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Evaluating the impact of energy efficiency strategies on households' energy affordability: A Spanish case study

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ABSTRACT

The low energy efficiency of the European building stock is both a social and environmental issue. However, plans and studies on energy retrofitting interventions do not usually evaluate the impact of these measures on households' energy affordability.

This paper analyses and compares the effect of alternative retrofitting strategies on thermal energy services' affordability in Spanish vulnerable households. This analysis was carried out by applying the Required Thermal Energy Expenditure model proposed in previous studies to several 2030 residential building stock scenarios, setting 2020 as a baseline. Therefore, this work proposes a methodological approach to assess the impact of the considered energy efficiency interventions on energy poverty in winter (WEP) and summer (SEP) and carries out both a 'social cost' and a cost-benefit analysis.

The dwelling's thermal-enclosure retrofitting stands out as a very WEP-reduction and social-cost effective measure. Instead, replacing old thermal systems with more efficient ones would have a higher impact on SEP. Combining both kinds of retrofitting measures could reduce heating and cooling required expenditures by, respectively, 49% and 59%, and decrease the WEP and SEP share, correspondingly, by 35% and 63%. These results might inform policymakers to enhance the targeting and design of energy efficiency programs.

1. Introduction

One of the main identified causes of the lack of energy affordability in developed countries (cfr. energy poverty - EP) is the low energy efficiency of housing [1,2]. Indeed, several studies, e.g. [3,4,5], show that energy-poor households typically live in energy-inefficient dwellings with old or no heating systems, which makes it difficult to achieve indoor environmental comfort. In particular, Barrella et al. [4] connect the older housing stock of low-income households with their greater exposure to the phenomenon of hidden energy poverty, which means that their actual energy consumption is usually far below their required energy needs. This is both a social and environmental issue because: on the one hand, vulnerable households cannot afford to pay high energy bills and they potentially live in thermal discomfort and, on the other hand, only subsidising their consumption (which is essential – but insufficient [6] – to tackle energy poverty in the short-term) could lead to an increase of the residential-sector carbon footprint or its total primary energy.

The Directive (EU) 2018/844 [7] sets the targets for the energy performance of buildings, taking into account that 50% of the EU's final energy consumption is used for HVAC (Heating, Ventilation and Air Conditioning, basically heating and cooling), of which 80% is used in buildings. According to this European directive, renovation in the residential sector would be needed at an average rate of 3%/year to achieve,

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Abbreviations: CENSUS, Population and Housing Census (Censo de Población y Vivienda); CO_2, Carbon dioxide; CTE, Spanish Technical Code for Building Construction (Código Técnico de la Edificación de España); DHW, Domestic Hot Water; EPC, Energy Performance Certificate; EU, European Union; EUROSTAT, European Statistical Office; GHG, Greenhouse Gases; HSPF, Heating Seasonal Performance Factor; HVAC, Heating, Ventilation and Air Conditioning; IDAE, Spanish Institute for Energy Diversification and Saving (Instituto para la Diversificación y Ahorro de la Energía); IPCC, Intergovernmental Panel on Climate Change (United Nations); LPG, Liquefied Petroleum Gas; LTRS, Long-Term Strategy for Energy Renovation in the Building Sector; RDL, Royal Decree-Law; RTEE, Required Thermal Energy Expenditure (heating, cooling and DHW); RWTEE, Required Winter Thermal Energy Expenditure (heating and DHW); SEER, Seasonal Energy Efficiency Ratio; SEP, Summer Energy Poverty; SPF, Seasonal Performance Factor; WACC, Weighted Average Cost of Capital; WHO, World Health Organization.

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cost-effectively, the EU's energy efficiency targets. Regarding the EU climate change plans, in 2021, the European Commission presented the amendments and actions of the European Green Deal climate initiatives. In particular, they announced the climate target plan to reduce net greenhouse gas emissions by at least 55% by 2030 (compared to 1990 levels) under the new Fit for 55 package [8]. In parallel, they proposed the establishment of a Social Climate Fund to mitigate the potential regressive impacts of the climate plans [9]. This is expected to provide €72.2 billion for the period 2025–2032 in the EU budget from the new Emissions Trading System to support European vulnerable households during the transition.

In this sense, several 'structural policies' have been implemented in the EU Member States during the last decades to promote energy efficiency in households [10]. However, according to the last EU comprehensive study on building energy renovation, 'the annual weighted energy renovation rate was estimated close to 1%' [11], that is much lower than the 3% target set in Directive (EU) 2018/844. Moreover, when energy efficiency policies have been implemented, their actual impact on energy affordability has not been analysed sufficiently [12], which involves not having a reference to correctly target and improve them in the future. Besides, a recurring issue when it comes to the financing of investments in housing for vulnerable groups is who should be the beneficiary of that aid. If the tenancy regime is rent, the paradox arises from financing the landlord, who could even raise the rent by having more efficient housing (cfr. landlord/tenant dilemma [13]). Considering the abovementioned problem, the best scenario for financing energy efficiency measures is social housing. Nevertheless, the governments face the challenge of implementing policies to finance and carry out renovations in all types of dwellings, especially those inhabited by energy-poor people, which could not afford to retrofit their homes [14,15,16]. The last-mentioned study identified this issue as 'retrofit poverty', defined as 'the inequality of opportunity to improve the energy performance of the home' [16]. On the other hand, another fundamental task of governments is the design of the appropriate regulation that establishes incentives for the contribution of private initiative.

To reduce energy consumption and consequently cut down the energy expenditure of vulnerable households, two main typologies of energy efficiency interventions can be carried out: active and passive measures. The former ones are applied to the active systems of the house/building, e.g. replacing the HVAC equipment with a more efficient one. The latter aim to improve the housing thermal insulation, thus including all interventions that retrofit the thermal enclosure (e.g. windows and walls renovation). Regarding the effectiveness assessment of alternative retrofitting strategies, a pioneering study by Clinch et al. [17] evaluated 'the economic benefit of improving households' thermal comfort post-retrofit' (mainly including passive interventions) for the Irish case study by using a computer-simulation program. A more recent work by Dascalaki et al. [18] modelled several scenarios for different renovation rates in Greece to identify the most beneficial strategies in heating and DHW systems' replacement for achieving the 2020 and 2030 national CO_2 emission targets. For the same country, Panagiotidou et al. [19] performed a multi-objective optimisation procedure to minimise the operating Greenhouse Gases (GHG) emissions and the lifecycle cost by implementing alternative passive or active measures in a typical multi-residential building in the four national climate zones. In another Mediterranean country, i.e. Portugal, Palma et al. [20] assessed the cost-effectiveness of thermal enclosure retrofitting measures for reducing the dwelling stock's HVAC energy demand at national and regional levels. These energy needs were calculated by applying a dwelling archetype bottom-up method that exploits energy performance certificates (EPC) data. Looking outside the EU, Yeganeh et al. [21] proposed a 'generalizable framework for analysing the feasibility of achieving regionwide or statewide zero-energy affordable housing' in the US. The authors of that work demonstrated that the net present value of rooftop solar systems' investments to achieve this kind of housing can be positive with a low risk.

Concerning the paper's case study, i.e. Spain, Ibañez Iralde et al. [22] presented a review of Spain's relevant literature on energy retrofitting of residential buildings. That study explored the following topics: 'the characterization of the existing building stock, which actions have been typically considered under the scope of retrofits, and which strategies have been implemented until' the date (2021). Among other data analysed in that work, Ibañez Iralde et al. pointed out that the funds earmarked for energy efficiency programs constituted only 8% of the needed declared investments, 'which along with the dispersion between the different procedures and the complexity of the processes, have significantly reduced the global impact of these actions without generating robust and oriented market dynamics'.

