83	62.5%	−17.1%	19.7	48.83	62.5%	−16.9%	17.3
	RB 4-E	44.34	63.4%	−10.4%	22.7	44.34	63.4%	−16.7%	20.3	44.34	63.4%	−17.5%	17.3
	RB 5-E	44.24	62.4%	−12.0%	21.5	44.24	62.4%	−18.1%	19.4	44.24	62.4%	−18.3%	16.7
	RB 6-E	44.12	61.3%	−10.9%	22.2	44.12	61.3%	−17.0%	19.9	44.12	61.3%	−17.7%	16.9
	RB 7-E	88.84	46.3%	−4.1%	>28	88.84	46.3%	−9.2%	23.7	88.84	46.3%	−17.4%	13.6
	RB 8-E	86.29	44.7%	−3.9%	>28	86.29	44.7%	−8.8%	24.0	86.29	44.7%	−17.7%	13.1
	RB 9-E	70.23	43.2%	−6.4%	23.0	47.16	61.8%	−10.4%	23.3	70.23	43.2%	−14.7%	14.6
	RB 10-E	44.56	61.6%	−8.8%	23.7	44.56	61.6%	−15.2%	21.1	44.56	61.6%	−17.0%	17.3
	RB 11-E	44.16	52.8%	−10.0%	21.5	44.16	52.8%	−15.2%	19.4	44.16	52.8%	−15.6%	16.6
	RB 12-E	76.48	50.9%	−7.9%	24.4	76.48	50.9%	−13.1%	21.6	76.48	50.9%	−20.7%	12.4
	RB 13-E	38.99	62.8%	−8.0%	23.9	38.99	62.8%	−14.6%	21.2	38.99	62.8%	−15.6%	20.9
	RB 14-E	75.73	50.5%	−10.5%	22.9	75.73	50.5%	−15.4%	20.5	75.73	50.5%	−23.6%	10.7
	RB 15-E	68.09	46.6%	1.1%	>28	68.09	46.6%	−4.6%	>28	68.09	46.6%	−13.6%	15.1
	RB 16-E	61.44	48.1%	−5.6%	24.6	61.44	48.1%	−10.7%	21.7	61.44	48.1%	−15.5%	15.0
	RB 17-E	60.48	47.7%	−1.4%	>28	60.48	47.7%	−7.0%	24.7	60.48	47.7%	−14.6%	15.3
Macro-economic approach	RB 1-E	55.07	70.6%	−22.7%	21.6	55.07	70.6%	−28.4%	20.0	55.07	70.6%	−29.2%	10.8
	RB 2-E	87.80	49.9%	−23.7%	17.9	41.00	76.6%	−27.3%	22.1	87.80	49.9%	−30.3%	10.4
	RB 3-E	48.83	62.5%	−25.7%	17.5	42.04	67.7%	−29.8%	18.5	48.83	62.5%	−28.8%	14.7
	RB 4-E	44.34	63.3%	−26.0%	17.9	37.71	68.8%	−30.2%	18.8	44.34	63.3%	−29.8%	14.6
	RB 5-E	44.24	62.4%	−26.7%	17.2	38.07	67.6%	−30.5%	18.4	44.24	62.4%	−30.1%	14.2
	RB 6-E	44.12	61.3%	−25.9%	17.6	37.88	66.8%	−29.7%	18.7	44.12	61.3%	−29.4%	14.4
	RB 7-E	88.84	46.3%	−18.0%	20.4	43.78	73.5%	−21.2%	23.8	88.84	46.3%	−25.4%	12.1
	RB 8-E	86.29	44.7%	−17.6%	20.7	41.19	73.6%	−19.4%	24.6	86.29	44.7%	−25.3%	11.7
	RB 9-E	47.16	61.8%	−20.7%	20.2	39.64	67.9%	−25.4%	20.7	47.16	61.8%	−25.0%	16.6
	RB 10-E	44.56	61.6%	−24.7%	18.5	37.25	67.9%	−28.9%	19.5	44.56	61.6%	−29.0%	14.6
	RB 11-E	44.16	52.8%	−22.5%	17.2	37.13	60.3%	−25.7%	19.5	44.16	52.8%	−25.5%	14.2
	RB 12-E	72.47	53.5%	−21.8%	20.1	37.75	75.8%	−26.1%	21.7	72.47	53.5%	−28.8%	11.2
	RB 13-E	33.88	67.7%	−24.2%	20.0	33.88	67.7%	−29.4%	18.7	33.88	67.7%	−28.2%	16.8
	RB 14-E	71.92	53.0%	−23.8%	19.2	71.92	53.0%	−27.3%	18.0	71.92	53.0%	−31.0%	9.8
	RB 15-E	68.09	46.6%	−14.0%	22.5	68.09	46.6%	−17.9%	20.7	68.09	46.6%	−22.1%	13.7
	RB 16-E	61.44	48.1%	−18.3%	19.1	44.33	62.6%	−21.2%	21.0	61.44	48.1%	−23.8%	13.1
	RB 17-E	60.48	47.7%	−15.8%	21.2	60.48	47.7%	−19.6%	19.7	60.48	47.7%	−23.1%	13.3

