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The dark side of energy poverty: who is underconsuming in Spain and why?

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Abstract

The traditional energy poverty 'objective' metrics are mostly focused on households spending a disproportionate share of income on energy. Nevertheless, vulnerable people could also restrict their energy consumption and this 'hidden energy poverty' is not sufficiently considered in metrics and policies.

This paper investigates this phenomenon and proposes a new methodology to determine an absolute threshold below which households' actual energy expenditures are too low to meet their required energy needs. Thereafter, an income criterion is introduced as a proxy to exclude households that have low energy expenditures for reasons other than lack of affordability. Finally, this article analyses the sensitivity of results to the assumptions made for the absolute energy expenditure threshold and the income threshold, thus presenting an alternative 'adjusted to reality' scenario.

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The results for the Spanish case study show that, in 2019, 45% of households had low absolute energy expenditures, but only 56% of these (25% of the total households) were suffering from hidden energy poverty. Besides, the average annual ‘energy poverty gap’ per household was €374, and the national budget needed to potentially fill this gap was €1,692m. Moreover, there was a broad regional disparity depending on climatology and income, and several key factors have been identified, i.e. household size, housing’s energy efficiency and tenure, and locality’s degree of urbanisation.

Thus, the macro-level analysis carried out in this paper makes it possible to characterise hidden energy poverty in Spain, and the policy recommendations provided might guide policymakers to target assistance programs more effectively.

Keywords

Energy poverty; Modelled energy costs; Hidden Energy Poverty; Absolute energy threshold; Energy affordability; Spain

Abbreviations[2]

[2] CTE Spanish Technical Code for Building Construction

DHW Domestic Hot Water

EPOV EU Energy Poverty Observatory

HBS Household Budget Survey

HDD Heating Degree Days

HEP Hidden Energy Poverty indicator

HVAC Heating, Ventilation and Air Conditioning

IDAE Spanish Institute for Energy Diversification and Saving

LPG Liquefied Petroleum Gas

RELE Required ELectricity Expenditure (cooking, electrical appliances and lighting)

RENE Required ENergy Expenditure

RTEE Required Thermal Energy Expenditure (heating, cooling and DHW)

SNSEP Spanish National Strategy against Energy Poverty

TLR Tariff of Last Resort (natural gas)

VPSC Voluntary Price for Small Customer (electricity)

1. Introduction

According to the description in recital 59 of the Directive (EU) 2019/944, households in energy poverty are unable to afford 'essential energy services to guarantee a decent standard of living and citizens' health', such as 'adequate warmth, cooling, lighting and the energy to power appliances', 'due to a combination of low income, high energy expenditure and poor energy efficiency of their homes' [1]. Several indicators have been proposed to estimate the share of households affected by this social issue. These metrics could be divided, in a simplified form, into three main groups : (1) indicators based on income-expenditure (objective indicators); (2) self-reported (subjective) indicators (both included in the classification of [2] and [3]); and (3) 'direct approach' indicators (described in [3]), which monitor parameters such as the indoor temperature. Among the objective indicators, the 'traditional' metrics, e.g. Boardman's Fuel Poverty Ratio [4], have been usually based on a disproportionate expenditure approach, which quantifies the so-called 'measured energy poverty' [5]. This term refers to households whose energy expenditure is considered too high compared to their income, i.e. households that spend too much of their disposable income on energy. On the other hand, low-income households often apply coping strategies to reduce their consumption [6,7,8,9], such as 'switching on heating only in one room, wearing more clothes or slipping under the duvet even during daytime' [6]. Energy spending reduction was identified in [7] as the primary strategy adopted by households to cope with the lack of financial resources. The term 'hidden energy poverty', introduced by Meyer et al. [5], refers to circumstances of '(self-)imposed restriction' of energy consumption, which is the most difficult to detect through existing administrative metrics and energy poverty indicators. Thus, this 'hidden face' of energy poverty has not been sufficiently reflected in measurement and policies [5,10].

1.1. Background on existing Hidden Energy Poverty metrics

To the authors' knowledge, the following are the most relevant European[3] studies on measuring hidden energy poverty (i.e. HEP indicators), which can be classified into two categories according to the kind of energy expenditure threshold proposed.

A. *HEP indicators based on relative energy-expenditure thresholds*

   The energy expenditure thresholds used in the four studies described hereafter are 'relative' because they are based on the median or average values of similar households in the corresponding country.

   - Meyer et al. [5] presented a methodology that fixes a relative energy expenditure threshold and eliminates households having equivalised disposable income excluding housing costs belonging to the five higher deciles and the ones living in 'well-insulated' dwellings.
   - The EU Energy Poverty Observatory (EPOV) introduced, among its primary metrics, the M/2 indicator, which is an underconsumption index that estimates 'the share of households whose absolute energy expenditure is below half the national median' [11]. That indicator is a proxy to identify households that might be in hidden energy poverty. However, the underconsumption circumstance detected in those households could be due to different reasons: high energy efficiency standards, physiological habits or cultural behaviour, ecological awareness, etc.
   - A recent study carried out for Italy [12] is aligned with the 'triple threshold' approach (energy expenditure, income and energy efficiency) used in [5], being the expenditure threshold set as the mean energy

[3] Europe is the geographical area where the energy poverty literature is most extensive and diverse [10].

expenditure of similar households[4] . On the other hand, the second and third constraints are set according to, respectively, both the conditions of absolute and relative poverty[5], and the building construction period.

- Moreover, Karpinska and Śmiech [13] analysed hidden energy poverty in eleven Central and Eastern European countries by considering multiple factors of exposure to this social issue, including housing parameters and location, households' composition, and regional characteristics.

B. *HEP indicators based on absolute energy-expenditure thresholds*

The HEP indicators using an absolute energy-expenditure threshold identify as energy poor the households whose actual energy expenditures are below their required or modelled energy expenditures. Hereafter are some examples of the application of this approach.

- Antepara et al. [14] analysed hidden energy poverty in three southern European countries (Portugal, Spain, and Greece[6]) by using an underconsumption criterion based on modelled energy costs, thus introducing an absolute energy expenditure threshold. These modelled energy expenditures, assessed following the methodology presented by Papada and Kaliampakos [15], were characterized by considering twelve input variables, e.g. income, energy price, or building energy performance. Specifically, in [15], expenditures for heating and cooling were modelled based on the requirements to achieve thermal comfort at home, while the

[4] Here similar households are households with the same size (number of persons) and living in the same climate zone (while in [5] the second condition refers to the dwelling size).
[5] The relative poverty threshold is based on the International Standard of Poverty Line. Whereas absolute poverty 'identifies as poor a household with a consumption expenditure lower than or equal to the monetary value of a basket of goods and services considered essential to avoid severe forms of social exclusion'.
[6] It has to be noted that, in the Portuguese and Spanish case studies, the indicator was applied to a single geographical area, i.e. Évora (PT) and Basque Country (ES).

rest of the energy uses (domestic hot water, cooking, lighting and electrical appliances) were estimated using Greek statistics.

- Papada and Kaliampakos [16] applied the same energy cost model to introduce a new indicator for the Greek case study, i.e. the 'Degree of Coverage of Energy Needs', which assesses the ratio of actual energy expenditure to required energy expenditure.
- In another southern European country, i.e. Italy, Faiella and Lavecchia [17] applied the absolute energy approach only to a single energy service. Specifically, they estimated the share of households in hidden energy poverty as the one whose total expenditure, net of the 'minimum heating expenditure' (absolute energy expenditure threshold), falls below the relative poverty threshold.

Table 1 summarizes the main characteristics of the HEP indicators proposed in the abovementioned studies.

Authors and references	Countries	Database	Energy expenditure threshold	Definition of energy poor	Results (extent)	Results (depth)
Meyer et al. [5]	BE	EU-SILC	Relative	• Actual energy expenditures < half the median expenditure of similar households • Equivalised disposable income excluding housing costs belonging to the five lower deciles • Dwelling being not well-insulated	3.4% (2011) 4.6% (2013) 3.9% (2015)	1140 €/yr (2011) 1123 €/yr (2013) 919 €/yr (2015)
EPOV [11]	EU member states + UK	HBS	Relative	Actual energy expenditures < M/2 (M= National median energy expenditure)	EU average: 14.6% (population, 2015)	-
Betto et al. [12]	IT	HBS	Relative	• Actual energy expenditure < mean expenditure of similar households (HEP1, HEP2) • Total expenditure < relative poverty threshold (HEP1, HEP2) • Absolute poverty (HEP2) • Dwelling being not well-insulated (HEP2)	HEP1: 10.1% (2018) HEP2: 2.3% (2018)	-
Karpinska and Śmiech [13]	Eleven Central and Eastern European countries	EU-SILC	Relative	[Household income − Estimated Household housing costs] < 60% Median (Household income - Estimated housing costs)	Average: 23.6% (2017)	(see [13])
Antepara et al. [14]	PT, ES, EL	Primary surveys	Absolute	• Actual energy expenditures < (Equivalised modelled energy expenditure) / 2 • Disposable income belonging to the five lower deciles	EL: 8.3% (2015) Évora (PT): 8.3% (2014) Basque country (ES): 16.3% (2018)	-
Papada and Kaliampakos [16]	EL	Primary survey	Absolute	DCEN[a] = Actual energy expenditure / Required energy expenditure < 0.8	45% (2015)	-
Faiella and Lavecchia [17]	IT	HBS	Absolute	(Total expenditure - Required heating expenditure) < Relative poverty threshold	11.7% (2014-2016)	550–600 €/yr (2014-2016)

Table 1. A brief review of the methodology and results of the main HEP indicators proposed in Europe

[a] When the value of the Degree of Coverage of Energy Needs (DCEN) is less than 0.8 the household is ‘compressing its energy needs’.

1.2. Suggested approach for the Spanish case study

The underconsumption approach makes it possible to identify the systematic ‘false negative’ cases of the ‘disproportionate expenditure’ metrics, i.e. households with very little energy expenditure. Nonetheless, among these ‘underconsuming households’, it is crucial to identify the ones that restrain their energy expenditure because they cannot afford it, thus suffering from hidden energy poverty. Regarding the threshold typology, using absolute thresholds makes it possible to assess energy poverty rather than energy inequality, the latter being the most common outcome of metrics based on relative thresholds. However, modelling energy costs is a complex work because of the multiplicity of influence factors to consider and, therefore, the numerous simplifying assumptions that have to be made. According to Sovacool et al. [18], simplified mathematical models ‘abstract from real-world complexities and focus on key mechanisms, either conceptually or by combining theoretical assumptions with empirical data’. In this regard, the above studies that attempted to apply the absolute approach either used mixed relative-absolute thresholds, e.g. [14,15,16], or focused only on a single energy service [17]. Therefore, to the best of the authors’ knowledge, the literature lacks a whole absolute hidden energy poverty approach that identifies the extent and the depth of this social issue by comparing households’ actual energy expenditures with their required ones. In this regard, this paper proposes using a theoretical model for estimating energy demand and energy expenditure as a transparent and adaptable tool to serve the decision-maker (who holds ultimate responsibility for fixing its key parameters: e.g. the comfort temperature). However, this is not intended to be used as a ‘substitute’ for the invariably-complex reality.

Particularly, in Spain, researchers from the Association of Environmental Sciences [19] and the research centre Economics for Energy [20,21] characterized the energy poverty phenomenon in an integrated way using different metrics. Nonetheless, in the abovementioned reports and, in general, in all studies concerning Spain, the HEP indicator is not considered or does not include a characterisation of the domestic required energy expenditures. Since 2009, the Spanish Government has been implementing mitigating measures to fight energy poverty from the policy perspective. Currently, households can apply (with a single submission and with income and tariff criteria[7], see [22]) for both a social electricity tariff (which has undergone frequent reforms in the last decade) and a Thermal Social Allowance (which was introduced in 2018). In the former aid scheme, applied to the electricity bill, the vulnerable consumer category receives a 25% discount on the billed energy and power costs, i.e. the discount is applied to the bill amount before taxes. In the case of severely vulnerable consumers, a 40% discount is applied. In the case of households at risk of social exclusion, the discount is ‘100%’, with 50% of this bill being paid by social services. The Thermal Social Allowance scheme is an annual payment for thermal energy services (heating, domestic hot water and cooking). This payment currently depends on the average value of the winter climate severity range for the climate zone of the locality and a coefficient that refers to the annual national budget earmarked for this scheme (see [22] for further details*)*. Despite the government's efforts to design and finance social tariffs, several studies, e.g. [23] and [22], have proved that these measures have had a limited impact on energy poverty in Spain. Nonetheless, since 2019, Spain has had an energy poverty roadmap for five years through the National Strategy against Energy Poverty 2019-2024 (SNSEP) [24]. Regarding the main topic of this paper, the SNSEP attempts to monitor hidden energy poverty by using the EPOV’s

[7] The basic requirements to obtain these aids are: (1) to have contracted the electricity regulated tariff and (2) to have a contracted power equal to or less than 10 kW. All consumers who meet these two basic criteria must also meet socio-economic requirements structured around an income criterion, according to the composition of the family unit.

M/2 indicator, which, as mentioned before, focuses only on 'relative' underconsumption that could be related to phenomena other than lack of affordability.

This paper aims to fill the abovementioned gaps (i.e. the lack of a full absolute HEP methodology and the characterisation of this phenomenon in Spain) by presenting an absolute approach to hidden energy poverty that might help stakeholders to address two critical outstanding queries (being the former the necessary first step to answer the latter):

1. *Who is underconsuming?* The first objective is determining an absolute energy expenditure threshold below which a household's actual energy expenditures are 'objectively' too low to attain a 'necessitated level of energy services' [25]. Therefore, a household is underconsuming if its actual energy expenditures are lower than the threshold.
2. *How to identify households in hidden energy poverty?* The second objective of this paper is defining a criterion to eliminate false positives, i.e. households that are underconsuming for reasons other than lack of affordability. This could make it possible to identify as 'in hidden energy poverty' only the households that cannot afford to satisfy their required energy needs.

Therefore, this article presents a methodology to characterise the extent (share of households in hidden energy poverty) and the depth (energy poverty gap) of this social issue. The first query (*Who is underconsuming?*) is addressed by determining an absolute energy expenditure threshold based on the Required ENergy Expenditure (RENE) model and estimating the share of households whose actual energy expenditures are lower than their threshold ('Low absolute energy-expenditure' indicator). Thereafter, an income criterion is introduced as a proxy to eliminate false positives, thus identifying households 'suspected' of being in hidden energy poverty (HEP indicator). Moreover, a sensitivity analysis assesses the impact of changing various primary parameters of the absolute energy expenditure threshold on the HEP results. Based on this, an alternative 'adjusted to reality' scenario is presented to address the potential overestimation of households' required energy expenditure in the base case scenario. Finally, the HEP indicator is calculated by using an alternative income criterion. The above methodology is applied to the Spanish Household Budget Survey (HBS) samples of four consecutive years (2016-2019). However, the reference year on which all post-analyses have been carried out is the latest in the series. This macro-level analysis characterises hidden energy poverty in Spain and might advise policymakers in targeting policies and prevention measures.