One year earlier, the 2020 update of the Spanish Long-Term Strategy for Energy Renovation in the Building Sector (LTRS) set out a specific plan to combat energy poverty throughout energy efficiency interventions (based on previous studies such as [23]). However, the LTRS did not evaluate these measures' impact on households' utility bills and energy deprivation. To address that gap, this paper presents a technoeconomic study of alternative energy retrofitting strategies and assesses their impact on energy poverty amongst Spanish vulnerable consumers. Firstly, this work applies an adapted version of the Required Thermal Energy Expenditure (RTEE) methodology presented in [6] and [4] to assess the effect of structural measures on reducing Spanish vulnerable households' thermal energy expenditure. Secondly, the impact on winter and summer energy poverty is assessed by using a disproportionate expenditure indicator. These NUTS3[1]-resolution [24] analyses make it possible to evaluate the differences between the current outline and different 2030 scenarios for all the Spanish provinces, thus assessing the effectiveness of various retrofitting measures. Particularly, the effect of these measures was assessed expanding the methodology proposed in [6] to all thermal energy services, i.e. adding cooling needs to the 'winter ones'. Therefore, the provincial and national average household's RTEE (heating, cooling and DHW) values were calculated under different housing retrofitting scenarios to compare their impact on vulnerable households' thermal energy expenses and energy poverty in winter (WEP) and summer (SEP). Specifically, the considered strategies include the implementation of thermal enclosure's retrofitting, thermal systems' replacement, or a combination of both interventions. Finally, this paper compares the socio-economic effectiveness and the national financial burden of different implementation scenarios of the studied policies, thus pointing out some policy implications and future research work.

The structure of the rest of the article is as follows. Section 2 describes key aspects of the main energy efficiency policies and plans proposed in Spain. Section 3 explains the methodology used to apply the RTEE model to the scenarios' characterisation. Moreover, it presents the procedure used to estimate the impact of alternative retrofitting strategies on thermal energy services' affordability and energy poverty (both WEP and SEP). Section 4 presents and discusses the results obtained by applying the analysed policies to the Spanish vulnerable households. Finally, Section 5 points out the conclusions and policy implications of this work.

2. Energy efficiency policies and plans for the Spanish residential sector

The regulatory framework that guides the implementation and promotion of energy efficiency in Spain is set out in the RDL 390/2021. This RDL transposed the Directive (EU) 2018/844 into Spanish law, mainly regarding the modification of the registration of energy performance certificates, 'which will allow the collection of data on measured or calculated energy consumption of buildings, as well as the linking of

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[1] Spain is a regionalised unitary state, and the regions (NUTS2) are additionally divided in provinces (NUTS3, second level of administrative division).

financial incentives for the improvement of energy efficiency to the expected or achieved energy savings'. Regarding financial incentives for energy efficiency improvements in the renovation of buildings, Article 14 links such subsidies to energy savings through the comparison of energy performance certificates issued before and after the renovation or, alternatively, through one or more alternative criteria including, for example, the results of an energy audit.

Concerning the programmes for energy retrofitting of dwellings, it can be highlighted, among others, the Programme of subsidies for Energy Retrofitting actions in Existing buildings (*Programa de ayudas para actuaciones de Rehabilitación Energética en Edificios existentes, PREE*), which replaced the PAREER-CRECE and PAREER II programmes, carried out between 2013 and 2018 and which had a combined budget of €404 million. These programmes enabled the energy-efficient refurbishment of around 80,000 Spanish dwellings. The budget allocation for the new programme, which comes from the National Energy Efficiency Fund (*Fondo Nacional de Eficiencia Energética*, created by Law 18/2014 of 15 October), was 300 million euros and has been distributed among the autonomous communities according to the number of primary dwellings. This programme has been coordinated by the Spanish Institute for Energy Diversification and Saving (IDAE), but the application for the granting of the subsidy must be submitted to the Autonomous Community where the property is located. The percentage of the state funding (with respect to the investment) varies according to the type of action and the type of building. It should be noted that in four of the seven types of action aimed at the residential sector, an additional percentage is foreseen for residential buildings whose owners benefit from the electricity social tariff (i.e. vulnerable consumers). A similar program (*PREE 5000*), but specific for rural areas, has been centrally managed by the Spanish Institute for Energy Diversification and Saving (IDAE in Spanish) and applied regionally by each Autonomous Community. Both programs provide subsidies for building thermal enclosure renovation and for equipment replacement.

The measures implemented to date are mostly framed within the 2020 update of the Long-Term Strategy for Energy Renovation in The Building Sector (LTRS) in Spain, which is the national roadmap for advancing towards the objective of decarbonisation and improving the efficiency of buildings. Moreover, this strategy aims to contribute to the National Energy and Climate Plan 2021–2030, which, among many other strategic objectives, is committed to the energy retrofitting of the existing building stock. Both roadmaps include a special mention of households in energy poverty which, in the case of the LTRS, translates into a specific action plan for them. Along the same lines, in October 2021, the RDL 19/2021 was approved. This RDL implements some of the measures proposed in the LTRS 2020 in the context of the Recovery, Transformation and Resilience Plan, development of the European instrument Next Generation EU, among others.

In the same month (October 2021), the RDL 853/2021 [25] regulated the subsidy programmes for residential refurbishment and social housing under the Recovery, Transformation and Resilience Plan. This Royal Decree Law articulates the plan in six programmes: one to five, linked to building retrofitting actions, and six, to the promotion of the construction of social rental housing. The first and third programmes, i.e. the Support programme for retrofitting actions at the neighbourhood level (*Programa de ayuda a las actuaciones de rehabilitación a nivel de barrio*) and the Support programme for retrofitting actions at the building level (*Programa de ayuda a las actuaciones de rehabilitación a nivel de edificio*), include a specific criterion for vulnerable households: in case the owners or beneficiaries meet the criterion of economic or social vulnerability, up to 100% of the cost of the action will be financed by European funds.

3. Methodology

3.1. Setting out the scenarios

This section describes the methodological approach used to simulate alternative scenarios of building energy retrofitting in the Spanish residential sector. Firstly, the Required Thermal Energy Expenditure (RTEE) model was applied to estimate the households' theoretical energy expenditures in alternative energy retrofitting scenarios. In order to do that, the calculation's methodology of the provincial Required Winter Thermal Energy Expenditure (heating and DHW – RWTEE) presented in [6] has been completed by estimating the required cooling expenditure (RCE) at provincial and national level. The latter calculation was performed by adapting the methodology presented in [4]. The resulting 'complete' characterisation of the RTEE (heating, cooling and DHW) in Spain made it possible to analyse the impact of different energy retrofitting strategies on energy services affordability and on winter energy poverty (WEP) or summer energy poverty (SEP)[2] in the medium-term, i.e. 2030.

Several 2030 scenarios of energy retrofitting in vulnerable households (vulnerable consumer family units benefitted from the Thermal Social Allowance in 2020) have been analysed, and a reference 2020 scenario was set as follows. 2020 energy prices have been considered as starting point to make it possible to apply the 2030 price projections presented in the LTRS. Particularly, the LTRS forecasted an average fossil fuel price increase of 43.3% in 2030 (compared to 2020). The rest of the reference scenario's parameters are based on official statistics such as the 2011 Census and the 2019 Household Budget Survey, as explained in [6]. On the other hand, for the 2030 scenarios, the medium-term (2020–2030) effect of temperature changes on the theoretical HVAC demand was considered 'negligible' according to the LTRS. Indeed, the LTRS forecasts that heating and cooling demand changes in this period would balance each other (having opposite tendency but similar absolute values), thus resulting in a negligible HVAC demand change between 2020 and 2030.[3] The WEP and SEP analysis was carried out by using the vulnerable consumers data at the end of 2019[4] [26,27], which make it possible to compare the effectiveness of these structural measures (see Section 3.2) in reducing energy poverty. The studied scenarios can be summarized as follows:

- Reference Scenario
- Projected Future Scenarios (2030):

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[2] The former refers to the heating and DHW affordability issues, while the latter to the ones related to cooling expenses.