less room for energy efficiency improvement). These results suggest that the combination of Bilbao's mild winters (in comparison with the more severe climates of other inland regions) and the financial costs that are needed to afford the investments, together with the low NG prices (in comparison with electricity), could make the economic benefit of acting on energy efficiency worthless.

As an example, Fig. 10 shows the GC distribution of certain variants corresponding to RBs 14. In RB14 – NG, it is verified that the cost-optimal variant implies a higher GC than the base case, so the energy cost reduction obtained does not overcome the required investment cost. In contrast, higher electricity prices push up the energy costs of RB14 – E, leading the cost-optimal variants to involve a GC saving over the base case. This GC saving, is in any case, limited among the different RBs with electric thermal systems: the mean GC saving of private cost-optimal variants is 7.7%.

Furthermore, in RBs which consume NG, the private GC curve is mainly flat in a wide range around the cost-optimal variant, in which the GC deviation, either above or below the base case GC, is low. Fig. 11 shows the curve obtained for RB 1 as an example. It means that, without requiring excessive public support, signifi-

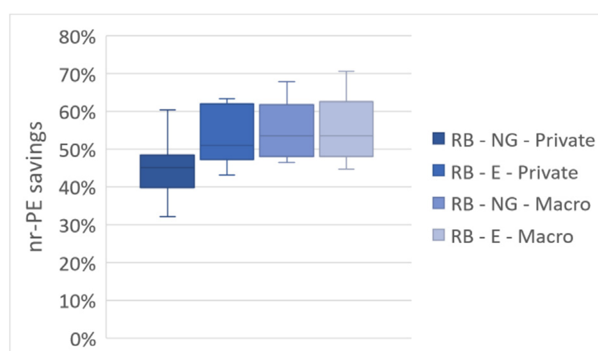

Fig. 9. Distribution of nr-PE savings obtained with identified cost-optimal variants.

Table 13
Weighted averages for cost-optimal levels obtained under the different scenarios.

		Reference Scenario	High Energy Prices Scenario	BRL Base Case Scenario
Private approach	nr-PE savings	48.4%	48.9%	48.4%
	GHG savings	46.7%	47.1%	46.7%
	GC savings	1.97%	6.0%	13.2%
Macroeconomic approach	nr-PE savings	57.1%	62.4%	57.1%
	GHG savings	56.2%	61.2%	56.2%
	GC savings	16.2%	19.3%	22.3%

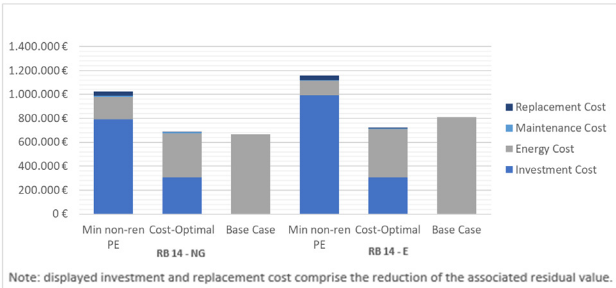

Fig. 10. GC distribution of certain variants corresponding to RB 14 – NG and RB 14 – E. Time horizon: 28 years.

cant nr-PE savings could be fostered by making the intervention variants located at the left edge of the flat curve marginally attractive to the users. In any case, for the sake of establishing the cost-optimal level, the Delegated Regulation stipulates that if several variants have a similar GC, the variant with the lowest primary use should be selected, as has been done in the present analysis.