The rest of the article is organised as follows. Section 2 introduces the methodology proposed to characterise underconsumption and hidden energy poverty and shows some initial findings. Subsequently, Section 3 analyses the results of the two metrics, with a special focus on the HEP indicator, and presents the main insights of the sensitivity analysis. Finally, Section 4 points out the conclusions and some policy recommendations in light of the paper's findings.

2. Methodology and initial results

2.1. Determining an absolute energy expenditure threshold

The literature on modelling domestic energy costs points out that building characteristics (age, building type and energy efficiency), location of the dwelling, household consumption patterns [26] and socio-demographic variables, such as household size and composition, are key parameters to define a required energy consumption[8] [27]. The studies carried out in the UK [28], Ireland [29] and Netherlands [30,31] stand out for the integrated approach applied which, in the British case, has led to an official national model, i.e. the Building Research Establishment Domestic Energy Model (BREDEM) [32]. The BREDEM established a methodology to estimate energy requirements for several end uses (lights, appliances, cooking, DHW, heating and cooling) using two kinds of input parameters: 'variable' parameters, which vary with the month of the year (e.g. external temperature), and constant parameters, which have the same value throughout the year (e.g. number of occupants). Raaij and Verhallen [30] conducted research relating personal, environmental and behavioural factors of household energy use. One of the conclusions of this study was that consumers are not always aware of the energy costs related to some of their household behaviour and this fact can lead to both lack of comfort and waste of energy. Other remarkable examples of research on this topic are the following ones. Brouner et al. [31] concluded in an investigation that thermal consumption is mainly determined by the structural characteristics of the dwelling (age, building type and 'building quality'), while electricity consumption is more related to the household composition and income level. Salari and Javid [33] studied the annual

[8] It is important to notice that the required energy consumption model proposed in this paper is primarily intended for applications to domestic energy poverty ('affordability issue') in industrialized countries such as Spain, which may differ from the modelling of basic energy needs used in studies on the 'accessibility issue' in developing countries [27].

electrical and thermal (specifically, natural gas) energy consumption of 168,046 US households for the period between 2010 and 2012 based on a multivariate analysis model. That work determined that five variables' groups can explain residential energy consumption in the US: socio-demographic composition of the household, building characteristics, location of the dwelling, temperature and energy price.

It is worth considering that the case of Spain is quite complex, as it covers a very broad framework of climatic conditions, housing types (in terms of construction age and characteristics) and multiple socio-demographic dimensions. Taking a statistical approximation of the structure of domestic energy consumption [34], heating accounts for the largest share of total consumption in Spanish households (42% in 2018), followed by consumption in household appliances and lighting (32%) and DHW consumption (17%). During the period 2016-2018, the Spanish Institute for Energy Diversification and Saving (IDAE) carried out a statistical analysis of the natural gas consumption in Spanish households with individual heating systems (SPAHOUSEC II [35]), which continued the research previously carried out for the Spanish residential sector [36]. The most significant result was that the climatology and the typology of the dwelling are the main factors influencing natural gas consumption.

Accurate knowledge on the relationship between household characteristics and energy consumption is therefore crucial. This could be used not only for the implementation of appropriate policies to plan investments aimed at optimising energy consumption, but also for a better characterisation of energy poverty (as mentioned in the SNSEP). Indeed, the latter is the first objective of this article, i.e. determining an absolute energy expenditure threshold to eventually characterise hidden energy poverty in Spain. In order to do that, this paper models the energy costs of households in the Spanish HBS[9], which statistically represent all the family units in the country. Nevertheless, this survey lacks of some household characteristics needed for the model, thus this work replaced them with 'proxies', e.g. the residence's region instead of the locality (for more details, see [37] and Appendix A). Thus, the methodology presented in this paper is an 'HBS-adaptation' of the models presented in [22] and [38]. This adapted model makes it possible to estimate the Required Energy Expenditure (RENE) of each HBS household, i.e. the theoretical energy costs that a household would have to pay for to meet its required energy needs, including both thermal energy (heating, cooling and DHW) and electricity (lighting, electrical appliances and cooking[10] [39]) uses. The RENE is estimated according to eight input parameters: (a) region[11]; (b) household size (number of household members); (c) dwelling typology (block dwelling or single-family house); (d) dwelling size; (e) dwelling energy-efficiency rate (according to its 'aggregated-construction-period'); (f) type of thermal energy carrier; (g) year's ownership rate of electrical appliances (h) energy prices and taxes. The HBS variables used for the calculation and the corresponding inputs of the model are shown in Table A1 of Appendix A.

2.1.1. Required Thermal Energy Expenditure (RTEE)

The Required Thermal Energy Expenditure (RTEE) model considers the theoretical costs in heating/cooling (HVAC) and domestic hot water (DHW). The methodology explained in [22] has been used (as a novelty of this paper, the cooling demand was integrated in the calculation) to estimate the annual specific thermal demand for the three services.

[9] The structure of the Spanish HBS is similar to the one of equivalent surveys in other Member States, which makes this model 'adaptable' to other countries. However, before adapting the model, the following country features should be analysed: socio-demographic characteristics, building's stock and regulation, energy prices and climatic characteristics.

[10] According to 2018 statistical data [39], more than 60% of the Spanish households use electricity to cook.

[11] This input is used to approximate the parameters related to the climatology, i.e. winter climate zone, summer climate zone, and network water temperature.

Therefore, the RTEE model is an extension of the model presented in [22] and is based on the requirements of the Spanish regulation (Spanish Technical Code for Building Construction, CTE 2019). The three most significant assumptions made in the calculation of the required HVAC demand according to the CTE 2019 are the following ones: (1) it sets a baseline comfort temperature of 20ºC; (2) it assumes that 100% of the dwelling's floor area is conditioned, (3) it supposes a 24h/7d occupancy. Furthermore, the required HVAC demand is based on climate data of a typical year, which are provided by the Spanish building regulator as complementary files of the CTE. Appendix B presents the details of the methodology used to calculate the annual specific thermal demand.

Firstly, it is necessary to determine which climate zone[12] each household belongs to (HVAC demand), as well as the network water temperature (DHW demand), both established based on their province of residence and the altitude of the locality (CTE 2019). As mentioned before, due to the lack of exact geographical information in the HBS, the specific thermal energy demand has been calculated as a regionally weighted parameter (see Appendix B)[13]. The provincial specific-demand values for heating [kWh⁄(m² year)] and DHW [kWh⁄(person year)], estimated using the methodology of [22], were weighted by number of inhabitants to calculate the regional specific demand values. On the other hand, the specific cooling demand [kWh⁄(m² year)] (which was not considered in [22]) was calculated for the 8,131 Spanish localities and then, weighted for each region. Secondly, households were grouped according to the dwelling type (block dwellings or single-family houses, see Table A1 in Appendix A). Thirdly, the energy efficiency parameter (EEP in [22]), which basically depends on the insulation level of the

[12] As in [22], the winter climate zone can vary from α to E, i.e. from the lowest to the highest heating demand. On the other hand, the summer climate zone is identified by a number, from 1 to 4, in order of increasing summer severity.
[13] Spain is a regional state, and the regions are further divided in provinces (second level of administrative division).

dwelling, was set according to the aggregated construction period. In this regard, the HBS indicates whether the date of construction of the building is ‘less than 25 years ago’, or ‘25 or more years ago’. However, this differs from the aggregated construction periods defined in [22]. Therefore, in order to set the value of the EEP, it has been necessary to adjust the age ranges of [22] to the HBS variable. In addition, the values of the efficiency parameter (see Appendix B) were updated based on the 2019 IDAE report on energy performance certificates [40].

Subsequently, the specific required HVAC demand [kWh/(m^2 year)] for each household has been assessed in relation to the region, the dwelling type and its year of construction (see Appendix B). The same procedure has been used to obtain the specific DHW demand [kWh/(person year)] of each household according to region and dwelling type. Afterwards, the values of required demand for HVAC and DHW [kWh/year] of each HBS household were calculated by multiplying the specific demand values, respectively, by the dwelling size or the number of household members (obtained from the variables shown in Table A1).

The required consumption for heating, DHW and cooling was then obtained by calculating the ratio between the required demand and, respectively, the seasonal performance factor for heating (HSPF) and DHW (SPF), and the Seasonal Energy Efficiency Ratio for cooling (SEER). The values of HSPF and SPF depend on the energy carrier and the type of installation (individual or central). However, as an approximation, all households have been considered to have individual systems (both for heating and DHW preparation) because of three main reasons: (1) there is no information available in the HBS to know whether a household has central or individual systems; (2) the values of HSPF and SPF are similar (see [41]) so using this assumption does not change the results to a large extent; (3) [41] estimates that only 10% of Spanish households have a centralised installation serving a group of dwellings. Regarding the energy supply of the heating and DHW systems, five types of energy carriers are distinguished (natural gas, LPG, heating gasoil, biomass[14] and electricity) whose seasonal average efficiency is given according to the values shown in Tables A10-A11 and Table A14. Secondly, for the SEER calculation, air-to-air units have been considered, as this is the most common type of air conditioning system in the Spanish residential sector (according to the IDAE [35], they are 92% of the installed air conditioning systems). Tables A12 and A13 show the SEER values used for the different summer climate zones. Starting from that, a weighted average of the SEERs of all localities in each region (according to the number of inhabitants of each locality) was calculated to set a weighted regional-average SEER.

Finally, to assess the expenditure allocated to the required thermal energy consumption, the different energy-price's terms have been determined according to the type of energy carrier and the year in question. Particularly, the yearly average regulated-market-prices and the regional tax rates (see Appendix C) have been applied to the required consumption of each service. Therefore, the sum of the required expenditure for heating, cooling and DHW gives the household's RTEE.

2.1.2. Required Electricity Expenditure (RELE)

In a previous study [38] , the Spanish households' 'Required Electricity Consumption', i.e. 'the theoretical annual consumption required to meet their electricity needs, according to the most representative household parameters', was estimated. That model considers the dwelling size and the number of household members (household size) as input parameters and includes the following electricity uses: cooking (stoves and oven),

[14] In the HBS biomass and coal are included in a unique energy carrier option, i.e. 'solid fuels'. Since the use of coal for reason other than cooking in Spanish households is limited (in 2019 only 4.2% of households declared expenses on this fossil fuel compared to 10.2% declaring expenses on biomass), the 'solid fuels' option was considered as biomass (see Table A1).

electrical appliances (washing machine, tumble dryer, refrigerator, freezer, dishwasher, television, computer and other uses) and lighting. The household size is the key parameter of this model as it determines the usage factors of all the electrical appliances, which were set according to the Spanish household habits included in official national studies (see [38] for further details). On the other hand, the dwelling size is included only in the lighting modelling. The results of [38] were compared with official statistics and validated by applying the model to an NGO's households-database. Both comparisons showed accordance of the modelled electricity consumption with the Spanish households' actual consumption. Regarding the parameters used to estimate the 2016-2019 consumption values of the most 'frequently-changed' appliances (lighting, computer, tablet, television and stoves), as a novelty of this paper, a forecast of the evolution of the ownership rate over the years has been made by analysing the results of national statistics, i.e. SECH-SPAHOUSEC (2010 data), SPAHOUSEC II (2016 data) and data provided by the Spanish National Institute of Statistics (INE) [42]. Based on this, and on the model presented in [38], the 'required annual electricity consumption of Spanish households from 2016 to 2019' has been estimated. Therefore, the value of the Required ELectricity Expenditure (RELE) of the households of each HBS was calculated by applying the 2016-2019 regulated electricity prices and taxes to the corresponding required consumption (see Appendix C), and including the fixed term related to the required power contracted by the household, set according to the hypotheses of [43].

2.1.3. Analysing the initial results of the RENE model

The Required Energy Expenditure (RENE) of each HBS household was finally calculated by summing up their RTEE and RELE. Fig. 1 summarizes the calculation and the components of the RENE.

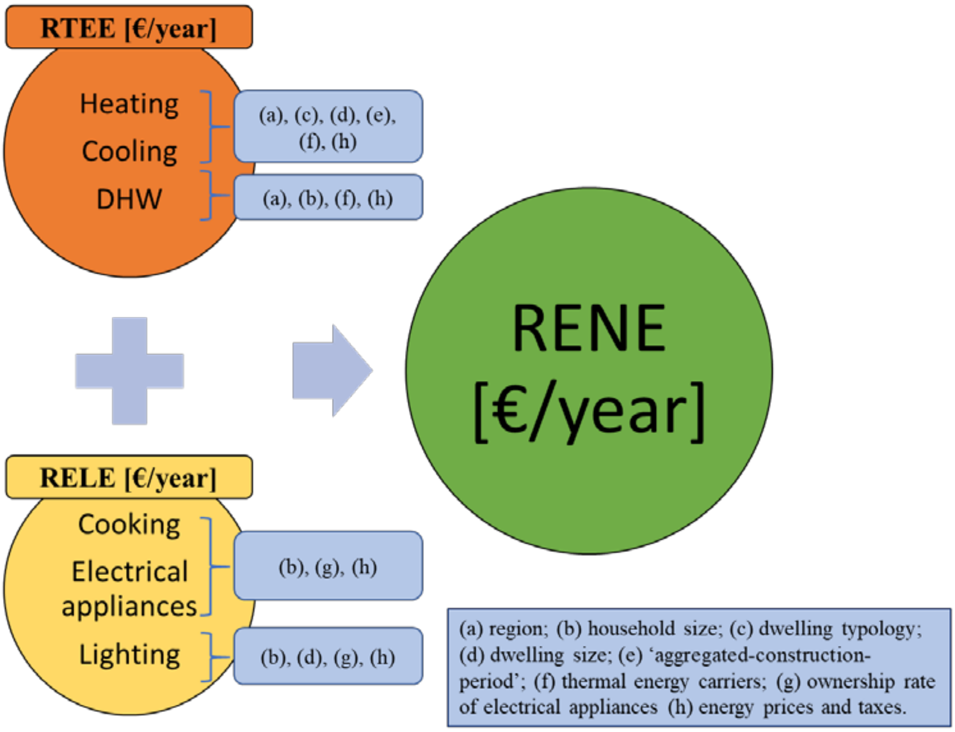

Fig. 1. Components and parameters involved in the calculation of a household's RENE

Thus, Fig. 2 shows the 2019 average required expenditure for each energy use considered in the model. The RELE is shown in an aggregated form because it was calculated from the required electricity consumption as a whole.