[3] The LTRS forecasts an increase of the domestic space cooling demand in Spain from 2020 to 2030 of between 10% and 21% (according to the climate zone). On the other hand, the space heating demand is expected to decrease by 3–4% in the same period. This tendency is also confirmed by a report analysing the adaptation to climate change in the Spanish Energy Sector [39]. Therefore, given the much higher heating share in the RTEE (see Fig. 1) and the LTRS forecasting, these two changes would balance each other resulting in a negligible HVAC demand change between 2020 and 2030. Nevertheless, a revision of the calculations in the future is desirable in view of new predictions, such as the most recent IPCC report [40].

[4] These consumers are the ones who received the Thermal Social Allowance in 2020.

Table 1
Required heating demand after a 'Low-cost building retrofit' with respect to the 'Business as usual' required heating demand [%] according to the climate zone.

Winter climate zone	$\frac{RD_{h,retrofit}}{RD_h}$[%]
A	29%
B	31%
C	38%
D	46%
E	53%

Table 2
Required cooling demand after a 'Low-cost building retrofit' with respect to the 'Business as usual' required cooling demand [%] according to the climate zone.

Climate zone	$\frac{RD_{c,retrofit}}{RD_c}$[%]
2	37%
3	44%
4	53%

- Scenario 0 – 'Business as usual': Neither building thermal-enclosure retrofitting nor thermal systems replacement's measures are implemented.
- Scenario I –'Low-cost building retrofit': a set of low-cost thermal-enclosure's retrofitting measures (own elaboration from[28][5]) are performed in vulnerable households living in dwellings built before 1981, which represent the 55% of the primary dwellings stock (according to the Census 2011).
- Scenario II – 'Thermal systems replacement': The existing thermal systems are replaced with the most efficient equivalent[6] (same energy carrier[7] and type) systems in 2030 (own elaboration from [29]):
  a. Heating + DHW systems
  b. Cooling systems
  c. HVAC and DHW systems (a + b)
- Scenario III – 'Multiple energy retrofit measures' (I + IIc): All the measures mentioned in Scenario I and IIc are implemented in vulnerable consumers' dwellings.

3.2. *Technoeconomic study and impact on energy poverty of alternative energy retrofitting strategies*

To assess the effectiveness of the structural measures proposed in the different scenarios presented above, it is crucial to understand how they contribute to reduce the energy burden of vulnerable households. The low-cost building retrofitting measures included in Scenarios I and III focus on improving the insulation of the dwelling's thermal enclosure. This improvement reduces the required demands for heating and cooling. In this regard, the 'reduction rates' were calculated by extrapolating the results of a previous study [28] to all Spanish climate zones. That work analysed in depth the category of measures included in Scenarios I and III. Particularly, that study proposed an express housing energy retrofitting comprising a series of low-cost measures that can be applied to Spanish low-income households. They calculated the energy saving resulting from the application of this low-cost energy retrofitting in a modelled building. The calculation, based on the adaptive comfort criterion (see [30]), was carried out for four Spanish cities (*Barcelona, A Coruña, Madrid* and *Seville*). An own elaboration of the report's results made it possible to estimate the reduction in thermal energy demand according to the winter climate zone (A to E, in order of increasing winter severity) or the summer one (2 to 4, in order of increasing summer severity[8]).

Table 1 and Table 2 show the results obtained for, respectively, heating and cooling needs. The post-intervention heating demand would be between 53% of the initial one in E zone and 29% in A zone, thus showing a higher relative impact in milder winter climates. On the other hand, the post-intervention cooling demand produced by a low-cost retrofitting would be between 53% of the initial one in Zone 4 and 37% in Zone 2, showing a higher relative impact in climate zones with a mild summer.[9]

On the other hand, the replacement of thermal systems with ones with a higher seasonal performance factor (respectively, HSPF for heating, SPF for DHW and SEER for cooling) reduces the household's required thermal energy consumption. The replacement of existing boilers with heat pumps is not included in this paper's 2030 scenarios, in line with the LTRS.[10] Moreover, given the tecno-economic nature of this analysis and the higher share of HVAC consumption than DHW one, the CTE primary energy requirements for the latter use are not considered relevant to this paper's purpose.[11] The seasonal performance factors assumed for 2030 were obtained by elaborating the results presented in [29]. Table A1, Table A2 and Table A2 summarise, respectively, the HSPF, SPF and SEER values assumed for the new 2030 thermal systems in the Scenarios II and III. The seasonal performance factors of [6] were assumed for the rest of scenarios that do not involve thermal system replacement. The considered new boilers would produce 33% and 23% average reduction of required consumption in, respectively, heating and DHW, compared to the old ones. Besides, the new air-conditioning systems would reduce the required cooling consumption by 38% on average.

Therefore, the Spanish households' RTEE in the different scenarios were estimated as follows. Firstly, the provincial and national average RTEE in Scenario 0 were calculated by applying the projected 2030 energy prices to the Reference Scenario, which was characterised by using the methodology described in [6] (for the heating and DHW expenditures) and [4] (for the cooling expenditures). The latter was

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[5] This scenario includes the three passive measures included in the 'express retrofitting' presented in [28]: wall insulation, roof insulation and windows replacement. These interventions are selected for being relatively low cost (compared to deep retrofitting), easy to implement (they are implemented from inside the dwelling and people do not need to leave their house during the refurbishment) and having a significant impact on HVAC consumption. Focusing on heating, according to an own elaboration of [28], they produce the following average theoretical reduction of demand, depending on winter climate severity: wall insulation (35%-45%), roof insulation (8%-13%) and windows replacement (11%-13%).

[6] In some real cases it would mean just installing an efficient thermal system if the household doesn't have any. This is particularly true for air conditioners, which according to the last available national statistics, are owned only by 35.5% of households [41].

[7] Previous work [42] projected fuel use in Western Europe to remain quite stable until 2030, i.e. no significant changes in energy carriers.

[8] The α and 1 climate zones were not considered in this calculation because they have, respectively, null heating and cooling demand.

[9] For estimating the absolute impact, the reader could apply these reduction percentages to, respectively, the RWTEE and RCE of the Spanish provinces (see Fig. 2 and Fig. 3).

[10] In this regard, the Strategy states that 'heat pumps have technical operating characteristics that in the short term (2021–2030) make their integration in all climate zones difficult'. Thus, in the 2030 LTRS horizon, the installation of aerothermal heat pumps is recommended only in areas with milder winters (up to climate zone C).

[11] The considered DHW energy carriers (except for biomass) would likely not respect the regulation of the CTE [43], which requires on-site renewables or solid biomass for DHW, between 60 and 70% of primary energy. In the case of HVAC systems, the CTE states that if no more than 25% of the building thermal enclosure is refurbished (which is the case of the considered low-cost building retrofit), it is not necessary to respect the primary energy requirements.

Table 3
Key points describing the analysed 2030 scenarios.

Scenario	Implemented measures	Vulnerable consumers involved	Unit investment cost	Useful life
Scenario 0 – 'Business as usual'	N/A	0	N/A	N/A
Scenario I –'Low-cost building retrofit'	Thermal-enclosure's retrofitting measures	588,882	€4,500	30 yrs
Scenario II – 'Thermal systems replacement'	a. Heating + DHW systems b. Cooling systems c. HVAC and DHW systems (a + b)	1,077,593	a. €1,500 b. €1,200 c. €1,500 + €1,200	a. 18 yrs b. 10 yrs c. 18 yrs – 10 yrs
Scenario III – 'Multiple energy retrofit measures' (I + IIc)	Thermal-enclosure's retrofitting measures/HVAC and DHW systems replacement	588,882 / 1,077,593	€4,500 / €1,500 + €1,200	30 yrs/18 yrs – 10 yrs

adapted to this paper's case study, i.e. weighted RTEE for each Spanish province were calculated. Secondly, the 'reduction rates' due to low-cost building retrofit (Table 1 and Table 2) were applied to the heating and cooling demands of dwellings constructed before 1981 to estimate the provincial and national average RTEE in Scenario I. Thirdly, starting from Scenario 0, the 2030 seasonal performance factors (Table A 1, Table A 2 and Table A 2) were applied to the thermal demand values to estimate the 'reduced' required consumption for, respectively, heating, cooling or DHW. This made it possible to assess the average RTEE in Scenario IIa (reduced consumption for heating and DHW) and IIb (reduced consumption for cooling); besides, Scenario IIc was characterised by applying the 2030 performance factors to the required consumption of all three analysed thermal services, i.e. obtaining the reduced consumption for heating, cooling and DHW. Finally, Scenario III was assessed by complementing the impacts of low-cost building retrofit (Scenario I) and thermal systems replacement (Scenario IIc), thus reducing, respectively (and simultaneously), the required HVAC demand and the required thermal energy consumption.