Conversely, within the same private perspective, the obtained clouds of points and derived cost curves corresponding to the RBs that use electricity for space heating show an appreciably different shape. In general, a higher number of variants fall below the GC of the base case, the curve is slightly more inclined along the right side of the cost-optimal area and the latter locates farther from the base case point, meaning that it involves a higher nr-PE saving. Those aspects can be verified in Fig. 12, which shows the results of RB 5-E.

Nevertheless, the PBPs corresponding to the cost-optimal variants are still excessive, being above 21 years for all the RBs. In some cases, they are even higher than the 28 years' time period considered within the application of the cost-optimal methodology, meaning that it is the obtained residual value at the end of the said period which makes some cost-optimal variants constitute a lower GC than the associated base cases.

The darker points in Fig. 12 refer to the variants that involve a substitution of the existing electric heating systems by a complete installation consisting of a new NG supply, condensing boiler and radiator system. This potential new installation makes the GC of related variants increase in a way that allows, for the majority of the RBs, them to be graphically distinguished from the other variants. Nevertheless, it is worth noting that only with this new NG installation could the CTE's nZEB consumption levels be reached by these buildings.

On the other hand, the macroeconomic perspective involves different cost-optimal variants in most of the RBs which consume NG. These variants entail lower nr-PE consumptions than in the private approach. In this macro approach, the cost-optimal area is more pronounced, implying an appreciable GC saving over the base case in all RBs, and the trend of the almost flat GC curve does not occur anymore. By contrast, in the RBs that use electricity for space heating, the macroeconomic perspective is more aligned with the private approach, providing in general the same cost-optimal results. Nevertheless, the macro approach gives in all cases lower – although still high – PBPs: above 21 and 17 years in RBs which consume NG and electricity respectively. In summary, the weighted nr-PE and GC saving averages increase to 57.1% and 16.23%, respectively, with cost-optimal variants obtained in the macroeconomic perspective (Table 13).

3.3. nZEB refurbishment levels

The maximum achievable nr-PE savings through energy retrofitting fall within the order of magnitude of the European energy consumption reduction target for 2050. In RBs that use NG as heating fuel, an average saving of 76% over the base cases could be reached (ranging from 69% to 84%, depending on the RB). Such a potential PE saving rises to 82% in RBs with electric heating systems (varying between 77% and 88%, depending on the RB). These results are depicted in Fig. 13, in which the size of the circles refers to the existing amount of each type of RB. All RBs would be able to meet the threshold value set by the CTE DB HE for new buildings, meaning that in all the cases, the existing buildings could, by means of a deep energy refurbishment, become nZEB as per the Spanish definition.

Nevertheless, the necessary private GC increase over the private base cases would be huge: an additional economic effort of around 54% would be needed, with a very similar average for RBs that use NG and electricity. By contrast, it is worth noting that this weighted GC increase is significantly lower in the macro assessment, i.e., 15%. Therefore, there is a relevant gap in the economic impact of deep energy interventions between both perspectives. From a macroeconomic perspective, there are even several RBs that require a small GC increase (although by concentrating and advancing it as an upfront investment) to become nZEB.

However, the effectiveness of such an economic effort would be unequal in terms of the obtained nr-PE unit savings per euro invested. Fig. 14 shows the necessary GC increase per saved nr-PE unit, depicted against the achievable nr-PE savings per retrofitted dwelling. The obtained "euro per saved kilowatt-hour" ratios