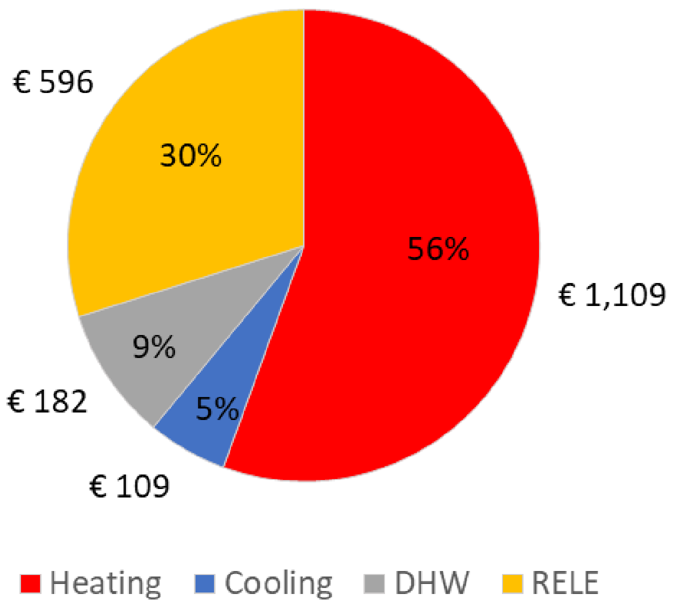

Fig. 2. Average required annual expenditure [€/year] and costs' share [%] for each energy use in the 2019 HBS

The weighted national average RENE for 2019 is €1,997 and the energy use that most contributes to the household's expenditures is heating (56%), followed by the appliances included in the RELE (30%). Table A15 provides some examples of RENE value in different Spanish households (2019), whereas Fig. A2 shows the average RENE results for the four years of the series. The predominance of heating is consistent with the distribution of the actual domestic consumption analysed in the statistics by IDAE [34]. However, the share of heating expenditure in the RENE is 32% higher than the heating-consumption share in IDAE statistics. On the other hand, there is a significant difference in the cooling share, which is five times higher in RENE than in statistics. This may be explained by the fact that only 35.5% of Spanish households own air-conditioning units [44] compared with 84.7% of population that would require it for some period during the year (own calculation from the RENE analysis), i.e. space cooling is still considered 'a luxury'. These findings were crucial to define most of the sensitivity analyses presented in Section 2.2.2. Moreover, it should be highlighted that the procedure to allocate the fixed term of the electricity and natural gas tariffs in the RENE model (see Appendix C) has also an impact on the cost's distribution. Particularly, it slightly increases the RELE share in all households and, depending on the household's heating fuel, it could produce a small increase of the share of heating expenditure.

2.2. Underconsumption and hidden energy poverty

This paper proposes two metrics that aim to distinguish households suffering from hidden energy poverty from the ones that are underconsuming for other reasons, such as high energy efficiency standards. Particularly, the 'Low absolute energy expenditure' indicator is introduced to estimate the trend of domestic energy underconsumption in the country by applying an absolute energy expenditure threshold (see Section 2.2.1). On the other hand, the hidden energy poverty indicator (HEP) introduces a second threshold (based on the results of the former metric) as a proxy to identify households that cannot attain an adequate level of energy services due to financial constraints (see Section 2.2.2). Both indicators are applied to the samples of the Spanish HBS of four consecutive years (2016-2019), thus characterising the extent (share of households in hidden energy poverty) and the depth (energy poverty gap) of this social issue in the country. The aim of the latter measurement is to calculate the difference between the actual energy expenditure of households identified as energy poor and the absolute threshold, thus quantifying the additional budget that these households would have to spend on energy to meet their required energy needs. Moreover, elevating this amount to the whole country makes it possible to have a reference of the national budget needed for a hypothetical hidden energy poverty mitigation policy.

2.2.1. Low absolute energy expenditure indicator

The difference between the general-population-household's actual energy expenditure and its RENE is the 'energy-expenditure gap'. Fig. 3 shows the 2019 boxplot of the energy-expenditure gap among the income deciles. The distance between the first and third quartiles (lower and upper parts of the box) shows the degree of dispersion (spread) in the gap data, and the lines indicate the variability outside the quartiles. The outliers are excluded from the plot.

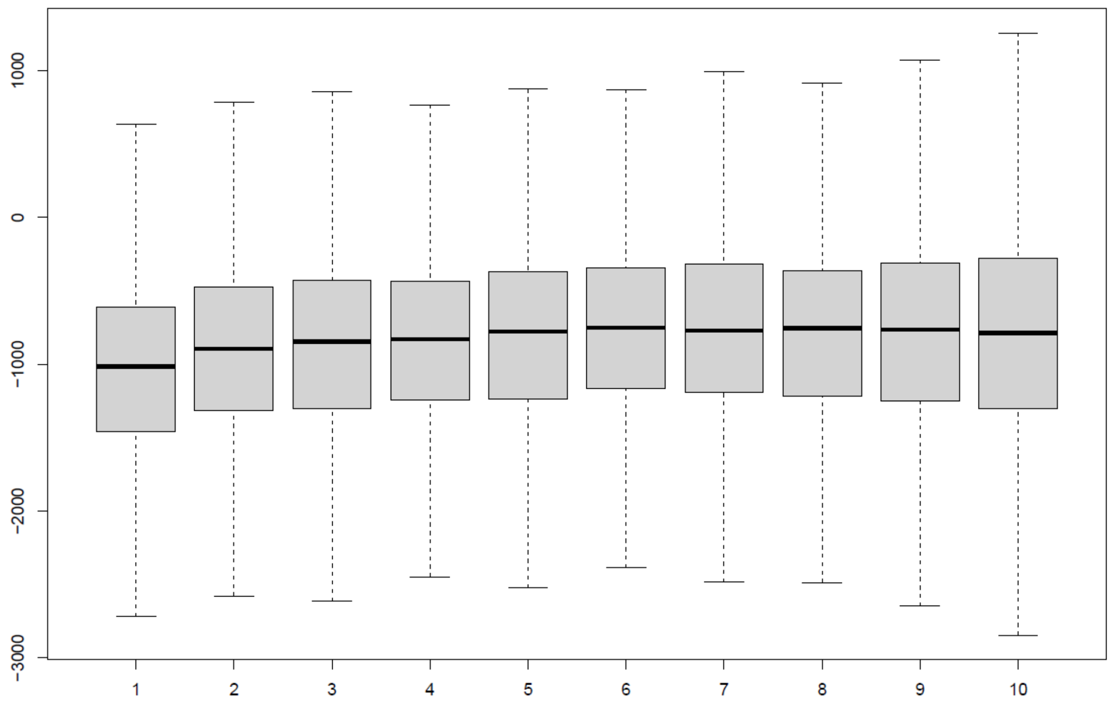

Fig. 3. 2019 distribution and median households' energy-expenditure gap [€/year] with respect to the RENE disaggregated by equivalised income decile

The median value of the gap is practically the same in the five highest income deciles, while it decreases (in absolute terms) with revenue in the five lowest income ones. Regarding the distribution, the number of positive gap cases and the value of the Maximum (100th percentile) increase with income, i.e. in the highest income deciles there is greater probability of finding households that overconsume ('energy obesity' [45,46]). On the other hand, the negative gap (underconsumption) cases have not a clear trend.

Indeed, the lowest Minimum of all the sample (lowest 0th percentile value) belongs to the highest income decile, whereas the lowest income decile has the smallest first quartile value. Overall, the highest two income deciles show the greatest degrees of data dispersion, i.e. the casuistry of richest households may be very diverse. The median value (black horizontal line in the chart) is negative in all the income deciles, i.e. averagely, the Spanish household actual expenditure is lower than their RENE. Thus, given the lack of exact household information in the HBS (see Appendices A and B) and considering the model assumptions, it can be deduced that the 'adapted RENE model' may overestimate the domestic theoretical energy costs. Therefore, following the literature on hidden energy poverty [5], the boxplot was redrawn considering half the RENE as reference value for the energy-expenditure gap and tentatively value for the absolute energy expenditure threshold of the indicator. Fig. 4 shows the 2019 boxplot of the energy-expenditure gap with respect to the RENE/2 disaggregated by income deciles.

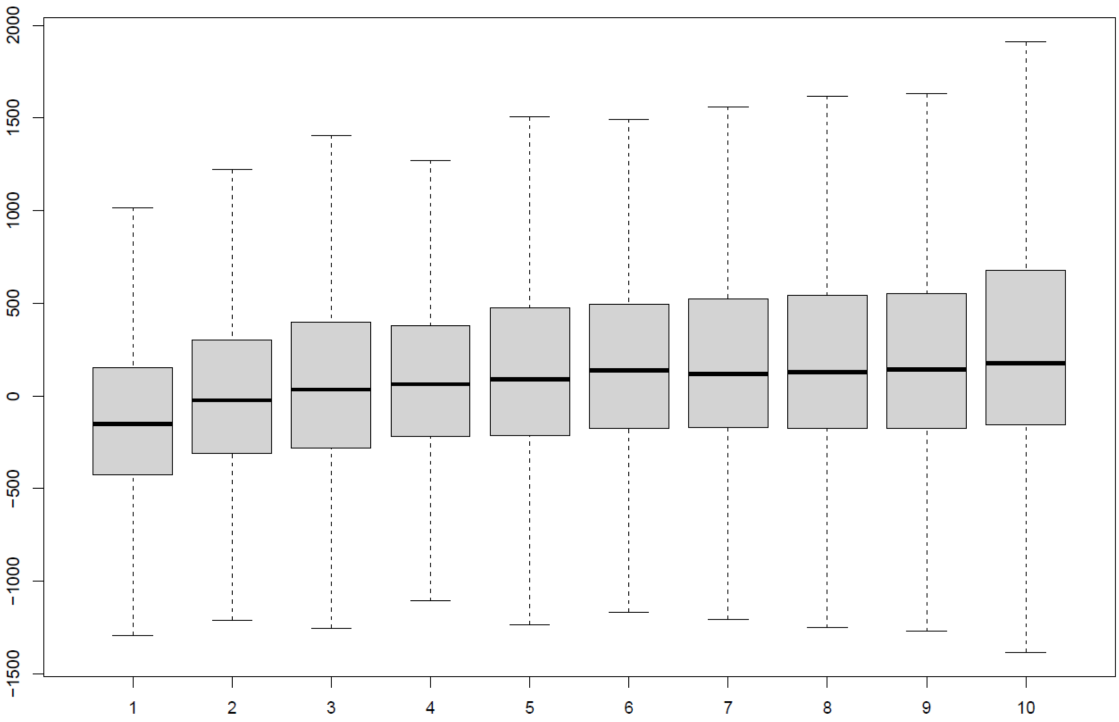

Fig. 4. 2019 distribution and median households' energy-expenditure gap [€/year] with respect to the RENE/2 disaggregated by equivalised income decile

In this case, the median energy-expenditure gap is negative (potential[15] underconsumption) only in the first two income deciles (lowest income). In the rest of deciles, it is positive (potential overconsumption). For reference purposes, the median energy-expenditure gap of the five highest income deciles was calculated, as it was assumed that these households, in principle, do not have financial restraints that 'force' them to underconsume. The results show that this value ranges between €65 (in 2017) and €139 (in 2019). This means that, averagely, the Spanish households belonging to the five highest income deciles spend on energy more than their RENE/2. Thus, this procedure was iterated to find the proportion of RENE that determines a median gap of the five highest income deciles equal to €0. The latter calculation was carried out to align the modelled absolute energy expenditure threshold with the Spanish situation. The null

[15] Energy prices and household behaviour could influence the results, so it is not possible to clearly identify underconsuming and overconsuming households at this stage.

value for 2019 is achieved by setting the threshold at RENE/1.73. Using the latter value as threshold for the 'low absolute energy expenditure' indicator would enhance the accuracy of the results. Nonetheless, when applying this methodology to a specific case study, the proportion of RENE that 'fits' with each year would have to be calculated, thus adding too much complexity to its adaptation. This would make the indicator difficult to integrate, for instance, in the annual energy poverty monitoring of the Member States' Climate Action Social Plans (defined in the 'Fit for 55' EU proposal [47]), e.g. in the SNSEP that is already carrying out this analysis for Spain. Furthermore, the other main objective of this paper is to propose a hidden energy poverty indicator scalable to other geographical contexts, e.g. other EU member states, both at national and regional level. The target of finding the exact proportion of RENE to 'zero the gap' would make the methodology difficult to explain and replicate. Therefore, given the above reasons and the relatively low median gap with respect to the RENE/2, setting half the RENE as absolute energy expenditure threshold for the paper's proposed indicators seems accurate enough to identify households that are underconsuming.

In the light of this finding, to calculate the 'Low absolute energy expenditure' indicator, the actual energy expenditure of each household of the HBS[16] has been compared with half their Required ENergy Expenditure (RENE/2), considering as 'underconsuming households' the ones whose actual energy expenditure is below their absolute energy expenditure threshold. Afterwards, the indicator was disaggregated by income deciles[17], with the aim of isolating those households whose low energy expenditure might be due to factors not related to a social vulnerability situation, such as high energy efficiency in

[16]The HBS assigns an expansion factor to each household, therefore the HBS households represent a statistically significant sample of the Spanish population.

[17] To classify the sample by equivalised income deciles, the household's equivalised total expenditure (see Table A1) was used as reference value following the same methodology as in [21]. Hereafter, this variable will be called 'equivalised income' or just 'income' for simplicity's sake.

housing. Indeed, the energy retrofit of a household's dwelling reduces its required energy consumption, something that the RENE/2 indicator is not able to detect (due to the lack of specific data in the HBS), which could lead to false positives. It is therefore necessary to introduce an income criterion to identify who is underconsuming due to lack of financial resources (affordability problem), i.e. who is truly in a situation of hidden energy poverty. Thus, Fig. 5 shows the 2019 share of underconsuming households in each income decile with respect to the total number of households in the decile under consideration.