Starting from the above results, the impact of different retrofitting strategies on thermal services' affordability was calculated by comparing the RTEE of the 2030 retrofitting scenarios with the 'Business as usual' one (Scenario 0). On the other hand, the WEP share in all scenarios was estimated by using the methodology described in [6], thus measuring the impact of the abovementioned structural measures on the $2M_t$ indicator[12] in Spain. On the other hand, the impact of these alternative energy efficiency strategies on SEP was estimated by using a disproportionate cooling expenditure index similar to the one used for winter, i.e. the $2M_{t,cool}$ indicator. In this case, $M_{t,cool}$ is calculated as the proportion of the national weighted average RCE over the national average net disposable income in the Reference Scenario. Thus, a household is considered as in summer energy poverty if their share of equivalised RCE in equivalised income is more than twice the $M_{t,cool}$. Each household's share was set as the ratio between the provincial required-cooling-expenditure (equivalised according to their composition category: Minimum pension; Without minors; 1 minor; 2 minors; Large family) and their social tariff's income limit (best-case scenario). The latter varies with the household's vulnerability level (Vulnerable consumers, Severely vulnerable consumers or Consumers at risk of social exclusion) and composition category. The applied expenditure's equivalisation indexes are the same as the ones used in [6] for heating needs.

Thereafter, the budgets needed to implement such measures in Scenario I, IIc and III were calculated by assuming the following unit investment costs: around €4500 per household for the low-cost building retrofit [28], €1500 approx. per household for the heating/DHW systems' replacement and €1200 for air conditioner replacement.[13] These amounts are set by assuming that the heating and cooling distribution systems are not refurbished. The third scenario includes the two kinds of measures analysed, which are applied to different numbers of vulnerable consumers. Therefore, its budget is the sum of the two measures budget, as shown in Table 6. Regarding the useful life of the thermal systems' replacement, the Spanish LTRS estimates it between 15 years for individual boilers and 25 years for centralised boilers, being the useful time of electric radiators or storage heaters around 20 years. Thus, applying the Census distribution assumptions to the number of centralised and individual installations existing at national level, the LTRS calculates an average useful lifetime of each kind of heating/DHW systems, i.e. heat pumps, natural boilers, etc. Giving the systems considered in this paper (see Table A 1), the average useful life would be 18.5 years for block dwellings (individual/centralised installations) and 16.7 years for single-family dwellings (individual installations). Therefore, giving the shares of these two types of dwellings in Spain (Census 2011), the average useful life of heating/DHW systems was set at 18 years. Moreover, the average air conditioner's useful life was set at 10 years [31]. On the other hand, the low-cost retrofit useful time (interval between each retrofitting intervention) was set at 30 years. This is in line with the literature and the timespan fixed in the city of Madrid to carry out a new Technical Building Inspection (ITE in Spanish) from the date of completion of the new building or renovation works (applying the national regulation [32]).

Table 3 summarises the key points describing the analysed 2030 scenarios.

Therefore, the levelised investment cost per household was calculated for each 2030 retrofitting scenario starting from the information described in the above paragraph. Considering the vulnerability of the beneficiaries, it is assumed that the investment would be fully covered by the State (coverage included in the programmes promoted by the RDL 853/2021, or with a mix of public–private financing), i.e. with a non-repayable grant. Thus, the paper considers an investment of the State in 2020 to finance the 100% of the retrofitting interventions in vulnerable households. Considering a reasonable discount rate ($wacc = 5\%$ [33,17]), the levelised investment cost (LI) was calculated as in Eq. (1a),

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[12] This indicator estimates 'the proportion of households whose share of equivalised RWTEE in equivalised income is more than twice the Mt, which is the national median share of thermal energy expenditure (heating and DHW) in income' [6].

[13] The latter two amounts were estimated applying a previous techno-economical study [44] (market prices in case of electric radiators [45]) to the characteristics of the Spanish residential buildings' stock and existing thermal systems ([46], [29] and Census 2011).

i.e. as the product of the investment cost (*I*) and the capital recovery factor (*CRF*), the latter being calculated by applying Eq. (1b). Moreover, in the low-cost building retrofit scenario, the levelised investment cost per average household takes into account that this measure would be applied only to the 55% of dwellings, i.e. the ones built before 1981.

$$LI\,[€] = I \bullet CRF \tag{1a}$$

$$CRF = \frac{wacc \bullet (1+wacc)^N}{(1+wacc)^N - 1} \tag{1b}$$

Regarding the 'operating costs', the levelised cost of the j-th energy carrier LC_{ecj} was calculated by applying Eq. (2a)-(2d).

$$LC_{ec_j}\,[€/\mathrm{MWh}] = C_{ec,10_j} \bullet f_{\sum_j} \bullet CRF \tag{2a}$$

$$C_{ec,10_j}\,[€/\mathrm{MWh}] = C_{ec,0_j} \bullet (1 + r_{ecj})^{10} \tag{2b}$$

$$f_{\sum_j}[-] = \left(\frac{k_{ecj}\bullet(1-k_{ecj}^{\,N})}{1-k_{ecj}}\right) \tag{2c}$$

$$k_{ecj}[-] = \frac{1 + r_{ec,j}}{1 + wacc} \tag{2d}$$

Where $C_{ec,10_j}$ is the j-th energy carrier cost at the base year (2030); $C_{ec,0_j}$ is the j-th energy carrier cost at the reference price year (2020); $r_{ec,j}$ is the nominal escalation rate of the j-th energy carrier, assumed according to the 2030 projections of the LTRS; $f_{\sum_j}$ is the accumulation factor of the j-th energy carrier; *N* is the thermal system useful life (according to the LTRS). When $r_{ec,j}$ is zero, $f_{\sum_j}$ is the inverse of the CRF, so$LC_{ec_j} = C_{ec,0_j}$. On the other hand, in all the analysed scenarios, the maintenance cost is assumed equal to zero. This calculation made it possible to compare the retrofitting scenarios among each other by considering the 'social cost' of each set of measures, i.e. the sum of the average levelised RTEE in that scenario and the levelised investment cost of the implemented measures.

Finally, to carry out a proxy of cost-benefit assessment, the number of households [hs] that have been lifted out of energy poverty thanks to each strategy has been divided by the related total investment [M€]. In particular, two 'benefit-cost ratios' have been calculated by applying Eqs. (3a) and (3b). The former refers to the WEP reduction benefit, while the latter to the SEP reduction benefit.

$$Benefit - cost_{WEP}[hs/M€] = \frac{NumberofhouseholdsmovingoutofWEP}{Totalinvestment[M€]} \tag{3a}$$

$$Benefit - cost_{SEP}[hs/M€] = \frac{NumberofhouseholdsmovingoutofSEP}{Totalinvestment[M€]} \tag{3b}$$

These indices give an idea of the 'return' per million euro invested, thus making it possible to identify which is the best measure in cost-benefit terms.

4. Results and discussion

4.1. Impact of retrofitting strategies on thermal energy services' affordability

Fig. 1 shows the results for the national average required expenditures for heating, cooling and DHW in the Reference Scenario. It displays both the absolute average expenditure values (left) and their shares in the RTEE (right). Summing up the three energy services' expenditures gives the average national RTEE, which is €993 per household.