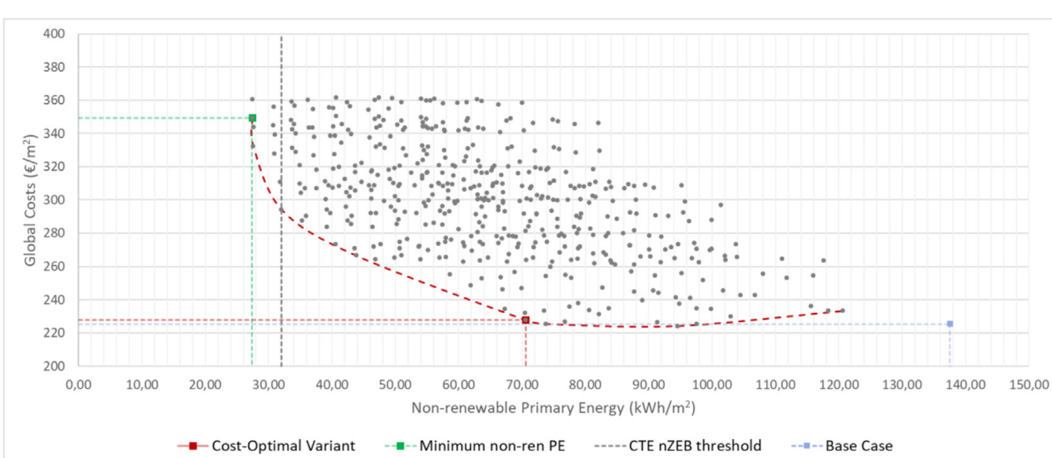

Fig. 11. GC curve obtained for RB 1 – NG.

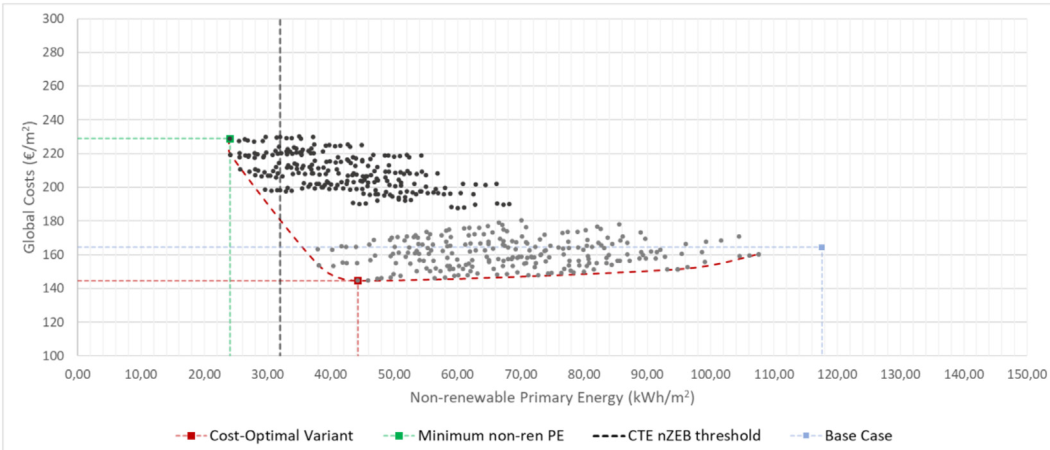

Fig. 12. GC curve obtained for RB 5 – E.

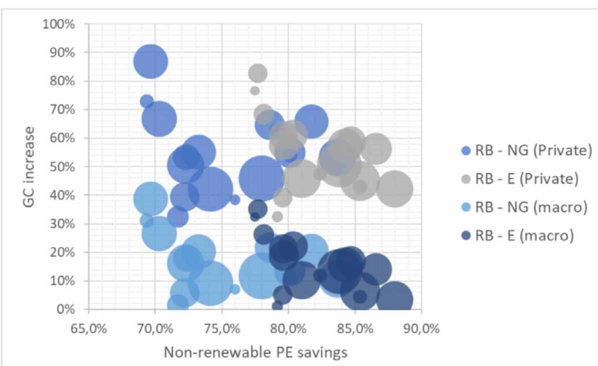

Fig. 13. Maximum achievable nr-PE savings through energy retrofitting, mapped against the associated GC increase.

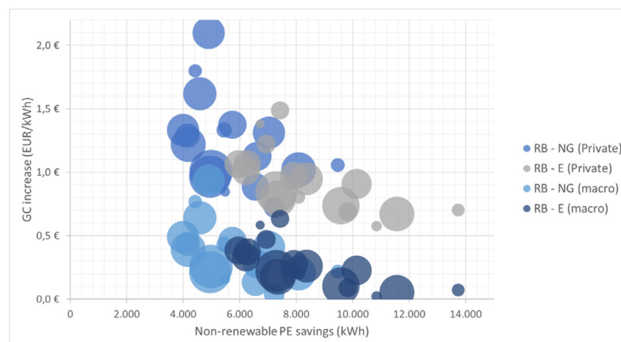

Fig. 14. Required GC increase per saved nr-PE unit, depicted against the nr-PE savings per retrofitted dwelling.

range between 2.1 and 93.6 cents in the macroeconomic approach, with the oldest and most recent RBs in the lower and upper ranges respectively. On the other hand, the lowest ratio obtained in the private assessment is above 50 cents, while the current costs of electricity or NG per kilowatt-hour of consumed nr-PE can be estimated as 6.5 and 5.6 cents, respectively, i.e., almost ten times lower.