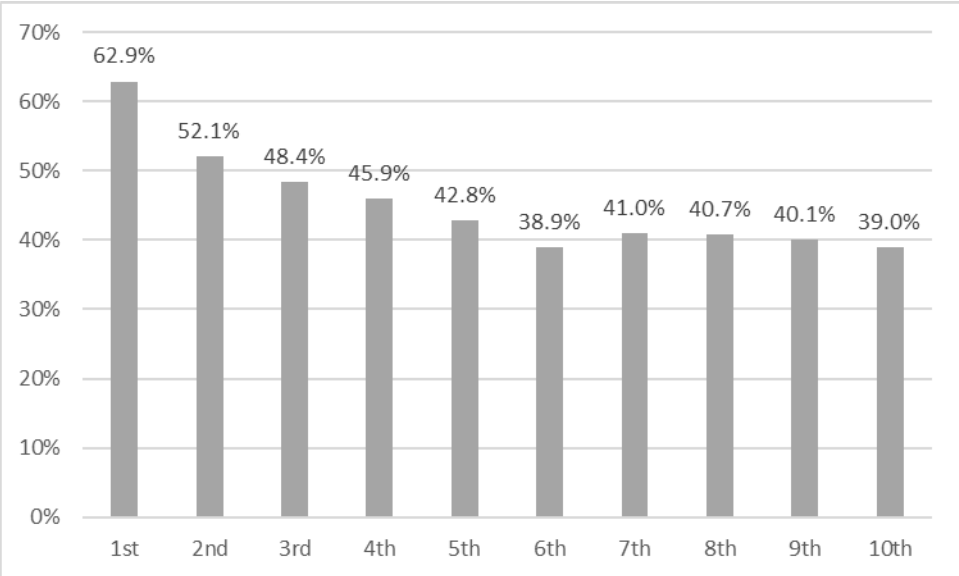

Fig. 5. RENE/2 indicator's values in 2019 for each equivalised income decile

The share of underconsuming households in the lowest income deciles is greater than in the highest income deciles. Indeed, there is a clear income-driven 'upward trend' (from 42.8% in the fifth decile to 62.9% in the first decile, a difference of 20%) only in the lowest five income deciles; in the five highest income deciles there is no clear trend and the indicator hovers between 38.9% and 41%. A similar RENE/2 trend was observed in the other years analysed, i.e. the share of underconsuming households in the first five deciles decrease with income, while it remains quite stable in the last five deciles (see Table A20 in Appendix E). Therefore, looking at the results of the indicator, it is reasonable to assume that there is a fixed percentage of households in the higher income deciles that underconsume for reasons unrelated to lack of affordability. This assumption is supported by several studies in the literature. For example, [48] pointed out that 'voluntary underconsumption' could be related to high energy efficiency standards, ecologist behaviour, conscious consuming or other drivers related to a higher education level, which are more common in high-income households. Indeed, 37% of Spanish households belonging to the five highest income deciles live in recent constructed dwellings (i.e. constructed less than 25 years ago), whereas this share is 25% lower for the five lowest income deciles (i.e. 28%). On the other hand, the limited financial resources of low-income households 'force' them to underconsume [49] and is a major barrier for the retrofitting of their dwellings or the purchasing of more efficient equipment [50]. Furthermore, several studies, e.g. [51], pointed out that low-income households are more often tenants than owners of their dwelling and that rented dwellings have a lowest energy efficiency than dwellings occupied by their owners. In these cases, the tenants have no decision-making power to retrofit the dwelling and landlords 'do not gain any direct advantage from improvements in energy efficiency in the property' [51] (cf. tenant-landlord dilemma). In this regard, in the paper's case study (i.e. Spain), 23% of households belonging to the five lowest income deciles live in rented dwellings compared with 13% of the highest income households (HBS, 2019). Moreover, as mentioned before, low-income households usually live in older dwellings: the 72% of them live in buildings constructed more than 25 years ago (HBS, 2019). Thus, the underconsumption situation identified in the latter can more likely be related to an issue of forced self-restriction. Therefore, the income criterion chosen for the calculation of the HEP indicator is to exclude the five highest income deciles, i.e. the households belonging to these deciles and being in underconsumption are considered as false positives.

2.2.2. Proposed new Hidden Energy Poverty indicator (HEP)

According to the proposed HEP indicator, a household is suspected to be in hidden energy poverty if: (1) its actual energy expenditure is below half its required energy expenditure (RENE/2), and (2) it belongs to one of the five lowest equivalised income deciles. Thus, this metric was applied to the analysed Spanish HBS samples as follows.

Firstly, the national share of households in hidden energy poverty (extent of hidden energy poverty in Spain) is estimated for the four years analysed. Then, for these households in hidden energy poverty, the 'energy poverty gap' (depth) is calculated as the difference between their RENE/2 and their actual energy expenditure. Furthermore, the national budget needed to fill this gap is calculated by multiplying each 'energy poverty gap' value by the household's 'spatial expansion factor'[18], i.e. scaling the result over the entire population. This calculation is partially inspired by the one proposed by the World Bank for the 'poverty gap' [52] and it has already been applied to energy poverty in other countries (using different methodologies), such as Belgium [5], France [53] and the UK [54].

Secondly, the paper presents five disaggregated analyses on the HEP extent. In the first one, the HBS households are clustered by region to explore the geographical and socio-economical differences. The second disaggregated analysis estimates the HEP extent according to the number of household members, thus analysing the influence of the household size on this social issue. The third one analyses the influence of the age of the building (as a proxy of its energy efficiency) on hidden energy poverty. The fourth and fifth disaggregated analyses focus on two characteristics that have been pointed out in

[18] The spatial expansion factors are used to raise the sample data to the population, so that the spatial expansion factor of a sampled household is the number of households in the population that it represents.

literature as influencing energy poverty, i.e. the status of owner or tenant [51] and living in urban or rural areas [55].

Finally, three types of sensitivity analyses were conducted by studying the influence of primary parameters of the absolute threshold on the HEP indicator's results:

- HDD_18 and. HDD_16 - Given the high share of the HVAC expenditure in the total RENE (see Fig. 2), it is relevant to analyse the impact of changing key baseline parameters of its calculation. Regarding heating expenditure (which represents 56% of the households' RENE), in the base case scenario, it was calculated by using IDAE reference demand [56] that applies 20 °C as baseline temperature. Nevertheless, according to the World Health Organization (WHO), the comfort temperature required to avoid health problems during the cold season is 18 °C. Therefore, the required heating demand calculation was repeated using 18 °C as baseline temperature. Table A16 shows the reference demand values to ensure comfort assuming the WHO lower threshold temperature. Setting the base temperature at 18°C instead of 20°C in the Heating Degree Days (HDDs) calculation reduces the heating demand by averagely 38% (in line with studies that use adaptive comfort thresholds [57]; see Table A17). Moreover, some studies (e.g. [58]) pointed out a lower indoor temperature threshold to avoid respiratory diseases, i.e. 16ºC. Therefore, the heating demand was calculated again by assuming a baseline comfort temperature of 16ºC. In this case, the heating demand decreases by averagely 63% (see Tables A18-A19). The results of these two calculations were applied to estimate two HEP scenarios with lower heating requirements: HDD_18 and HDD_16.
- A_0.9/0.8/0.7 - The second sensitivity analysis has been carried out assuming a decrease in the floor area conditioned (HVAC) by households. This scenario is

considered because it is common that households do not have (or do not use) HVAC appliances in all dwelling's rooms. For example, storage rooms and kitchens are spaces that frequently do not need to be climate-controlled. Given the variability of this parameter, different percentages of air-conditioned floor area (90%, 80% and 70%) were assumed for the calculation. Therefore, these new demand values were integrated in the HEP estimation, thus introducing three new HEP scenarios (A_0.9/0.8/0.7).

- RENE/4 and 3/4 RENE - The third kind of sensitivity analysis focused on the percentage of RENE set as absolute threshold. On the one hand, some 'severely vulnerable households' tend to compress their energy consumption to an extreme point. Therefore, to detect this 'extreme hidden energy poverty', the calculation of the indicator was repeated by setting the threshold to RENE/4 as a proxy of the household's minimum energy expenditure. On the other hand, some households are either placed outside but close to the energy poverty area defined by the threshold RENE/2 or are approaching that area. Thus, a higher threshold, i.e. 3/4 RENE, was considered as a proxy to identify households that could be 'vulnerable to hidden energy poverty'.

The results of the 'Low absolute energy expenditure' indicator (see Fig. 5) and the HEP sensitivity analysis (see Section 3.2 and Appendix E) pointed out that the required HVAC expenditure estimated according to the Spanish regulation might not be aligned with the actual consumption patterns of a considerable share of Spanish households. This could lead to an overestimation of the households affected by hidden energy poverty. Therefore, this paper proposes an alternative scenario 'adjusted to reality' (in line with the literature from other countries, e.g. Portugal [45]) as an additional sensitivity analysis: the HEP indicator was calculated adjusting the HVAC demand's primary parameters to the

Spanish residential sector's features and the WHO recommendations, i.e. 18 ºC as baseline comfort temperature (WHO), 75% of heated floor area [59] and 60% of cooled floor area [60].

Finally, the HEP indicator was calculated by using as income criterion the EU 'at risk of poverty' threshold (AROP) [61], i.e. 60 % of the national median equivalised income, which was already applied in several studies on energy poverty (e.g. [13]). It has to be noticed that the equivalised income proxy used for this threshold is the same as the one used in the base case scenario (see Section 2.2.1).

3. Results and discussion

3.1. The extent and depth of hidden energy poverty in Spain

To understand the HEP metric presented in this paper, it is crucial to analyse the absolute energy expenditure threshold set for the two indicators. Fig. 6 shows the regional weighted-average RENE calculated a posteriori from the required energy expenditure assigned to each 2019 HBS household.

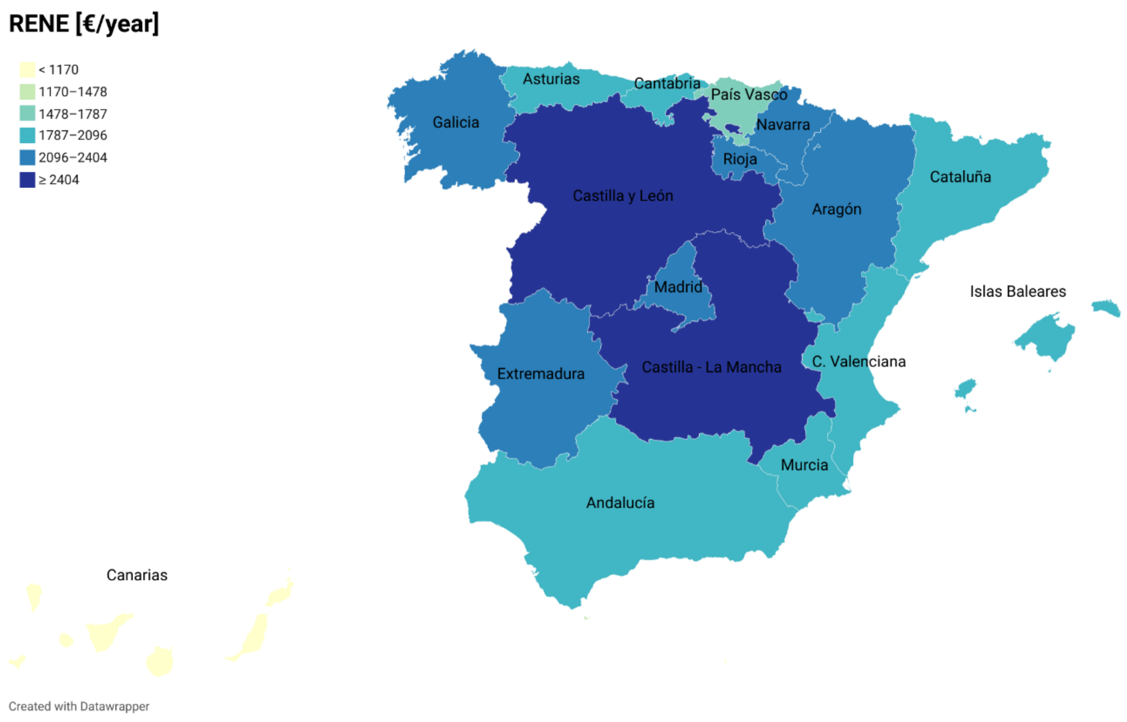

Fig. 6. Regional weighted-average RENE per household in 2019 [€/year]

The average RENE for Ceuta and Melilla (two autonomous cities not shown in the map) is, respectively € 1,262 and € 1,055. Fig. 6 highlights that the required energy expenditure varies significantly depending on the household's region of residence, with a marked difference between the inland and the coastal regions. The main driver to explain this difference is climatology, which influences the HVAC and DHW demand. Particularly, the winter severity is the parameter that largely explains these differences, being the average required heating expenditure 56% of the total energy one (see Fig. 2). Indeed, this share is much higher in the two regions with the highest RENE (65% and 68%, respectively, in *Castilla - La Mancha* and *Castilla y León*) than the ones with the lowest required expenditure on energy (23% and 28%, respectively in *Melilla* and *Canarias*). Two outstanding cases are *Extremadura* and *Canarias*. The former has high energy expenditure both on heating and cooling, having indeed the highest air-conditioning expenditure value within the country. On the contrary, *Canarias* is a mild climate region, thus having the lowest required expenditure for heating and among the lowest required cooling costs in the country. On the other hand, the RELE mainly depends on the household size (it increases with the number of members), and it does not vary with climatology. Therefore, it has a lower geographical variability than the RTEE.

Fig. 7 shows the trends of the RENE/2 and HEP indicators for the four consecutive years analysed. The shares of households identified by both metrics decrease after 2017. Nevertheless, it has to be noted that they are measuring two related phenomena, i.e. underconsumption and hidden energy poverty, thus it is essential to deeply analyse the results to understand the causes and effects of these issues.

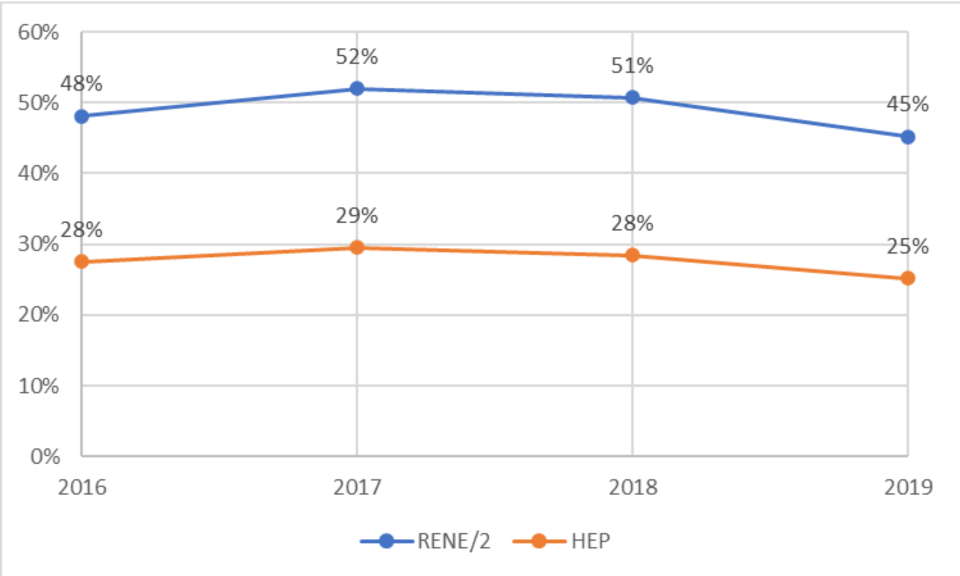

Fig. 7. Values of the RENE/2 and HEP indicators from 2016 to 2019

The higher values of both indicators were achieved in 2017, followed by the 2018 values. A possible partial explanation of this result is the higher energy prices reached in these two years (see Appendix C) that may have induced households to reduce their energy consumption. It is not possible to clearly assess the impact of the climatology across the years because the RTEE model uses climate data of a typical year, following the Spanish regulation (CTE, 2019). Nevertheless, the years in question (2016-2019), according to the Meteorological State Agency of Spain (AEMET), registered similar average temperature values: 15.8ºC (2016); 16.2ºC (2017); 15.5ºC (2018); 15.9ºC (2019). The average temperature of the typical year (15.1ºC) differs significantly only from the 2017 one, which was a particular warm year. This could also have contributed to determine higher values of the indicators in that year[19]. However, according to [62], the temperature sensitivity of the Spanish actual daily electricity consumption is very low, especially around 15ºC. Therefore, the actual consumption variation due to temperature changes might have been small over the four years.