The most evident insight of the three calculations is that heating expenditure has the highest share in RTEE by far. However, this share varies according to the province of residence of the households. In this sense, Fig. 2 and Fig. 3 map, respectively, the RWTEE (heating and DHW) and the RCE (cooling) for the 'provincial weighted-average households' in the Reference Scenario. The RWTEE and RCE of the two Autonomous Cities not shown in these figures are, respectively, €554.2 and €112 for *Ceuta*, and €440 and €118.4 for *Melilla.*

Concerning the 'winter needs', Fig. 2 shows that the inland provinces have generally a higher required expenditure than the coastal ones and the islands. In particular, the two provinces of Canary Islands have the lowest RWTEE because of their mild climate that generate a very low or

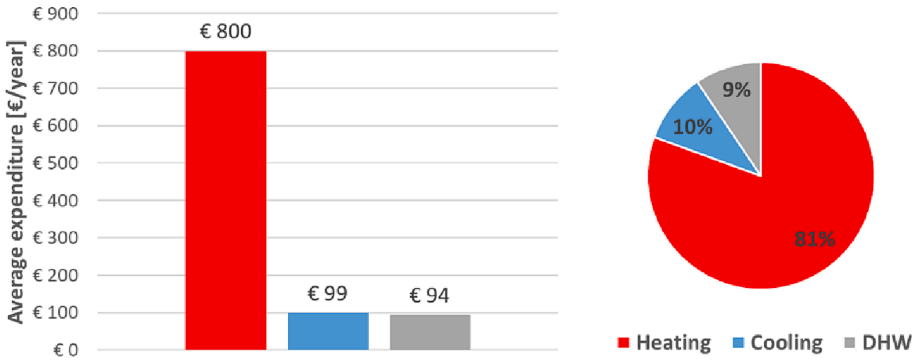

Fig. 1. Thermal services' average required expenditures (left) and their shares in the RTEE (right) for the Reference Scenario.

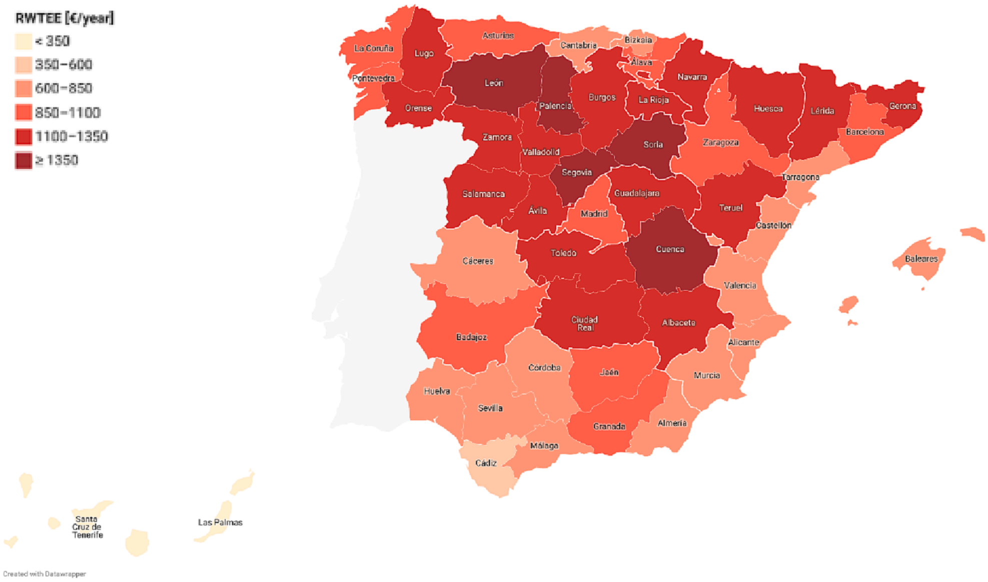

Fig. 2. Provincial results of the household RWTEE analysis [€/year].

null energy demand for heating homes. On the other hand, the RCE is much higher in the southern provinces than in the northern ones. Indeed, most of the latter provinces has null or very low cooling needs.

Fig. 4 compares the thermal services' average required expenditures in the 2030's Scenario 0 ('Business as usual') with the Reference Scenario's ones. The Scenario 0 considers energy prices changes but characterises the thermal energy needs of the original building stock, i.e. it does not take into consideration later renovation measures. Indeed, Fig. 4 shows that heating and DHW expenditure increase, respectively, by 24% and 26%, whereas cooling expenditure does not change. This can be explained, on the one hand, by the projected fossil fuel prices' increase and electricity price's stability and, on the other hand, by the

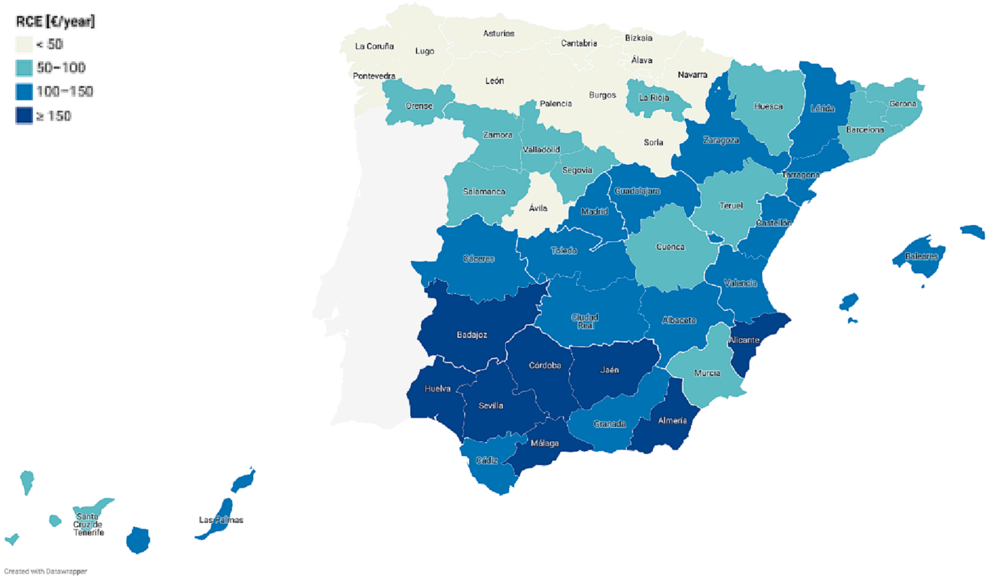

Fig. 3. Provincial results of the household RCE analysis [€/year].

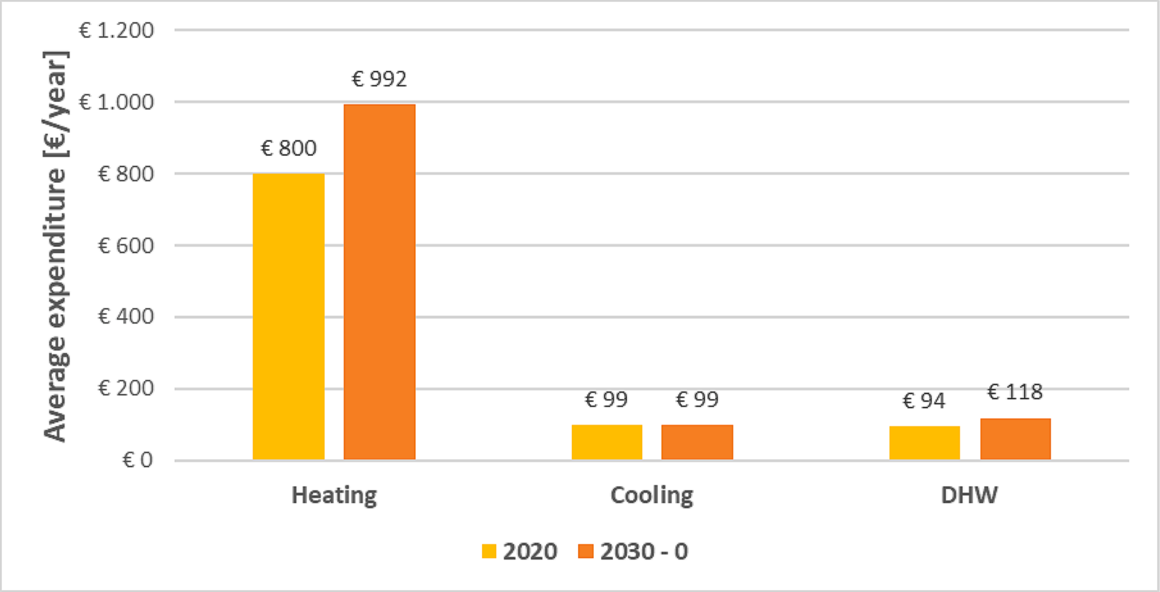

Fig. 4. Thermal services' average required expenditures in the Scenario 0 compared to the Reference Scenario.