These results could inform public support schemes that may be required to encourage an energy efficiency improvement level actually aligned with the long-term energy saving objectives. However, it is relevant to highlight that, even from a macroeconomic perspective, the achievement of nZEB refurbishment levels would not be cost-effective within the assumed reference scenario. The framework that could eventually make these deep interventions profitable would necessarily involve a reduction in investment costs (due to learning curves and economies of scale), higher than expected energy commodity prices and lower financing interests at the same time.

3.4. High energy prices scenario

A sensitivity analysis has been carried out to investigate the influence of the evolution of the NG and electricity prices on the results. Thus, an alternative scenario with higher energy prices is defined, while the rest of the model parameters remain fixed.

According to [73], the average annual electricity price increase in Spain along the 2011–2018 period was 3.2%. Nevertheless, the mean annual increment that arises from the reference scenario is 1.82%. Therefore, a constant annual increase of 3% is defined in the alternative scenario. Concerning GN, the projection to 2030 considered in the Spanish National Energy and Climate Plan (NECP) [75] involves a substantially greater commodity cost evolution than the rest of the relevant analyses considered in the determination of the reference scenario. Although such a huge price increase seems not to be supported by relevant market analysts [94], an intermediate NG price evolution, between the reference scenario and the NECP's assumption, is defined in the alternative scenario. Both alternative commodity price evolutions are presented in Fig. 5.

The resulting cost-optimal levels achieved for RBs which use NG for thermal uses are the same as in the reference scenario in private and macro approaches (Table 11), so the gap between both perspectives persists. At best, the PBPs are modestly improved (by approximately 1.5 years), but certain RBs remain in which even acting on cost-optimal levels, they would continue to be cost-ineffective. Therefore, the results show a limited effect of the higher NG price.

In RBs that are electricity consumers, the private cost-optimal levels follow the same pattern and it is only changed in RB9 – E (Table 12). The PBPs are in general slightly improved by 2–3 years. Nevertheless, the relevant impact is on macroeconomic cost-optimal levels, which are generally shifted to lower nr-PE consumption ranges. Therefore, while the private and macroeconomic cost-optimal levels were in general aligned in the reference scenario, a notable gap emerges (similar to that of RBs which use NG) between both perspectives in the alternative scenario.

3.5. Base refurbishment level scenario

In the reference scenario, the base cases represent the RBs without any kind of retrofitting. Nevertheless, there may be circumstances in which an old building faces a necessary and unavoidable maintenance intervention. In such a situation, the economic framework to evaluate the cost-effectiveness of substitute EEMs changes. Thus, a baseline retrofitting level (BRL) of intervention is defined in RBs' base cases, which represent the minimum level of façade renovation applicable to a building in need of restoration. A very commonly used refurbishment method of external walls in Spain is selected to be considered as an inevitable expense in these base cases, consisting of an exterior covering of 15 mm of single-layer mortar. Although its impermeable and breathable properties provide good hygrothermal façade behaviour, it does not improve the thermal insulation of the façade. A cost of 35 €/m^2 is considered for this BRL.

In this scenario, the nr-PE consumption and GC of all the variants remain the same as in the reference scenario (it only changes the GC of the base case), so the GC graph does not change and the cost-optimal levels are those of the reference scenario (Tables 12 and 13). Nevertheless, the cost-effectiveness evaluation of the cost-optimal levels is modified, due to the increase in the expense of the base cases, and significant PBP reductions are observed over the reference scenario. In this case, cost-optimal levels are highly cost-effective in all the RBs, with private PBPs between 14 and 23 years for NG consumers (12–18 years in the macro approach) and 11–17 years for RBs that consume electricity for thermal uses (10–15 years in the macro approach). It is therefore verified that the profitability of more profound energy refurbishments is highly suggestive in a context where a building requires a façade rehabilitation.