Focusing on the last year of the series (2019), 45% of Spanish households had a 'too low' energy expenditure, but only 56% of the latter (25% of the total family units, i.e. 4.7 million of households) were affected by hidden energy poverty. Comparing the latter number of households with the ones that benefitted from the social tariffs in 2019, i.e. 1.3 million households [63], lead to the conclusion that at least 3.3 million of households in hidden energy poverty did not benefitted from the national mitigating measures. As explained above, the HEP indicator considers the underconsuming households belonging to the five highest income deciles as false positives because, among other possible reasons (e.g. physiological and generational habits [58] or long-term absence due to business trips; see Fig. 3[20]), they have more purchasing power. Therefore, although for the HBS they live in old buildings[21], they could have retrofitted their houses thus reducing their required energy consumption. On the contrary, according to a Red Cross report [64], 81% of Spanish vulnerable households (low-income deciles) do not use energy-saving

[19] The modelling of the required heating demand for the 2017 HBS (based on the typical year climate) considerably overestimated the required heating needs of that year (being the 2017 significantly warmer than the typical year).
[20] Fig. 3 shows that the lowest 0th percentile value belongs to the highest income decile, i.e. there is a considerable number of very high income households that have an extremely low actual energy consumption, which is certainly not due to energy poverty.
[21] The limited information on the building construction age and the absence of data on the energy performance certificate prevents a detailed analysis of the influence of energy efficiency on hidden energy poverty.

systems, either because they are unaware of them or cannot afford them. Moreover, the quality of appliances in rented apartments depends sometimes on the goodwill of the owner (cf. there could be different appliances provided by the owner who could prefer a low cost appliance to an energy efficient one). However, the majority of the people surveyed by the Spanish Red Cross declared to be very cautious in spending on electricity and gas services. Consequently, given the above and considering the constancy of the richest households' underconsumption share shown in Fig. 5 (surely not income-driven), the income criterion set for the HEP indicator can be considered an acceptable assumption.

Fig. 8 shows the results of the HEP indicator and the equivalised net disposable income disaggregated by region.

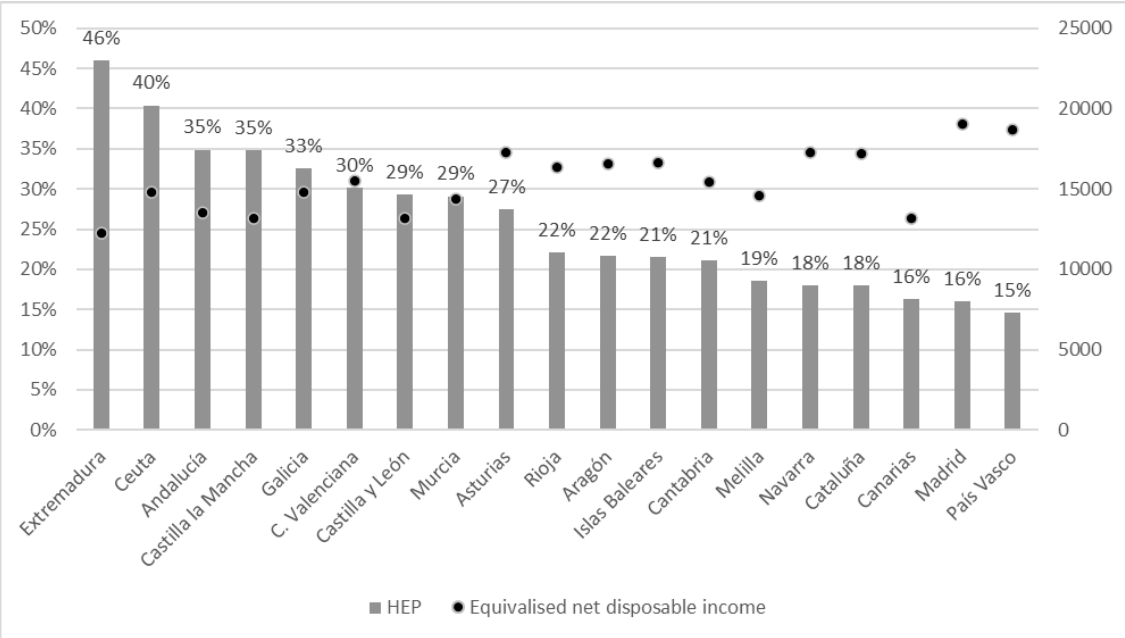

Fig. 8. 2019 HEP indicator [%] and equivalised net disposable income [€/year] (OECD modified equivalisation of the IMPEXAC variable of the HBS 2019) disaggregated by region

There is a wide disparity in the results across Spanish regions. Although a priori the high shares of energy poverty in *Ceuta* and *Andalucía* might be surprising (their RENE values are not among the highest ones in the country), this may be explained by two issues: they are low-income regions (their equivalised net disposable income, respectively, €14,788 and €13,556, are lower than the national average one, i.e. €15,786) and a large number of households living there do not own heating devices (respectively, 98% and 78%, according to the HBS) even if they would require them to achieve comfort (as shown in Table A4). On the other hand, the drivers that make *Extremadura* the region with the highest share of HEP are more evident. As mentioned before, households living in this region have high required expenditure both on heating and cooling. Moreover, they have the lowest net disposable income within the country. On the contrary, the richest regions, i.e. *Madrid* and *País Vasco,* experienced the lowest HEP shares.

Furthermore, HEP proportion varies quite significantly with the household size, as shown in Fig. 9. Particularly, households with more than four members are the most affected by this social issue, followed by single-member households. On the one hand, Spanish large families have lower equivalised net disposable income and need more energy than the rest of the households. On the other hand, a possible explanation of the high HEP share of single-member households lies in the fact that people living alone might spend less time at home and use HVAC devices only in one or two rooms.

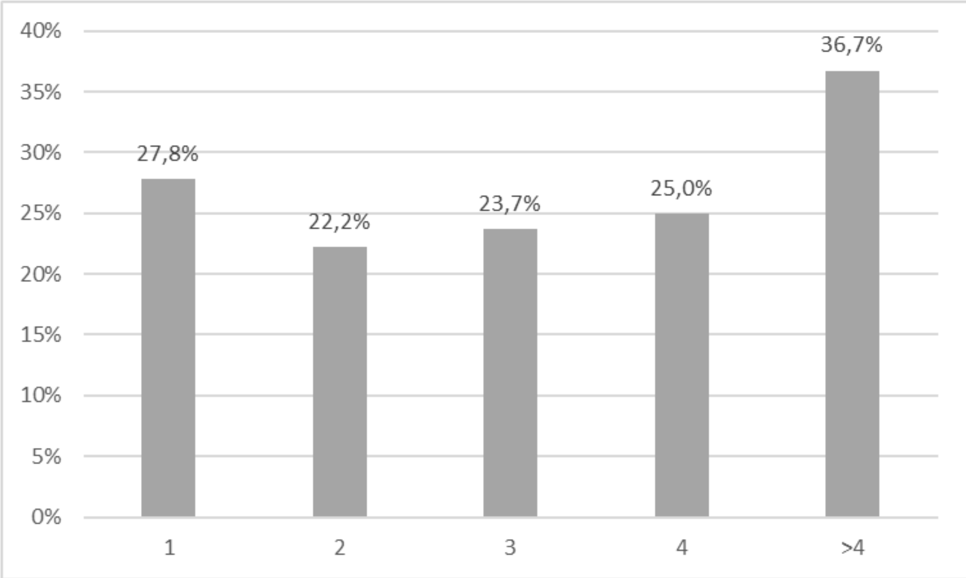

Fig. 9. HEP indicator in 2019 disaggregated by household size

Moreover, analysing the influence of the dwelling age on energy poverty, the HEP disaggregated value for buildings constructed 'less than 25 years ago' is 13.8%, while 30.7% of households living in buildings constructed '25 or more years ago' are in hidden energy poverty. Therefore, considering that the HVAC is the most energy-intensive service (see Fig. 2), the results point out that the building construction period is a major factor influencing the household's ability to pay the required costs for maintaining an adequate indoor temperature. This finding clearly points to the relevance (at least concerning their ability to impact on energy poverty) of designing and implementing policies and strategies that support building retrofitting, such as the 2020 Spanish Strategy for Energy Renovation in the Building Sector [65]. In this regard, it is also important to analyse the HEP results disaggregated according to the type of tenure: 31% of tenants are affected by hidden energy poverty compared to 23% of owners that suffer from this social issue. Thus, according to the paper's results, the status of tenant increases the probability of being energy poor. Particular mention should be made of households that live in semi-free or rent-free houses whose HEP share reaches 36%. This phenomenon might be due to the fact that households living in social housing are included in this subgroup. On the other hand, considering the urbanisation degree of the area of residence, households living in rural areas experience higher levels of hidden energy poverty than households living in urban areas. Indeed, the HEP share in the former is 35% compared to the 24% of the latter. This could be partially explained by the characteristics of the Spanish building stock and households' consumption patterns[22]. On the one hand, in rural areas more households live in single-family houses (Census 2011 and HBS) with higher energy needs than block dwellings (which are more common in urban localities). Therefore, the RENE is averagely higher for households living in villages than for households living in cities. On the other hand, further studies should be carried out to characterise Spanish households' consumption patterns in urban and rural contexts, thus unpacking the intrinsic reasons of the difference in HEP level.

Finally, the 'energy poverty gap' makes it possible to estimate the depth of HEP in the country. In 2019, this gap was averagely 374 euros per household and the budget to address it and ideally eradicate hidden energy poverty in Spain was €1,692m (0.14% of the Spanish GDP[23]; see table A21 for the results in each analysed year). Comparing this value with the actual budget dedicated to social tariffs in 2019 (€214m[24]), i.e. the national financial aids to tackle energy poverty, the one calculated in this paper is almost eight times higher than the actual 2019 one. Moreover, the average household gap calculated for Spain is comparable with the one estimated for the UK (€381), but it is significantly lower than the French one (between €526 and €735, depending on the metric used). However, to carry out an accurate comparison, the values would have to be calculated

[22] The difference in altitude (so in climate severity) between urban and rural areas is also a key factor but it could not be included in the paper's analysis because of the lack of information on the locality in the HBS.
[23] https://datosmacro.expansion.com/pib/espana?anio=2019
[24] Summing up the budget for the social tariff for electricity and the thermal social allowance, which, in 2019, were granted to 1.3 million of households.

with the same methodology and adjusted to consider socio-demographic, building stock, energy prices and climatic differences.

3.2. Sensitivity analysis

Fig. 10 shows the sensitivity analysis of the HEP indicator to several primary parameters of the absolute energy-expenditure threshold considered (described in Section 2.2.2).

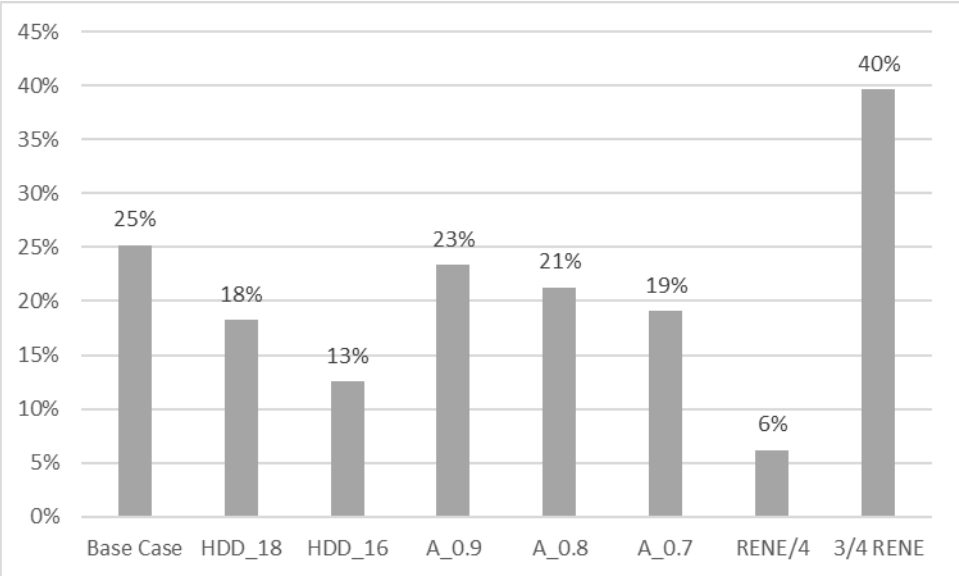

Fig. 10. Sensitivity analysis of the HEP indicator in 2019 (HDD_18 – comfort temperature at 18ºC; HDD_16 – comfort temperature at 16ºC; A_0.9/0.8/0.7 – reduced percentage of conditioned floor area at 90%, 80% and 70%; RENE/4 – extreme hidden energy poverty; 3/4 RENE - vulnerable to hidden energy poverty)

The first five results of the sensitivity analysis (from HDD_18 to A_0.7) were obtained by changing primary parameters of the RTEE model. Analysing the results obtained in 2019 for the base case and the different RTEE scenarios studied, it can be observed that the variation of the winter comfort temperature has the largest impact on the value of the energy poverty indicator. Indeed, assuming lower comfort temperatures, i.e. 18ºC and 16ºC, the share of households affected by hidden energy poverty decrease, respectively, by 28% and 50% compared with the base case scenario. Since 18°C is considered by the WHO as the minimum temperature value to ensure comfort, the related indicator's result could be considered as the ‘minimum comfort-temperature scenario’. On the other hand, 16ºC was pointed out as the minimum indoor temperature threshold to avoid respiratory diseases. Thus, this extreme scenario could be considered as the ‘minimum healthy-temperature scenario’. Figs. A3 and A4 show the 2019 ‘Low absolute energy expenditure’ indicator’s results in these two scenarios disaggregated by income deciles. In both scenarios, the reduction in the indicator value with respect to the base case (shown in Fig. 5) is less significant in the low-income deciles. This result highlights the lower sensitivity of the indicator to the assumed winter comfort temperature in these deciles or, in other words, it might point out that the poorest households are more likely to live in dwellings with an extremely low indoor temperature during winter. Furthermore, the variation in air-conditioned floor area has also a significant influence on the energy poverty results. HEP values show a reduction of more than 24% by switching from the baseline scenario to the 70% floor area scenario. Moreover, the decrease of the indicator value from A_90 to A_70 is quite linear. It is therefore considered useful to obtain more information on the proportion of floor space that is air-conditioned in households in order to obtain a more accurate picture of the reality of the problem. However, low-income households often live in dwellings with a small floor area (HBS, 2019)[25], thus they would therefore need to air-condition most of their homes to achieve a comfortable indoor climate (also given the inefficiency of their dwellings). The last two cases of the sensitivity analysis to the energy-expenditure threshold focus on the percentage of RENE set as absolute threshold. Fig. 10 shows that 6% of households compress their energy expenditure below a quarter of the RENE, thus experiencing ‘extreme hidden energy poverty’. On the other hand, 40% of Spanish households have actual energy expenditures below 75% of their RENE, thus they could be ‘vulnerable to hidden energy poverty’. Finally, only 10% of Spanish

[25] Exception cases exist, such as the single older people who are still living in their big family-dwellings.

households are considered in hidden energy poverty according to the ‘adjusted to reality’ scenario. This means that the national ‘adjusted to reality’ HEP value decreases by 58% with respect to the base case scenario. Nonetheless, the reduction of the ‘low absolute energy expenditure’ indicator (RENE/2) is even more significant: the underconsuming households in the alternative scenario are 16%, i.e. the share decreases by 64% compared with base case scenario. In this regard, Fig. A5 shows the RENE/2 indicator’s values in the ‘adjusted to reality’ scenario disaggregated by equivalised income decile. The share of underconsuming households follows a similar pattern as that of the base case scenario (see Fig. 5), i.e. it is lower and quite stable in the five highest income deciles and it decreases with revenue in the five lowest income deciles. However, the reduction with respect to the base case is more significant in the former, where the RENE/2 share ranges between 9.5% and 12.5%.