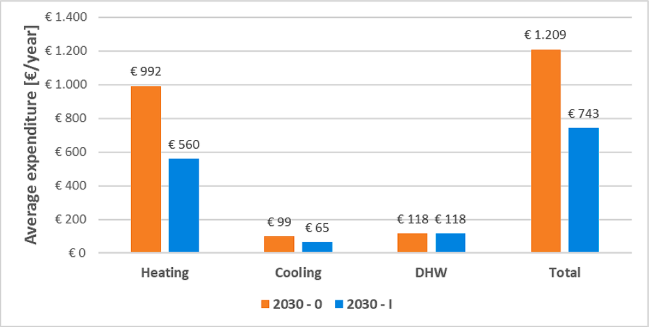

Fig. 5. Thermal services' average required expenditures in the Scenario I compared to Scenario 0.

assumption on the 'negligibility' of temperature changes in 2030.

Fig. 5 and Fig. 6 show the impact on the RTEE of, respectively, low-cost building retrofitting (Scenario I) or thermal systems replacement (Scenario II), having the latter several subscenarios.

The low-cost building retrofit (Fig. 5) achieves the greatest RTEE reduction, i.e. it reduces the average household thermal energy burden by 25%, being heating and cooling expenditures the ones affected by this measure. On the other hand, Fig. 6 shows that, to have a significant impact on the RTEE, it is recommended to replace all the thermal systems with new ones (Scenario IIc), thus achieving a 10% reduction in expenditure. Finally, Fig. 7 shows the joint impact of low-cost building retrofitting and thermal systems replacement, i.e. the Scenario III, compared to the Reference Scenario. It is evident that combining both kinds of retrofitting measures could have the higher effectiveness, i.e. it could reduce heating and cooling required expenditures by, respectively, 49% and 59%. On the other hand, one common insight from all analysed scenarios is that the rise in fossil-fuel prices projected for 2030 is expected to increase the RWTEE if no measure is taken (Scenario 2030–0). Moreover, it could affect the impact of the energy retrofitting strategies included in the analysis. Particularly it might significantly reduce or outset the positive effect of, respectively, heating or DHW systems replacement.

Table 3 summarises the RTEE variation in the 2030 retrofitting scenarios with respect to the Scenario 2030–0. As expected, the most effective structural measure in reducing the RTEE (among the analysed

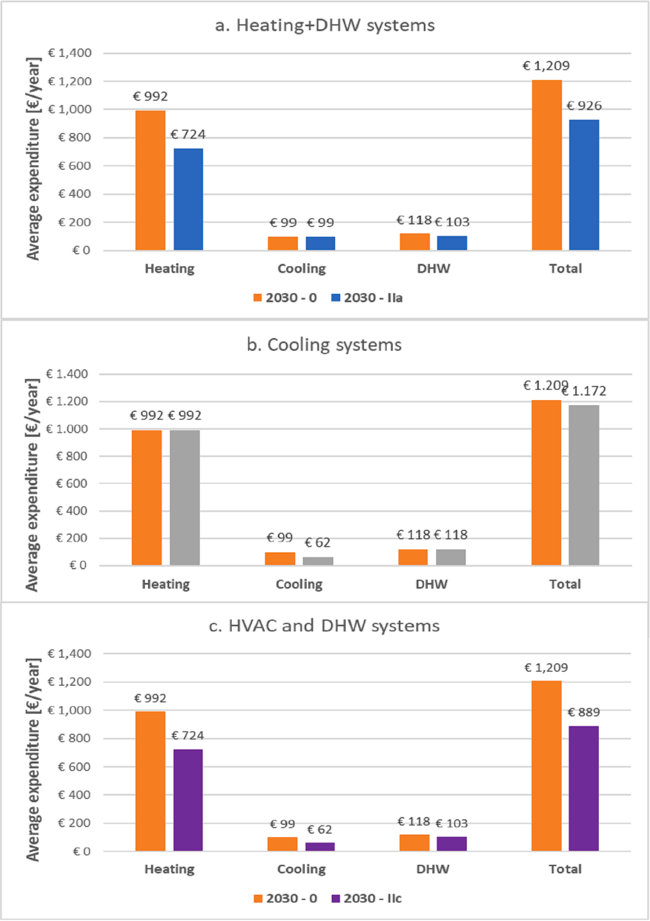

Fig. 6. Thermal services' average required expenditures in the different sub-scenarios of Scenario II compared to Scenario 0.

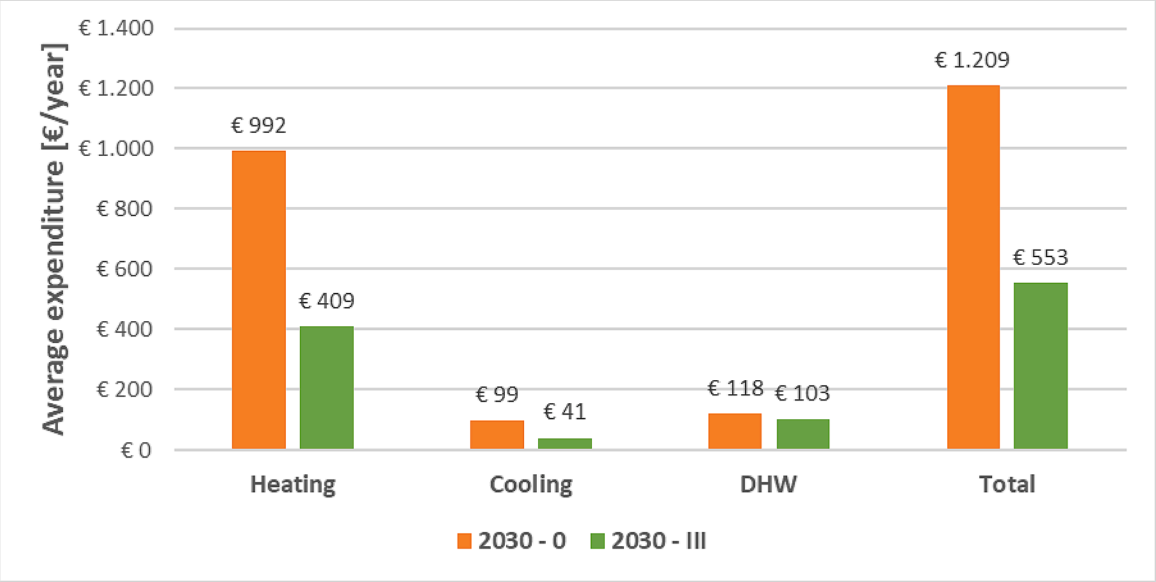

Fig. 7. Thermal services' average required expenditures in the Scenario III compared to the Scenario 0.