3.6. Subsidies

The results presented in the previous sections constitute a refurbishment scenario where noticeable gaps exist between macroeconomic and private economic outcomes, some interventions are not cost-effective for the private investor and, when profitable, the PBPs of such investments prove to be excessively high. All this demonstrates the necessity for public aid to make energy retrofitting sufficiently attractive to the public.

Fig. 15 depicts the weighted average of the investment grant required for acting on the calculated macroeconomic cost-optimal levels and obtaining distinct target private PBPs. An iterative process has been carried out by increasing the level of subsidies and checking at each step if the desired PBP is achieved. The introduction of each degree of subsidy would obviously make the optimal level of the private approach vary continuously, so the present analysis focuses on the obtained macroeconomic cost-optimal ranges, which are fixed. The calculation has been done twice for every RB, one for the reference financing rate of 4% and one for a reduced – soft loan – rate of 2%.

Although ideally a near 10-year PBP should be intended to make an investment sufficiently attractive to a domestic investor, the results suggest that, in the defined reference scenario, the fastest investment return that could be extensively promoted would have to be limited to around 15 years. The mean public grants that this target PBP would require are already huge, but pointing closer to 10-year PBPs makes the covered investment shares escalate steeply.

On the other hand, the results show the value of combining direct grants with low-interest loans. The contribution of the latter is demonstrated as being essential to reduce the outlay of direct subsidies to a range comparable to previous public support programs, in which the aid could typically reach up to 30–35% of the investment [95]. With a finance rate of 2%, the weighted average subsidy required in the reference scenario is 38%.

Nevertheless, significant differences exist between the public grant required by each RB to ensure a PBP below 15 years for their cost-optimal level intervention. Fig. 16 maps the share of subsidy needed by each RB, assuming a financing rate of 2%, against the nr-PE savings that such energy retrofitting would imply. The size of the circles refers to the existing number of dwellings.

It is verified that the need for public support of RBs with electric thermal systems is notably lower than in RBs which consume NG. While in the former such support falls within usual subsidized rates, in the latter it escalates to an average of 48% of the investment. The lower NG price in comparison with electricity (currently the variable – energy – term of the bill is approximately half for NG in relation to electricity as shown in Table 10), leads to lower annual energy expenses in RBs which consume NG for thermal end-uses in comparison with RBs with electric thermal systems. Consequently, the economic savings associated with a given energy consumption reduction are lower for NG consumers, which leads to larger PBPs for similar energy efficiency investments. The main consequence is the need for higher subsidies to make the energy efficiency investments attractive enough for the end-user.

The defined high prices scenario shows a similar subsidy distribution for 15 years PBP, as can be observed in Fig. 17. Although the macroeconomic optimums of this scenario involve higher energy savings than in the reference scenario (Table 13), the required subsidies are similar in both scenarios. In contrast, the required support in the BRL scenario is notably reduced, with several RBs which do not demand any public aid to ensure a PBP of 15 years.

Aiming to estimate the additional governmental support that may be needed for more profound interventions, a deeper level of energy refurbishment is selected for each RB. While still being within or near nZEB range, this represents a suitable compromise between savings and costs. The required subsidy distribution to achieve such levels of interventions, with which a weighted nr-PE average consumption of 36.0 kWh/m^2 would be obtained, is shown in Fig. 17 for each of the three scenarios.

It is worth noting that, in the high prices scenario, the mean subsidy (43%) gets close to the average aid needed for cost-optimal levels in the reference and high prices scenarios. This means that the energy commodities cost could have a significant impact on making the nZEB level interventions subsidizable. On the other hand, the latter would be ensured, at a reasonable mean public aid of 25%, in buildings in need of restoration.