Regarding the second threshold’s sensitivity analysis, the value of HEP indicator calculated by using the ‘at risk of poverty’ threshold as income criterion (16%) is much lower than the one obtained in the base case (25%). This significant difference can be explained by comparing the thresholds used in the two cases, i.e. €9809 in the former and €11716 in the latter. In other words, the ‘at risk of poverty’ threshold is almost equal to the maximum income value considered in the third income decile. This means that in the sensitivity analysis case, the indicator considers only the households belonging to the first three income deciles.

These findings highlight the sensitivity of the HEP indicator proposed in this paper to both the absolute energy expenditure threshold and the income threshold considered. Nevertheless, giving the model’s flexibility, the paper’s methodology and its current and further applications might guide decision-makers both in the definition of households’ required energy needs and in the design of energy poverty indicators and policies.

4. Conclusions and policy implications

The ‘traditional’ energy-poverty expenditure-based indicators have been usually based on a disproportionate expenditure approach, thus estimating the share of households whose energy expenditure is too high compared to their income. Nevertheless, vulnerable families often apply coping strategies to compress their consumption, but this ‘hidden face’ of energy poverty has not been sufficiently addressed in the EU member states.

In this regard, the Spanish National Strategy against Energy Poverty (SNSEP) includes in its energy poverty monitoring the EPOV’s M/2 indicator (as a proxy of the HEP indicator). Nevertheless, this metric applies a relative energy expenditure threshold (national median energy-expenditure); thus it does not characterise the households’ required energy expenditure. Therefore, the EPOV’s approach could lead to a misestimation of underconsumption in the country. Moreover, the M/2 indicator does not include a criterion to exclude false positives, i.e. those households that are ‘voluntary’ underconsuming (or, in other words, those that are not forced to reduce their energy consumption because of lack of affordability). The methodology presented in this paper aims to fill these two gaps and is based on the same survey as the SNSEP (i.e. the HBS), so it could be integrated into the official monitoring of energy poverty in Spain.

In this regard, the analysis presented in this paper shows that the hidden energy poverty is a dimension of the phenomenon that cannot be overlooked. Indeed, the high values obtained for the HEP indicator in Spain imply that there are households affected by energy poverty that are not being considered by the national support schemes. Specifically, the five lowest income deciles are the most affected by this social issue. In that regard, this work presents a methodology to distinguish the ‘voluntary energy underconsumption’, i.e. self-restriction driven by reasons other than an energy affordability issue (e.g. high energy efficiency standards, conscious consuming and physiological habits), from hidden energy poverty. The first objective of this method is to determine an absolute threshold below which households' actual energy expenditures are 'objectively' too low to attain an adequate level of energy services (underconsumption). Thus, this paper introduces the Required ENergy Expenditure (RENE) model, which assesses the theoretical energy costs that a household would have to pay for to meet its required energy needs, including both thermal energy (heating, cooling and DHW) and electricity (lighting, electrical appliances and cooking) uses. Thereafter, the analysis carried out using the data from the Spanish HBS makes it possible to 'validate' the RENE/2 as absolute energy expenditure threshold and define an income criterion as a proxy to estimate the share of households in hidden energy poverty. Finally, the 'energy poverty gap', calculated (only for households identified as energy poor) as the difference between half the household's RENE and their actual energy expenditures, makes it possible to estimate the depth of hidden energy poverty in Spain. Moreover, it might enable policymakers to calculate the annual budget needed to eradicate this social issue from the country.

According to the paper's results, in 2019, 45% of Spanish households were underconsuming, but only 56% of them (25% of the total households) were affected by hidden energy poverty. In the same year, the average 'energy poverty gap' per household was €374 and the national budget needed to fill this gap was €1,692m. This amount is eight times higher than the actual budget earmarked for the social tariffs in that year; this is also because at least 3.3 million of households in hidden energy poverty did not benefitted from the national mitigating measures. Another result obtained is the significant disparity between the different regions. The absence of HVAC devices or their sparing use (especially in households living in apparently mild winter climate regions), together with a low-income level, determine a higher HEP rate and raise the energy poverty gap in these households. Indeed, analysing the pattern of the regional RENE, the different climatology in the various Spanish regions has a major influence on the result. Considering the household size and income characteristics, large families with low-income are the most affected by this social issue, followed by single-member households. Moreover, the building construction period significantly influences this issue, i.e. households living in older dwellings are the most affected by hidden energy poverty. The other two HEP key factors analysed are housing tenure and the degree of urbanisation of the area where the household lives. According to the paper's results, tenants are more affected by hidden energy poverty than owners, as well as households living in rural areas compared to the ones living in more urbanised municipalities.

Furthermore, this paper presents a sensitivity analysis of the HEP indicator to primary parameters set for the absolute energy expenditure threshold. In this regard, varying the baseline heating temperature from 20ºC (comfort temperature in the Spanish regulation) to lower values, i.e. 18ºC (WHO comfort temperature) and 16ºC (minimum 'healthy-temperature' according to [58]), has a significant impact on the results obtained (the HEP value decreases, respectively, by 28% and 50%). Moreover, changing the share of RENE considered in the threshold makes it possible to identify, on the one hand, households in 'extreme hidden energy poverty' (using RENE/4) and, on the other hand, households 'vulnerable to hidden energy poverty' (using 3/4 RENE). Alternatively, the paper presents a scenario 'adjusted to reality' that goes beyond the HVAC requirements of the Spanish regulation by adopting the WHO winter comfort temperature and the share of conditioned dwelling floor area based on typical Spanish households' features. On the one hand, the alternative scenario's results show the same underconsumption pattern across the income deciles as the base case scenario, thus confirming that the richest households with a low absolute energy expenditure should not be identified as energy poor. On the other hand, the HEP indicator in the 'adjusted to reality' scenario identifies a significantly lower share of households in hidden energy poverty, thus pointing out the advisability (for the society) of engaging in a socio-political debate on what should be considered basic and required energy needs. Finally, an income sensitivity scenario based on the EU 'at risk of poverty' threshold shows that the income criterion selected to eliminate the false positives is also a key determinant of the share of households identified as affected by hidden energy poverty.

4.1. Policy recommendations and further work

The paper's results show that low-income is the main cause of hidden energy poverty in Spain, being the consumption's forced self-restriction highly related to the household's financial resources. In addition, the results show that climatology and dwelling's energy efficiency are also key factors influencing the ability of families to meet their required energy needs.

In the light of these findings, the following policy implications are pointed out:

1. *Mitigating measures should consider the multifaceted nature of energy poverty.*

   The current national mitigating policies in Spain are not reaching all the households affected by energy poverty, and their impact is limited (as shown in [22] and [23]). The lack of knowledge partially explains the former problem, i.e. vulnerable households often do not know the support programs or are uninformed about how to apply for them. Thus, the SNSEP proposals to tackle this issue should be implemented in the short-term 'to raise people awareness on energy poverty and improve households' information in respect of energy use and support programs available to consumers' [66].

On the other hand, the insufficient characterisation of energy poverty in the country has caused an inaccurate design of these measures. Indeed, according to the results of this paper for 2019, at least 3.3 million households in hidden energy poverty did not benefit from the social tariffs. Therefore, energy poverty mitigation programs need to be adapted to incorporate this widespread casuistry. Nonetheless, social tariffs would hardly eradicate hidden energy poverty because a (small) discount does not remove the 'fear of the bill'. One key to alleviating this hidden face of energy poverty could be to complement or replace social tariffs with the implementation of a minimum vital supply (MVS, which was already included in the SNSEP as future regulatory proposal), or apply social tariffs to more household categories by targeting those more vulnerable to hidden energy poverty.

2. *The energy efficiency programs should prioritise vulnerable households.*

   The EU Renovation Wave and the long-term national strategies for energy renovation in the building sector need to adopt the perspective of vulnerable households, also acknowledging externalities caused by housing market mechanisms. Energy renovation measures, such as retrofitting the building envelope or replacing the thermal systems and household appliances, can help households (of all income levels) to achieve better comfort conditions in their home while reducing their bills. Given the paper's results (30.7% of the households living in older dwellings are in hidden energy poverty), the renovation should prioritise vulnerable households living in inefficient houses, which frequently cannot attain a required level of energy services. Moreover, given the higher share of tenants in hidden energy poverty compared to the HEP share in households that own their home, it is important to design effective schemes to solve the tenant-landlord dilemma, thus supporting the energy retrofitting of rented dwellings. Furthermore, the HBS should contain more specific information on the energy efficiency and age of dwellings. These data could help stakeholders and scholars to monitor the implementation of the energy renovation strategies and assess their impact on energy poverty.

3. *Local actions are crucial to tackle energy poverty.*

   The local differences in climatology (especially in a changing climate scenario [44]) and socio-demographic features should be taken into account when designing policies. In this sense, the paper's results point out that the geographical area and urbanisation degree of the municipalities where households live are crucial factors to consider when analysing and tackling hidden energy poverty. Thus, national and local administrations, together with other stakeholders, should enhance their collaboration to target mitigating and structural energy poverty measures appropriately. In this line, the new EU Energy Poverty Advisory Hub aims to provide direct support, training, and information to local authorities and civil society organisations and identify and promote local actions to tackle energy poverty.

These policy recommendations could be integrated within the European framework of the New Green Deal to develop and implement policies that support a 'right to (modern and clean) energy' [67,68] as well as a 'right to energy efficiency' [69].

Further work may analyse the influence of other household characteristics, such as their composition and employment[26] [70], or the impact of temperature and climate changes across the years (by using the HDD and CDD). Moreover, the methodology presented in

[26] Both household characteristics contribute to determine the consumption patterns [26]; these could be studied using the time use surveys, which are carried out both at national and European level, or specific surveys on the households' energy lifestyle [70].

this paper could be adapted to other countries by considering the differences in socio-demographic characteristics, building stock and regulation, energy prices, and climatic features, as pointed out in previous studies [71].

Eventually, this paper provides a flexible methodology to estimate the share of households that are underconsuming because of a lack of affordability. However, considering the weaknesses of official statistics such as the HBS (e.g. lack of: disaggregated geographic information, information on the financial supports the households benefit from and their contracted energy tariffs, etc.), the macro-level analysis carried out in this paper provides a general picture of hidden energy poverty in Spain, but does not make it possible to identify individual cases. Notably, there are some social groups not included in the HBS (households living in informal dwellings, Roma communities, etc., see [72] for an example from Spain) that are excluded from traditional analyses ('invisible energy poverty'). Furthermore, various assumptions and simplifications have been made to adapt the RENE model to the HBS, which, in some instances, could have led to a less accurate estimation of the theoretical energy costs. Indeed, the first explanation of the detected high under-consumption is that the strict HVAC standard set by the CTE does not correspond to the actual habits of all Spanish households (even the richest one), neither in the set-point temperature, nor in the heated or cooled floor area, nor in the hours of use. Some of these limitations have been addressed by proposing an 'adjusted to reality' scenario that 'enhances' the RTEE hypotheses. Eventually, giving the model's adaptability, the paper's methodology and its current and further applications might help policymakers implement policies and prevention measures that properly tackle hidden energy poverty at both national and regional levels.

Finally, it should be highlighted that the HEP indicator presented in this paper is not proposed as an alternative to subjective indicators such as the 'inadequate temperature at home' (both in winter and summer), which could also detect situations of hidden energy poverty (i.e. self-imposed restriction of heating or cooling consumption), but as a complementary indicator. Therefore, further work is needed to, on the one hand, carry out and analyse primary energy poverty surveys (which could provide micro-level information on this issue) and, on the other hand, complement the HEP indicator with other metrics to consider the multidimensional nature of energy poverty.

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Appendices

Appendix A – Spanish HBS variables and indicators' inputs

Table A1 shows the Spanish HBS variables used for the assessment of the indicators and the corresponding inputs.

HBS variable	Variable description	Possible values in the HBS	Indicators' inputs
CCAA	Region of residence	1 Andalucía 2 Aragón 3 Asturias, Principado de 4 Balears, Illes 5 Canarias 6 Cantabria 7 Castilla y León 8 Castilla – La Mancha 9 Cataluña 10 Comunitat Valenciana 11 Extremadura 12 Galicia 13 Madrid, Comunidad de 14 Murcia, Región de 15 Navarra, Comunidad Foral de 16 País Vasco 17 Rioja, La 18 Ceuta 19 Melilla	1 Andalucía 2 Aragón 3 Asturias 4 Islas Baleares 5 Canarias 6 Cantabria 7 Castilla y León 8 Castilla la Mancha 9 Cataluña 10 C. Valenciana 11 Extremadura 12 Galicia 13 Madrid 14 Murcia 15 Navarra 16 País Vasco 17 La Rioja 18 Ceuta 19 Melilla
FACTOR	Spatial expansion factor	Any value other than b and 0	FACTOR/1000000
NMIEMB	Number of household members	1-20	1-20
ANNOCON	Date of construction of the building	1 Less than 25 years ago 6 25 or more years ago -9 No record	1 Less than 25 years ago 6 25 or more years ago -9 25 or more years ago [73][27]

[27] According to the Spanish CENSUS 2011 and the 2019 data of [73] the great majority of dwellings were constructed 25 or more than 25 years ago.