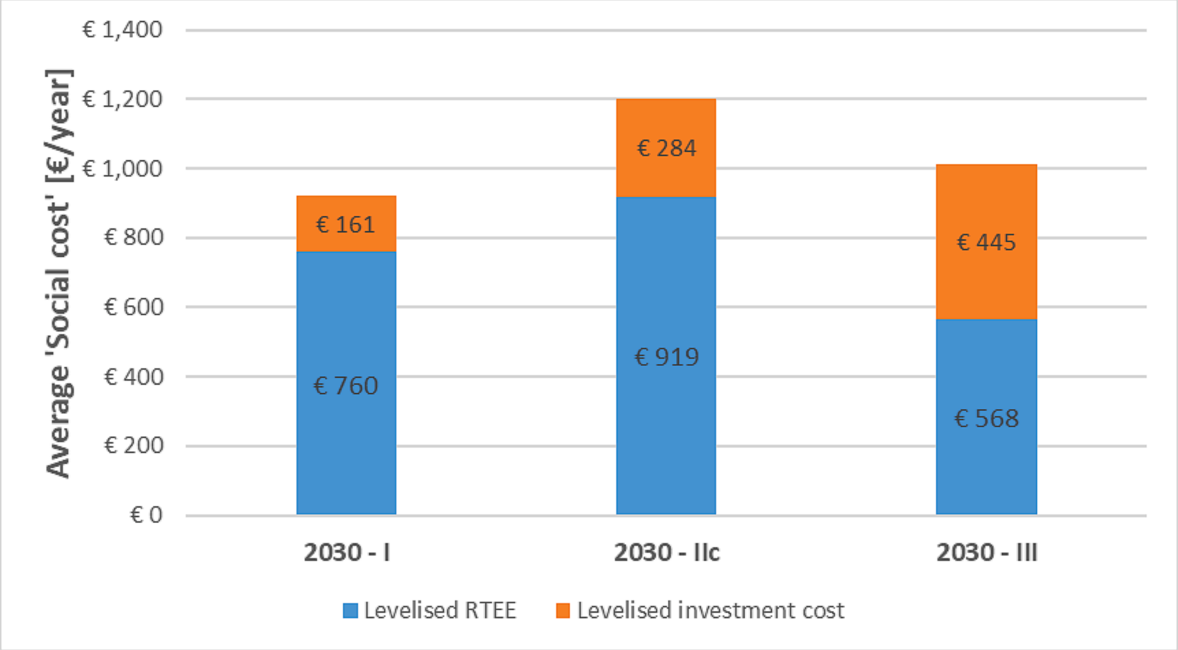

Fig. 8. 'Social cost' (levelised RTEE + levelised investment cost) per average household of the main 2030 scenarios.

Table 4
RTEE variation in the 2030 retrofitting scenarios with respect to Scenario 2030–0.

Service	2030 - I	2030 - IIa	2030 - IIb	2030 - IIc	2030 - III
Heating	−44%	−27%	0%	−27%	−59%
Cooling	−34%	0%	−37%	−37%	−59%
DHW	0%	−13%	0%	−13%	−13%
Total	−39%	−23%	−3%	−26%	−54%

Table 5
WEP shares in the main 2030 scenarios analysed and their variation with respect to the Reference Scenario (2020).

Scenario	Vulnerable consumers	Severely vulnerable consumers	Consumers at risk of social exclusion	Total	WEP variation
Reference Scenario	84%	97%	100%	93%	0%
2030 - 0	92%	98%	100%	96%	+4%
2030 - I	50%	90%	99%	77%	−17%
2030 - IIc	67%	94%	99%	85%	−8%
2030 - III	23%	80%	87%	61%	−35%

Table 6
SEP shares in the main 2030 scenarios analysed and their variation with respect to the Reference Scenario (2020).

Scenario	Vulnerable consumers	Severe vulnerable consumers	Consumers at risk of social exclusion	Total	SEP variation
2020	63%	77%	53%	72%	0%
2030 - 0	63%	77%	53%	72%	0%
2030 I	26%	62%	51%	50%	−31%
2030 IIc	20%	59%	46%	45%	−37%
2030 III	0%	41%	39%	27%	−63%

Table 8
'EP benefit-cost ratios' of the main considered strategies.

Scenario	$Benefit - cost_{WEP}[hs/M€]$	$Benefit - cost_{SEP}[hs/M€]$
2030 I	71	127
2030 IIc	31	137
2030 III	67	122

scenarios) is the combined solution of retrofitting the thermal enclosure and replacing the thermal systems with more efficient ones, i.e. Scenario III.

Finally, Fig. 8 shows the 'social cost' (levelised RTEE + levelised investment cost) per household of the main 2030 retrofitting scenarios. This economical comparison shows that the 'low-cost building retrofit' scenario (2030-I) is the most social-cost effective among the analysed ones, followed closely by the 'multiple energy retrofit measures' scenario (2030-III). This result can be partially explained by the higher reduction of RTEE produced by the low-cost building retrofit compared to the thermal systems' replacement. Combining the two kind of measures (2030-III) would have an even higher impact on the RTEE (see Fig. 8). However, the thermal systems replacement's levelised investment cost per average household (€284) is significantly greater than the one for low-cost building retrofit (€161[14]), which determines a higher 'social cost' in the Scenario III (€1,012) than in the Scenario I (€921).

4.2. Impact of retrofitting strategies on winter and summer energy poverty

Regarding the effectiveness of the analysed structural measures in mitigating energy poverty during winter, Table 4 shows their impact on the WEP share among vulnerable consumers and its variation with respect to the Reference Scenario.

If no action against energy poverty is taken (Scenario 0), the calculation shows that WEP would increase by 4% in 2030 due to the fossil fuel prices' rise. On the other hand, implementing both kinds of analysed structural measures (Scenario III), i.e. building retrofitting in the oldest dwellings and thermal systems' replacement in all vulnerable households, would reduce WEP by 35%. The rest of scenarios would rank in between Scenario 0 and III, Scenario I generating a higher WEP reduction than Scenario IIc.

Table 5 shows the impact of the same strategies on SEP, i.e. including only the cooling affordability issue.

Giving the simplification assumptions (see Section 3), there would be no change in the SEP level in the 2030 'business as usual' scenario compared to the 2020 reference one (they have the same RCE). On the other hand, the most SEP reduction effective measure would be replacing the thermal systems of all vulnerable households (Scenario IIc). This could partially be explained by the much higher performance factor of new air conditioners than old ones (Table A 2 and [6]) that would produce a substantial decrease of the RCE (see Fig. 6) in all the case study households. Nevertheless, as was expected, the joint implementation of thermal enclosure retrofitting in very old dwellings and thermal systems' replacement (Scenario III) would produce an even higher SEP reduction.

Table 7 shows the calculation of the budgets that would have to be earmarked to implement the three most effective 2030 scenarios. Scenario III includes two kinds of measures (i.e. low-cost thermal enclosure retrofitting as 1st measure and thermal systems replacement as 2nd measure), which target different numbers of vulnerable consumers. Eventually, the strategies implemented in Scenario I and IIc would need a quite similar budget, but with very different impacts on WEP (Table 4) and SEP (Table 5), and a distinct 'social cost' (see Fig. 8).

Table 8 shows the results of the 'cost – EP benefit' analysis of the main considered strategies for both WEP and SEP. Regarding the former, the Scenario I is the one with the highest WEP benefit – cost ratio, closely followed by Scenario III; in particular, each million euro invested within this strategy would help 71 households to move out from winter energy poverty. On the other hand, the strategy considered in Scenario IIc would move more households out of summer energy poverty per million euro invested than the other analysed strategies (10 more than the second best one).