Nevertheless, if the main target is to reduce GHG emissions caused by domestic energy consumption, it may not be worthwhile promoting deep – nZEB level – interventions in RBs with electric thermal systems. On the one hand, the GHG emission savings that would be achieved with macroeconomic cost-optimal interventions reach a worthy 56.2%. On the other hand, the planned power

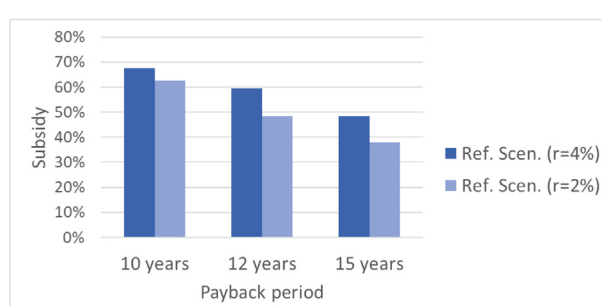

Fig. 15. Weighted average subsidies required to ensure distinct private PBPs macroeconomic cost-optimal levels.

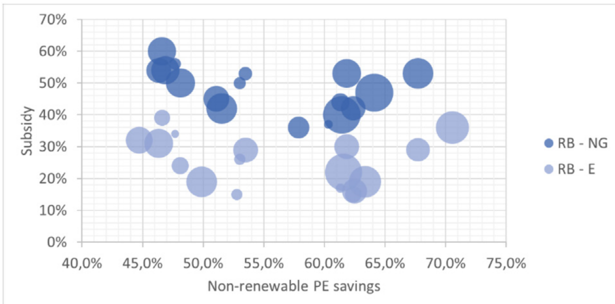

Fig. 16. Subsidies needed in the private approach with a financing rate of 2% to ensure 15 years PBP of cost-optimal interventions.

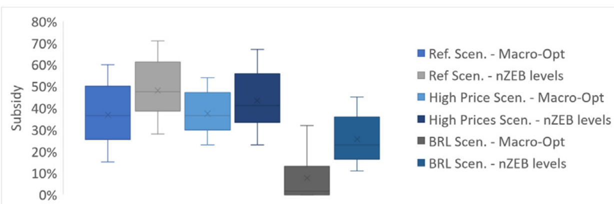

Fig. 17. Grants distribution for a 15 years PBP.

grid decarbonization would itself minimize the emissions associated with the remaining PE consumption. Based on the Spanish electricity mix depicted by [75] for 2030, a conversion factor of 0.08 kg_{CO2}/ kWh_{FE} can be estimated for consumed domestic electricity, which constitutes a quarter of the present factor. Therefore, this driver could align a cost-optimal intervention with the long-term emission reduction target of 80–90%.

4. Conclusions

Economic evaluations of EEMs are often based on a single building or type of building, which cannot be scaled-up to an existing building stock. In other cases, the limited number of RBs defined to represent a large building stock hinders the capture of the existing great heterogeneity into sufficiently homogeneous building typologies to allow a reliable extrapolation of the assessment results. The present paper proposes the application of the cost-optimal approach at city level and investigates the cost-optimal levels for the residential building stock of Bilbao under different scenarios. The vast portfolio of defined RBs assures a tailored characterization of the residential building stock which allows the suitable range of energy performance that is reasonable to promote for different types of buildings to be identified.

The approach incorporates proven EEMs in the form of envelope improvements, active system retrofits and renewable use. Optimum external façade insulation of 7–8 cm is observed. In general, the cost-optimal levels of buildings with electric thermal systems appear to be made up of a combination of both façade external insulation and solar thermal collectors sized to cover 60% of DHW demand. On the other hand, the cost-optimal benchmarks for buildings that are NG consumers are more heterogeneous: in some cases, they are made up of the external insulation of the building's façade only, while in others they are combinations of the latter with either solar thermal collectors or photovoltaic systems. The latter show a similar result in the defined reference scenario, but as the exploitation of PV is optimized, the benefits of such a system over the solar thermal collectors would accordingly increase.

The outcomes of the calculation provide weighted cost-optimal levels of 59.01 kWh/m^2 and 50.34 kWh/m^2 in private and macroeconomic approaches respectively, which represent half of the current nr-PE consumption for thermal end-uses (116.10 kWh/m^2). Nevertheless, the results reveal that the cost-optimal nr-PE consumption varies significantly between the different RBs, due to the distinct geometrical characteristics, the level of the building's contiguity and the fuel used for thermal uses. It demonstrates the need for a close focus when determining the cost-optimal levels of the existing building stocks, as those levels could guide the energy efficiency policy and related economic instruments. Even more so considering that, in decentralized countries like Spain, the latter are often largely set (or complemented) domestically by regional authorities.