TIPOEDIF	Type of building in which the dwelling is located	1 Detached single-family house 2 Semi-detached or semi-detached single-family dwelling 3 With less than 10 dwellings 4 With 10 or more dwellings 5 Other (used for other purposes or fixed accommodation) -9 No record	1, 2: Single-family house 3, 4, 5: Block dwelling -9: (Excluded)
SUPERF	Dwelling's floor area	35 35 metres or less 36-299 metres (actual value) 300 300 metres or more -9 No record	35 35 m^2 36-299 X m^2 (actual value) 300 300 m^2 -9 (Excluded)
AGUACALI	Presence of DHW system	1 Yes 6 No -9 No record	1 Yes 6 Yes -9 Yes
FUENAGUA	DHW energy carrier	1 Electricity 2 Natural gas 3 Liquefied gas 4 Other liquid fuels 5 Solid fuels 6 Other b Not applicable (if AGUACALI=6) -9 No record	1 Electricity 2 Natural gas 3 Liquefied petroleum gas (LPG) 4 Heating gasoil 5, 6 Biomass b Regional mode -9 Regional mode
CALEF	Presence of heating system	1 Yes 6 No -9 No record	1 Yes 6 Yes -9 Yes
FUENCALE	Heating energy carrier	1 Electricity 2 Natural gas 3 Liquefied gas 4 Other liquid fuels 5 Solid fuels 6 Other b Not applicable (if CALEF=6) -9 No record	1 Electricity 2 Natural gas 3 Liquefied petroleum gas (LPG) 4 Heating gasoil 5, 6 Biomass b Regional mode -9 Regional mode
CODIGO	Expenditure code [€]	4.5.1.1 Electricity 4.5.2.1 Natural gas 4.5.2.3 Liquefied gas 4.5.3.1 Liquid fuels 4.5.4.1 Coal 4.5.4.8 Other solid fuels (All values are for the main dwelling)	Actual Energy expenditure = Sum (Annual energy expenditures in the main dwelling)
REGTEN	Type of tenure	1 Property with no current loan or mortgage 2 Property with ongoing loan or mortgage 3 Rent 4 Reduced rent (old rent) 5 Provided semi-free 6 Provided free	1, 2 Owner-occupied dwelling 3, 4 Rented dwelling 5, 6 Semi-free or rent-free dwelling

ZONARES	Type of area of residence	1 Upmarket urban area 2 High-income urban area 3 Middle-income urban area 4 Low-income urban area 5 Industrial rural area 6 Fisheries rural area 7 Agricultural rural area -9 No record	1, 2, 3, 4 Urban area 5, 6, 7 Rural area -9 (Excluded from the disaggregated analysis)
UC2	Equivalent household size. Modified OECD scale	1-110 (actual value)	1-110 (actual value)
GASTOT	Total amount of monetary and non-monetary expenditure raised temporally and population-wise	1-999999999999999	Equivalised total expenditure = GASTOT/(FACTOR* UC2)
IMPEXAC	Exact amount of the total net monthly household income	0-99999	Equivalised net disposable income = (IMPEXAC*12)/UC2

Table A1. Spanish HBS variables used for the calculation of the indicators and corresponding inputs

Appendix B – Calculation of the household's required thermal energy consumption in the 'adapted HBS' RENE model

The annual specific required-demands for heating and cooling ($\mathrm{kWh/(m^2\ year)}$) have been calculated using the methodology described in [22] and [74], and applying the requirements set in CTE 2019. These variables depend on the annual specific reference-demand values (also in $\mathrm{kWh/(m^2\ year)}$), which are calculated by the IDAE for a baseline comfort temperature of 20ºC[28]. Particularly, these reference demands depend on the climate severity indexes (winter climate severity and summer climate severity) and the building correlation coefficients. The former are estimated for each winter and summer climate zone and depend on, respectively, the Heating Degree Days (HDD) and Cooling Degree Days (CDD), and the ratio of the number of sunshine hours to the number of maximum sunshine hours. The building correlation coefficients are the result of modelling thirteen types of building geometry [74] and vary according to the dwelling typology (block dwelling or single-family house). Subsequently, the values of the annual specific required demand for DHW ($\mathrm{kWh/(person\ year)}$) were calculated as a function of the average monthly network-water-temperature (ºC) of the Spanish provincial capitals and the daily specific hot water consumption (l/(person day)) at a given temperature T = 60 °C, which depends on the dwelling type (CTE 2019 and [75]). For localities other than the provincial capitals, the network-water-temperature is estimated by considering the difference between the locality's altitude and provincial capital's altitude.

The database of all the Spanish localities belonging to each region (and each province in the region) has been used as a starting point for the approximation of the thermal demand according to the CCAA variable of the HBS (see table A1). In this database, the number

[28] In concrete terms, the baseline comfort temperature is the set point temperature of the thermal system.

of inhabitants [76] and the altitude of each locality [77] is known. Using the latter parameter and the locality's province, it is possible to assign the winter and summer climate zone (which determines the heating and cooling specific demand), and the network-water-temperature (which determines the DHW specific demand) to each Spanish locality (CTE, 2019).

Therefore, for each locality, the specific required thermal demand is determined for single-family houses and block dwellings (from TIPOEDIF variable in Table A1) by distinguishing (for the HVAC demand) from buildings constructed 25 or more years ago and buildings constructed less than 25 years ago (from ANNOCON variable in Table A1). Tables A2 and A3 show the energy efficiency parameter (EEP) assigned to each of these dwelling's type according to the winter climate zone. These values have been obtained using the methodology of [22] updated based on the 2019 IDAE report on energy performance certificates.

Winter climate zone	**≥ 25 years ago**	**< 25 years ago**
α	3.55	1.77
A	3.55	1.77
B	3.27	1.71
C	3.05	1.65
D	2.94	1.63
E	2.89	1.61

Table A2. EEP values in block dwellings according to the winter climate zone and the building construction period

Winter climate zone	≥ 25 years ago	< 25 years ago
α	3.11	1.61
A	3.11	1.61
B	3.05	1.62
C	2.96	1.60
D	3.19	1.64
E	3.19	1.61

Table A3. EEP values in single-family houses according to the winter climate zone and the building construction period

Subsequently, a weighted average (according to the number of inhabitants) of the specific demand values by provinces has been carried out. These provincial weighted specific-required-demand values ($\overline{\mathrm{SRD}}_{j,i}$) were calculated applying the procedure presented in [22] to each thermal energy use considered in this paper, i.e. heating, cooling and DHW. Finally, because of the regional disaggregation of the Spanish HBS, the weighted average was carried out by region (Eq. A1), considering the provincial demand values ($\overline{\mathrm{SRD}}_{j,i}$) and the number of inhabitants in each province belonging to the region. Eq. A1 shows the mathematical formulation used to calculate the regional weighted average of the specific-required-demand ($\overline{\mathrm{SRD}}_{j,k}$)[29].

$$\overline{\mathrm{SRD}}_{j,k} = \frac{\sum_{i=1}^{n} \overline{\mathrm{SRD}}_{j,i} \cdot \mathrm{NI}_i}{\sum_{i=1}^{n} \mathrm{NI}_i} \qquad \text{(A1)}$$

Where i is the i-province of the k-region, NI_i is the number of inhabitants of the i-province [76], and j can be heating, cooling or DHW. This computation has been reiterated for each combination of aggregated-construction-period (only for heating and cooling) and dwelling typology for all the regions. Thus, Tables A4, A5 and A6 shows the values of the regional weighted specific demand, respectively, for heating, cooling and DHW.

[29] Note that the regional weighting of the specific demands of heating, cooling and DHW by number of inhabitants in each province of the region aims to 'weight', respectively, the winter climate zone, the summer climate zone and the network-water-temperature.

Region	≥ 25 years ago		< 25 years ago	
	Block dwelling	**Single-family house**	**Block dwelling**	**Single-family house**
Andalucía	64.40	91.09	35.00	50.94
Aragón	133.02	174.20	75.82	103.56
Asturias	114.56	150.21	64.84	89.37
Baleares	58.36	84.25	31.39	46.35
Canarias	15.48	24.09	8.05	12.43
Cantabria	96.24	128.76	53.95	75.19
Castilla y León	153.40	199.25	87.94	118.76
Castilla - La Mancha	130.89	170.86	74.56	101.98
Cataluña	98.23	131.15	55.13	76.77
C. Valenciana	66.79	93.94	36.41	52.77
Extremadura	98.69	130.86	55.41	77.12
Galicia	104.62	139.03	58.93	81.68
Madrid	133.40	174.80	76.05	103.93
Murcia	70.68	98.95	38.73	55.76
Navarra	133.32	173.52	76.00	103.84
País Vasco	112.28	148.65	63.49	87.61
La Rioja	134.53	176.34	76.72	104.78
Melilla	41.65	64.22	21.46	33.53
Ceuta	58.30	83.93	31.35	46.30

Table A4. Regional weighted specific demand for heating [kWh/(m^2 year)] per aggregated construction period and dwelling type

Region	≥ 25 years ago		< 25 years ago	
	Block dwelling	**Single-family house**	**Block dwelling**	**Single-family house**
Andalucía	44.27	55.93	25.29	33.59
Aragón	29.02	39.26	17.53	24.34
Asturias	0.00	0.00	0.00	0.00
Baleares	36.48	46.73	20.93	28.02
Canarias	32.49	39.85	17.77	23.25
Cantabria	0.00	0.00	0.00	0.00
Castilla y León	7.49	10.63	4.39	6.32
Castilla - La Mancha	32.76	43.95	19.82	27.43
Cataluña	19.29	26.70	11.19	15.82
C. Valenciana	40.25	51.74	23.25	31.19
Extremadura	45.12	59.76	26.93	36.86
Galicia	2.63	3.65	1.55	2.18
Madrid	32.72	44.15	19.85	27.48
Murcia	35.77	46.50	20.76	28.03
Navarra	3.78	5.32	2.21	3.18
País Vasco	0.00	0.00	0.00	0.00
La Rioja	16.41	23.29	9.62	13.84
Melilla	39.24	47.62	21.60	28.04
Ceuta	36.48	46.59	20.93	28.02

Table A5. Regional weighted specific demand for cooling [kWh/(m^2 year)] per aggregated construction period and dwelling type

Region	Block dwelling	Single-family house
Andalucía	488.96	536.05
Aragón	506.69	559.76
Asturias	508.72	565.24
Baleares	507.73	534.45
Canarias	496.76	522.91
Cantabria	506.29	562.55
Castilla y León	533.15	579.71
Castilla - La Mancha	528.07	557.75
Cataluña	502.67	553.47
C. Valenciana	487.62	540.03
Extremadura	520.85	548.26
Galicia	524.97	562.81
Madrid	502.15	557.94
Murcia	502.51	543.25
Navarra	526.44	569.12
País Vasco	511.02	567.80
La Rioja	511.19	567.99
Melilla	498.36	524.59
Ceuta	489.03	543.36

Table A6. Regional weighted specific demand for DHW [kWh/(person year)] per dwelling type

Then, the weighted standard deviation of each region ($\sigma_{\mathrm{j,k}}$) was calculated to evaluate the grade of variation of the provincial values with respect to the regional weighted average value. Therefore, the weighted coefficient of variation ($\mathrm{CV}_{\mathrm{j,k}}$, defined as in [78]) of the specific required demand in each region was computed by applying Eq. A2, i.e. computing the ratio of the region's weighted standard deviation to the regional weighted mean ($\overline{\mathrm{SRD}}_{\mathrm{j,k}}$).

$$\mathrm{CV}_{\mathrm{j,k}} = \frac{\sigma_{\mathrm{j,k}}}{\overline{\mathrm{SRD}}_{\mathrm{j,k}}} \tag{A2}$$

Tables A7, A8 and A9 show the results of the latter calculation.

Region	≥ 25 years ago		< 25 years ago	
	Block dwelling	**Single-family house**	**Block dwelling**	**Single-family house**
Andalucía	9.7%	8.1%	10.7%	9.4%
Aragón	0.8%	0.8%	0.8%	0.7%
Asturias	0.0%	0.0%	0.0%	0.0%
Baleares	0.0%	0.0%	0.0%	0.0%
Canarias	34.0%	37.1%	33.5%	34.2%
Cantabria	0.0%	0.0%	0.0%	0.0%
Castilla y León	3.7%	3.5%	3.8%	3.5%
Castilla - La Mancha	1.6%	1.8%	1.7%	1.6%
Cataluña	6.8%	6.2%	7.2%	6.7%
C. Valenciana	1.0%	0.8%	1.1%	1.0%
Extremadura	2.2%	2.5%	2.3%	2.2%
Galicia	6.9%	6.3%	7.3%	6.8%
Madrid	0.0%	0.0%	0.0%	0.0%
Murcia	0.0%	0.0%	0.0%	0.0%
Navarra	0.0%	0.0%	0.0%	0.0%
País Vasco	10.9%	10.1%	11.5%	10.8%
La Rioja	0.0%	0.0%	0.0%	0.0%
Melilla	0.0%	0.0%	0.0%	0.0%
Ceuta	0.0%	0.0%	0.0%	0.0%

Table A7. Weighted coefficient of variation of the specific required heating demand in each region per aggregated construction period and dwelling type

Region	≥ 25 years ago		< 25 years ago	
	Block dwelling	**Single-family house**	**Block dwelling**	**Single-family house**
Andalucía	3.2%	2.9%	3.5%	3.3%
Aragón	2.5%	2.5%	2.8%	2.7%
Asturias	0.0%	0.0%	0.0%	0.0%
Baleares	0.0%	0.0%	0.0%	0.0%
Canarias	16.1%	7.2%	17.8%	14.5%
Cantabria	0.0%	0.0%	0.0%	0.0%
Castilla y León	1.6%	1.8%	1.7%	1.8%
Castilla - La Mancha	1.3%	1.3%	1.4%	1.4%
Cataluña	3.2%	2.9%	3.4%	3.1%
C. Valenciana	5.3%	4.7%	5.6%	5.0%
Extremadura	1.1%	0.8%	1.1%	1.0%
Galicia	3.5%	3.7%	3.7%	3.7%
Madrid	0.0%	0.0%	0.0%	0.0%
Murcia	0.0%	0.0%	0.0%	0.0%
Navarra	0.0%	0.0%	0.0%	0.0%
País Vasco	0.0%	0.0%	0.0%	0.0%
La Rioja	0.0%	0.0%	0.0%	0.0%
Melilla	0.0%	0.0%	0.0%	0.0%
Ceuta	0.0%	0.0%	0.0%	0.0%

Table A8. Weighted coefficient of variation of the specific required cooling demand in each region per aggregated construction period and dwelling type

Region	Block dwelling	Single-family house
Andalucía	0.9%	0.4%
Aragón	1.4%	0.5%
Asturias	0.0%	0.0%
Baleares	0.0%	0.0%
Canarias	0.4%	0.4%
Cantabria	0.0%	0.0%
Castilla y León	0.9%	0.3%
Castilla - La Mancha	0.7%	0.7%
Cataluña	1.5%	0.6%
C. Valenciana	0.7%	0.3%
Extremadura	0.6%	0.6%
Galicia	1.8%	0.6%
Madrid	0.0%	0.0%
Murcia	0.0%	0.0%
Navarra	0.0%	0.0%
País Vasco	0.6%	0.6%
La Rioja	0.0%	0.0%
Melilla	0.0%	0.0%
Ceuta	0.0%	0.0%

Table A9. Weighted coefficient of variation of the specific required DHW demand in each region per dwelling type

The single-province regions have 0% of demand variation for the three thermal energy uses (since their regional weighted demand is equal to the demand of the only province belonging to that region). In the rest of the regions, the coefficients of both heating and cooling demands are higher than the DHW ones, i.e. the HVAC demand has a higher variability. Particularly, the variation coefficients of the DHW demand are lower than 1.8% in all regions. Whereas, for the HVAC demand, the higher values are achieved in *Canarias*[30], where the weighted coefficient of variation reaches 37.1% for single-family houses constructed 25 or more years ago. Moreover, the heating coefficients are generally

[30] This is because the two provinces of *Canarias* have almost the same number of inhabitants but quite different HVAC demand values (especially the heating one).

higher than the cooling ones. Eventually, giving the significant variability of the HVAC demand among the provinces in some of the Spanish regions, more disaggregated geographical information should be added to the HBS. Particularly, in the light of the analysis on the coefficient of variation, the household's province of residence is considered a crucial data to improve the accuracy of the 'HBS adapted' RENE model.