5. Conclusions and policy implications

Structural measures, e.g. housing energy efficiency interventions, usually take a longer time to be implemented, but they have been pointed out as more effective to avoid 'chronifying' energy poverty in the medium-long term. In that regard, this paper presents an effectiveness assessment of several energy retrofitting strategies in improving energy affordability amongst Spanish vulnerable households. This analysis was carried out by applying the RTEE model proposed in previous studies and estimating: (1) the strategies' impact on energy poverty – both in winter (WEP) and summer (SEP) – throughout an adapted 2 M indicator using households' required energy expenditures; (2) their 'social cost', which includes both the investment and operating costs; (3) their 'cost-benefit' ratios, as the number of households moving out of energy poverty per million euro invested.

Several insights and policy recommendations can be pointed out by analysing the results of the retrofitting strategies' scenarios presented in this article:

Table 7
Numbers of beneficiaries and budgets of the three most effective 2030 energy retrofitting scenarios.

Scenario	Vulnerable consumers involved (1st measure)	Vulnerable consumers involved (2nd measure)	Investment per measure (1st measure) [M€]	Investment per measure (2nd measure) [M€]	Budget [M€]
2030 I	588,882	0	4,500	0	2,650
2030 IIc	1,077,593	0	2,697	0	2,906
2030 III	588,882	1,077,593	4,500	2,697	5,556

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[14] It should be reminded that this value considers that the low-cost building retrofit would only be implemented in 55% of vulnerable households and has a much higher useful time than the thermal systems.

- The Spanish residential sector urgently needs an energy refurbishment. The elevated value of the average required thermal energy expenditure is a symptom of both a disproportionate high required energy burden in vulnerable households and a potential unsustainable high emission of ‘theoretical’[15] greenhouse gases.
- The dwelling’s low-cost thermal-enclosure retrofitting is the most ‘WEP-reduction effective’ measure (among the analysed ones). Moreover, the 2030′s Scenario I shows that the most ‘social-cost’ and ‘cost - WEP benefit’ effective strategy could be implementing such kind of measure in vulnerable households living in building constructed before 1981 (the ones with the lowest energy efficiency).
- On the other hand, replacing old thermal systems with more efficient ones (2030′s Scenario IIc) would have a higher impact on SEP (in particular, driven by the installation of new air conditioners) than thermal enclosure’s retrofits. This primacy is also confirmed by the cost-benefit analysis: indeed, this measure would move more households out of summer energy poverty per million euro invested than the other analysed strategies. However, the ‘social cost’ of Scenario IIc measure would be significantly greater than the one considered in Scenario I because the thermal systems’ replacement has a much higher levelised investment cost.
- Combining both kinds of analysed retrofitting measures (2030′s Scenario III) could produce the highest RTEE and energy poverty reduction (among the analysed scenarios) with the second best ‘social-cost’ effectiveness. Namely, it could reduce heating and cooling required expenditures by, respectively, 49% and 59%, and decrease the WEP and SEP share, correspondingly, by 35% and 63% (with respect to the 2020 Reference Scenario’s level), at an average ‘social cost’ of €1,012 per household (slightly higher than the one of the first scenario).
- However, the increase in fossil-fuel prices projected for 2030 could reduce or outset the positive effect of some retrofitting measures (e.g. heating + DHW systems replacement). One feasible alternative solution to both avoid high energy burdens in vulnerable households using fossil fuels and ‘green’ the residential sector could be the electrification of heating and DHW services (grounded on an already strong political will), as shown in [34]. In this regard, the replacement of existing boilers with heat pumps is included in the LTRS proposals. Nevertheless, the LTRS states that ‘heat pumps have technical operating characteristics that in the short term (2021–2030) make their integration in all climate zones difficult’. Therefore, an analysis of the impact of their integration in a 2050 scenario is more aligned with the Spanish government plans and could be an interesting further work. In the same line, other technologies could also have a significant role in ‘greening’ the residential sector energy consumption, e.g., those using solar thermal energy or biomethane.
- The current legislation and funding implemented in Spain, reviewed in the introductory sections, do not include specific programs for vulnerable people. However, given the paper’s results, promoting these kinds of programs might be essential to boost energy efficiency in those low-income households and significantly improve their energy vulnerability situation in a just energy transition scenario.

Additional future work could analyse the following unexplored topics:

- The variables included in the 2030 analysis may change in many ways. A sensitivity analysis could be performed to include these changes, e.g. different energy prices scenarios or the implementation of the ETS for the residential sector.
- A 2050 scenarios’ analysis could be carried out by analysing some parameters’ long-term variation, e.g., the impact of temperature changes on energy affordability and summer energy poverty.
- Moreover, occupant behaviour and socio-economical parameters also affect energy consumption and saving habits. Therefore, further work could include different household consumption patterns in the RTEE and energy poverty scenarios.
- Another interest research line could be analysing the effect of thermal comfort on the human productivity, which might change depending on the indoor temperature. This effect could be more significant in the warm season, especially when considering the projected future temperature rise, and for people working from home. Thus, further work might investigate a potential connection between the actions taken to reduce SEP and effects on the national economy.
- Additionally, the improvement of electrical appliances could be considered by including a theoretical electricity expenditure analysis (as the one proposed in [35]) both in the 2030 and 2050 scenarios.
- Finally, buildings’ deep-renovation scenarios could be included to analyse their impact on energy poverty and their social-cost effectiveness.

Finally, it should be highlighted that the implementation of the analysed structural measures does not entail the immediate shut down of the current energy-poverty mitigating measures (e.g. social tariffs). Indeed, the latter are even more necessary in the current energy prices crisis’ scenario. On the other hand, previous studies (such as [6;36]) showed that mitigating measures produce a limited impact on energy poverty, especially in a long run perspective. Therefore, as pointed out in this paper, they must be complemented by structural energy efficiency measures in the medium to long term to avoid cronifying this social issue in a socio-economic effective way.

CRediT authorship contribution statement

Roberto Barrella: Formal analysis, Investigation, Methodology, Resources, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **José Ignacio Linares:** Formal analysis, Investigation, Methodology, Project administration, Supervision, Validation, Writing – review & editing. **José Carlos Romero:** Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Validation, Writing – review & editing. **Eva Arenas:** Methodology, Supervision, Validation, Writing – review & editing.

Declaration of Competing Interest

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

Data availability

Data will be made available on request.

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[15] This refers to the theoretical greenhouse gases that would be emitted by vulnerable households if they meet their required energy needs.

Acknowledgements

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Appendix

Table A1, Table A2 and Table A3 show the seasonal performance factors of the new thermal systems.

Table A1

Seasonal performance factor for new heating systems (HSPF) assumed in the 2030 scenarios (own elaboration from [37]) - Individual: individual heating system; Central: central heating system; Portable: portable heater; NG: natural gas; LPG: liquefied petroleum gas (butane/propane); Gasoil: heating gasoil; Bio: biomass; Electricity - Electric Radiator or Electric Storage Heater).

Energy carrier	Individual	Central	Portable
NG	1.00	0.94	1.00
LPG	0.99	0.99	0.99
Gasoil	0.93	0.86	0.93
Bio[a]	0.70	0.69	0.70
Electricity	1.00	1.00	1.00

[a] Biomass was assumed to replace all the coal-fuelled heating systems.

Table A2

Seasonal energy efficiency rating for cooling (SEER) per summer climate assumed for new cooling systems in the 2030 scenarios (own calculation using the methodology described in [38]).

Summer climate zone	SEER[a]
1	6.14
2	5.92
3	5.60
4	5.45

[a] Reversible air-to-air aerothermal heat pumps (76% of cooling equipment in dwellings according to SPAHOUSEC II).

Table A3

Seasonal performance factor for new DHW systems (SPF) assumed in the 2030 scenarios (own elaboration from [37]) - Individual: individual DHW system; Central: central DHW system; NG: natural gas; LPG: liquefied petroleum gas (butane/propane); Gasoil: heating gasoil; Bio: biomass; EWH: electric water heater).

Energy carrier	Individual	Central
NG	0.95	0.92
LPG	0.94	0.92
Gasoil	0.94	0.92
Bio[a]	0.72	0.72
EWH	0.99	0.99

[a] Biomass was assumed to replace all the coal-fuelled DHW systems.

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