In fact, the gap between the cost-optimal levels of private and macroeconomic approaches, which is limited to the RBs that use NG in the reference scenario and extends to the RBs with an electric system in the high energy prices scenario, indicates that public support may be needed to realign the private investor interest with society's.

Furthermore, financial support is proven to be essential to reduce the obtained long private PBPs, which are above 21 years for all cost-optimal levels of the RBs, and thus make such energy retrofitting sufficiently attractive for the domestic user. In most of the RBs that use NG, the GC of the private optimal variants are very similar to the GC of the base cases (or even slightly higher), which suggests that the combination of the mild climate of Bilbao, the financial costs needed to afford the investments and low NG prices prevent action on the energy efficiency of a building from being economically interesting for a private investor.

Nevertheless, in certain situations where an existing building requires a façade maintenance retrofit, the incentive to intervene on energy efficiency increases substantially. The corresponding GC savings improve sufficiently to constitute a unique occasion for enhancing the energy performance of a building, in many cases even without the need for public aid to ensure a reasonable PBP. This highlights the fact that ensuring appropriate access to information about viable energy efficiency measures is essential in order to seize the opportunity.

Otherwise, usual ranges of public grants could only achieve an average reduction of the cost-optimal level's private PBP to around 15 years. In buildings which use NG, such a PBP would inevitably be higher. On the other hand, it is quantitatively verified that soft loans play a pivotal role in reducing the need for direct support.

Although the calculated optimal energy refurbishment solutions entail a broad potential for nr-PE savings (48.4%) over the current consumption of the residential stock, it is still far from the European targets for 2050. In a context of international calls for promoting nZEB buildings, it leads to the crucial question of whether maximising the economic performance would actually allow a far enough reach concerning the main aim of reducing CO_2 emissions and related environmental damage; in other words, whether the economic approach could somehow relegate the environmental perspective to a second place. Nevertheless, the cost-optimal methodology constitutes an instrument which enables us to identify the framework conditions that must be improved to encourage building energy retrofitting towards more ambitious environmental goals.

In this sense, the role of renewable energy sources is proven to be fundamental toward the achievement of nZEB levels: as long as they are not used, the performance of the retrofitted buildings is, in all cases, still far from reaching the nZEB ranges. On the other hand, the results suggest that the combination of proven passive and active EEMs, together with renewable technologies, is sufficient to transform all the existing buildings into nZEB. To this effect, the recent Spanish self-consumption regulation represents a relevant step forward, which in the authors thinking should be followed by a simplification of the administrative process to encourage neighbourhood communities to adhere to the new legal figures.

Nevertheless, it is worth noting that a relevant paradox exists concerning the most appropriate fuel that should be promoted to comply with long-term environmental targets. While the outcomes of the study show that the buildings which satisfy the thermal end-uses through electrical consumption could only reach nZEB levels by changing the domestic thermal system to NG, the planned power grid decarbonization could turn electricity into the preferable fuel, and this will probably depend on its future price evolution.

In summary, this work aims to assist policymakers in outlining the most suitable long-term policy and determining the priority targets that require the mobilisation of investment for the energy refurbishment of the existing residential building stock. The conducted research helps to evaluate the achievable energy consumption savings under different retrofitting scenarios. In addition, the outcomes of the analysis can inform the formulation of an energy efficiency policy through the assessment of the impact of economic incentives that could foster private investments in energy refurbishment.

Nevertheless, the application of the methodology from a private approach involves the assumption of a typical mean end-user. On the one hand, it could hide relevant socioeconomic disparities between different residents. On the other hand, each occupant could value the numerous benefits that energy refurbishment involves in a different way, so the willingness to pay for energy efficiency measures could significantly vary from case to case. Therefore, the authors believe that a further family income analysis, together with a discrete choice experiment aimed at shedding some light on motivations to invest in energy efficiency, could interestingly complement the present study for the development of a tailored support scheme that could allocate public resources most efficiently.

CRediT authorship contribution statement

Jon Fernandez-Luzuriaga: Methodology, Investigation, Data curation, Writing - review & editing. **Luis del Portillo-Valdes:** Conceptualization, Supervision. **Iván Flores-Abascal:** Resources, Validation, Visualization.

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.

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