Afterwards, the values of required demand for HVAC and DHW [kWh/year] of each HBS household were calculated by multiplying the specific demand values, respectively, by their dwelling size (SUPERF) or the number of household members (NMIEMB). Finally, the household's required consumption values were calculated by dividing its required thermal energy demand by the seasonal performance factor of the corresponding thermal systems (following the official procedure established by the IDAE [74]). The seasonal performance factors of HVAC systems (i.e. HSPF and SEER) for buildings constructed less than 25 years ago have been calculated as a weighted average (depending on the HBS year) between the parameter for existing buildings and that for new buildings (since the boundary year in [22] is 2008, i.e. entry into force of the CTE, which falls within those 25 years). On the other hand, the factors of HVAC systems for buildings constructed 25 or more years ago was set as the ones of existing buildings. No differentiation was considered for the DHW systems. Tables A10-A14 show the values set for the seasonal performance factors of each system considered.

Energy carrier	**HSPF**
Natural gas	0.75
LPG	0.75
Heating gasoil	0.70
Biomass	0.35
Electricity	0.99

Table A10. Seasonal performance factor of heating systems (HSPF) for buildings constructed 25 or more years ago

Energy carrier	**HSPF** (2016)	**HSPF** (2017)	**HSPF** (2018)	**HSPF** (2019)
Natural gas	0.80	0.81	0.81	0.82
LPG	0.79	0.80	0.81	0.81
Heating gasoil	0.74	0.75	0.75	0.76
Biomass	0.46	0.48	0.49	0.50
Electricity	0.99	0.99	0.99	0.99

Table A11. Seasonal performance factor of heating systems (HSPF) for buildings constructed less than 25 years ago (depending on the HBS year)

Summer climate zone	**SEER**
1	3.82
2	3.69
3	3.49
4	3.39

Table A12. Seasonal energy efficiency rating for cooling (SEER) per summer climate zone for buildings constructed 25 or more years ago

Summer climate zone	**SEER** (2016)	**SEER** (2017)	**SEER** (2018)	**SEER** (2019)
1	4.17	4.22	4.26	4.30
2	4.02	4.06	4.10	4.14
3	3.80	3.84	3.88	3.92
4	3.70	3.74	3.78	3.81

Table A13. Seasonal energy efficiency rating for cooling (SEER) per summer climate zone for buildings constructed less than 25 years ago (depending on the HBS year)

Energy carrier	**SPF**
Natural gas	0.77
LPG	0.77
Heating gasoil	0.77
Biomass	0.37
Electricity	0.99

Table A14. Seasonal performance factor of DHW systems (SPF)

Appendix C – Energy prices and regional tax rates used in the RENE model and RENE results

The regulated-market-price, i.e. the Voluntary Price for the Small Consumer (VPSC), is applied to the consumption of electricity, both in the RTEE and RELE models, as it is the tariff selected by around 40% of the Spanish households [79] and by all vulnerable consumers benefitted from the social tariff for electricity (according to the data provided by the Ministry for the Ecological Transition and the Demographic Challenge). On the other hand, the contracted power term is not considered in the RTEE because it is assigned to the RELE. The regulated market tariff was also used for the natural gas, i.e. the Tariff of Last Resort (TLR), since, between 2017 and 2019, around 75% of households (within the ones that were aware of their natural gas tariff) declared to have the TLR [39]. In the paper's case study (Spanish HBS), if the household uses natural gas for both heating and DHW, the DHW system is considered the same as the heating system. Thus, the fixed term is only considered in the calculation of the heating expenditure. For heating gasoil and biomass, the IDAE's quarterly price reports have been taken as a reference, and these prices were weighted annually. Finally, the price of regulated bottled LPG has been taken as a reference, which includes a term for the cost of the raw material, a term for the marketing cost and a term for mismatch. In *Ceuta*, *Melilla* and *Canarias* a marketing surcharge/extra cost is applied due to logistical costs. Fig. A1 shows the energy prices across the four years analysed.

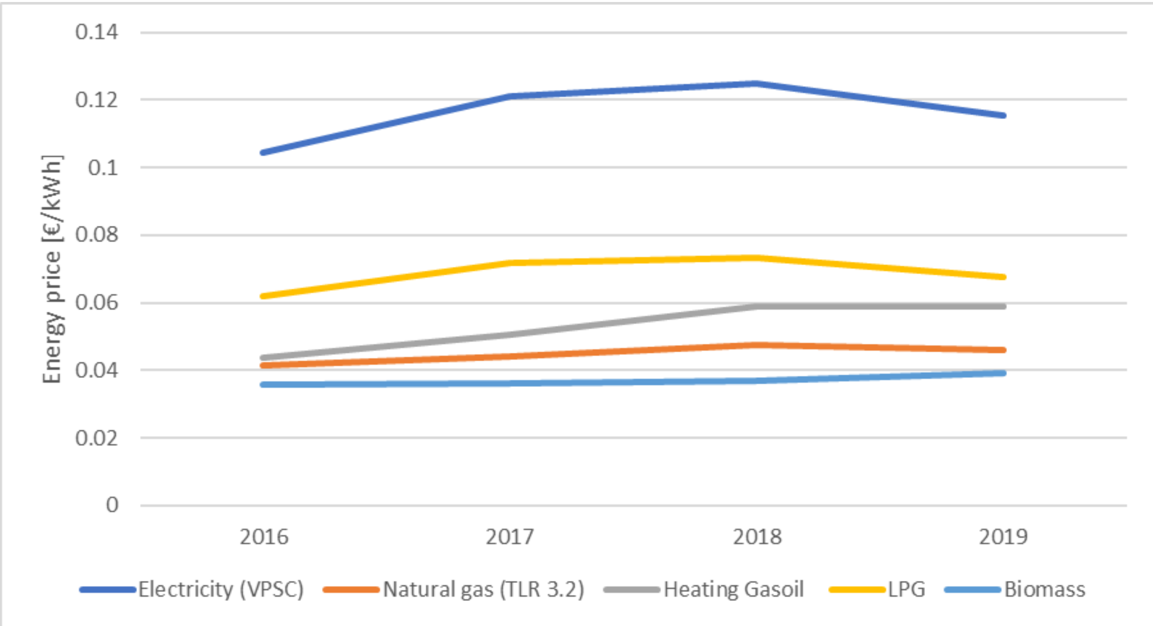

Fig. A1. Energy prices across the four years analysed (2016-2019)

2017 and 2018 were the years with the highest energy prices for electricity, natural gas and LPG, which constitute the major share of final energy consumption in the Spanish residential sector [34]. On the other hand, the prices for heating gasoil and biomass reached their maximum in 2019. Regarding the tax rates, the fossil-fuel and electricity taxes and the VAT have been set according to the Spanish regulation [80,81], considering the different VAT policy in *Canarias*, *Ceuta* and *Melilla*. These regions apply different VAT values depending on the energy carrier, whereas, in the rest of the country, the VAT is 21% for all fuels.

Fig A2 shows the national average RENE in the four years of the analysed series.

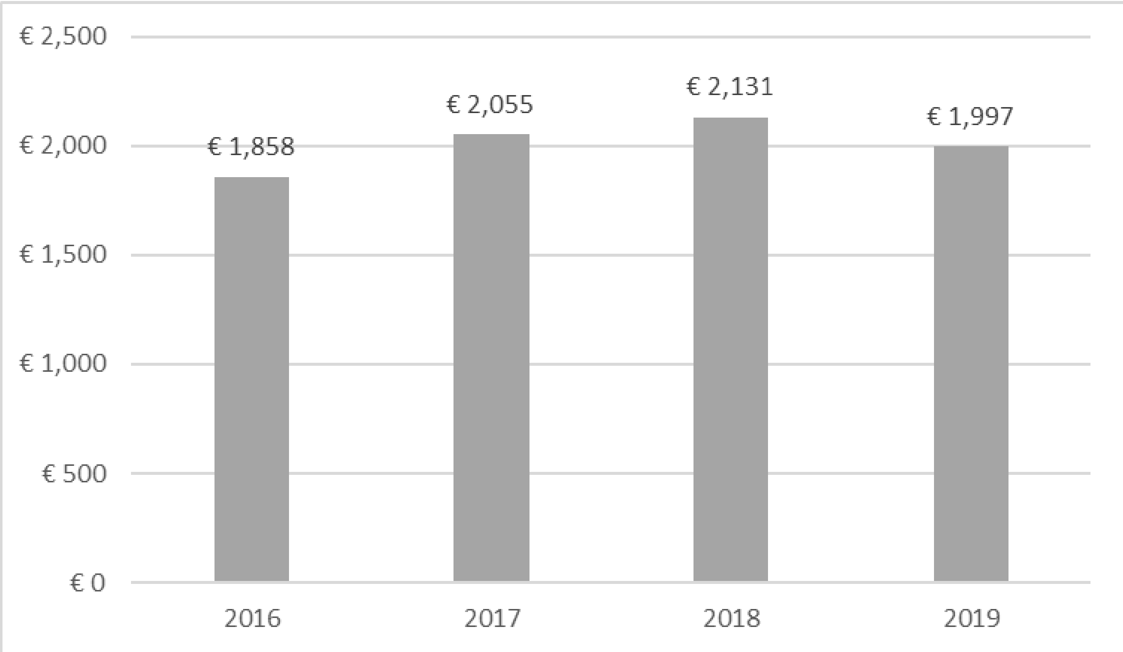

Fig. A2. National average RENE values in the 2016-2019 series

Finally, Table A15 shows some examples of the value of the RENE for different household types in 2019. The examples referred to actual HBS households that were selected to show the RENE variation according to the most influent parameters, i.e. region, household size, dwelling's typology and construction period. The dwelling size was not included in the selection process (even if it is a key parameter) because its value is difficult to categorize (its range of values is much wider in comparison to the other parameters).

Region	Household size	Dwelling typology	Dwelling size [m^2]	Construction period	Heating energy carrier	DHW energy carrier	RENE [€/year]
Canarias	1	Block dwelling	100	≥ 25 years ago	Electricity	LPG	480
Canarias	4	Single-family house	100	< 25 years ago	Biomass	Electricity	871
Andalucía	1	Block dwelling	70	< 25 years ago	Natural gas	Electricity	890
Andalucía	2	Single-family house	140	≥ 25 years ago	Electricity	Electricity	1684
Madrid	1	Block dwelling	72	≥ 25 years ago	Natural gas	Natural gas	1175
Madrid	5	Block dwelling	90	< 25 years ago	Natural gas	Natural gas	2136
Castilla - La Mancha	2	Block dwelling	99	≥ 25 years ago	Electricity	Electricity	1762
Castilla - La Mancha	1	Single-family house	132	< 25 years ago	LPG	LPG	1327

Table A15. Examples of the value of the RENE for different HBS household types in 2019

Appendix D – Minimum heating demands

Table A16-A19 show the minimum heating demand values used in the winter-baseline-temperature sensitivity analyses (HDD_18 and HDD_16) and the relative difference with the base case scenario.

Region	**≥ 25 years ago**		**< 25 years ago**	
	Block dwelling	**Single-family house**	**Block dwelling**	**Single-family house**
Andalucía	31.02	49.49	17.08	28.03
Aragón	96.79	129.53	55.18	77.02
Asturias	79.91	107.87	45.26	64.20
Baleares	24.34	41.55	13.09	22.86
Canarias	4.00	9.34	2.10	4.85
Cantabria	63.05	87.91	35.36	51.35
Castilla y León	114.85	151.71	65.84	90.43
Castilla - La Mancha	94.91	126.69	54.07	75.63
Cataluña	64.65	89.83	36.33	52.64
C. Valenciana	32.95	51.74	18.05	29.20
Extremadura	65.35	90.12	36.71	53.12
Galicia	70.77	97.37	39.89	57.24
Madrid	97.23	130.16	55.43	77.39
Murcia	36.80	56.60	20.28	32.07
Navarra	97.12	129.15	55.36	77.29
País Vasco	77.82	106.17	44.03	62.61
La Rioja	98.24	131.52	56.02	78.15
Melilla	8.97	23.25	4.62	12.14
Ceuta	24.27	41.35	13.05	22.81

Table A16. Regional weighted specific demand for heating [kWh/(m^2 year)] using 18°C as baseline temperature (minimum comfort-temperature heating demand) per aggregated construction period and dwelling type

Region	≥ 25 years ago		< 25 years ago	
	Block dwelling	**Single-family house**	**Block dwelling**	**Single-family house**
Andalucía	-52%	-46%	-51%	-45%
Aragón	-27%	-26%	-27%	-26%
Asturias	-30%	-28%	-30%	-28%
Baleares	-58%	-51%	-58%	-51%
Canarias	-74%	-61%	-74%	-61%
Cantabria	-34%	-32%	-34%	-32%
Castilla y León	-25%	-24%	-25%	-24%
Castilla - La Mancha	-27%	-26%	-27%	-26%
Cataluña	-34%	-32%	-34%	-31%
C. Valenciana	-51%	-45%	-50%	-45%
Extremadura	-34%	-31%	-34%	-31%
Galicia	-32%	-30%	-32%	-30%
Madrid	-27%	-26%	-27%	-26%
Murcia	-48%	-43%	-48%	-42%
Navarra	-27%	-26%	-27%	-26%
País Vasco	-31%	-29%	-31%	-29%
La Rioja	-27%	-25%	-27%	-25%
Melilla	-78%	-64%	-78%	-64%
Ceuta	-58%	-51%	-58%	-51%

Table A17. Relative difference [%] between the regional weighted values of the minimum comfort-temperature heating demand (18°C as baseline temperature) and the required heating demand (20°C as baseline temperature), per aggregated construction period and dwelling type

Region	≥ 25 years ago		< 25 years ago	
	Block dwelling	**Single-family house**	**Block dwelling**	**Single-family house**
Andalucía	13.89	23.65	7.76	13.68
Aragón	66.45	92.03	37.89	54.72
Asturias	51.91	73.57	29.42	43.81
Baleares	4.63	16.88	2.49	9.29
Canarias	0.75	1.31	0.40	0.72
Cantabria	37.40	56.28	20.99	32.89
Castilla y León	82.12	111.26	47.09	66.32
Castilla - La Mancha	64.82	89.66	36.93	53.52
Cataluña	38.81	57.99	21.84	34.02
C. Valenciana	11.92	25.58	6.61	14.54
Extremadura	39.37	58.31	22.13	34.38
Galicia	44.04	64.41	24.85	37.89
Madrid	66.81	92.53	38.09	55.02
Murcia	15.19	29.66	8.47	16.94
Navarra	66.72	91.80	38.04	54.94
País Vasco	50.11	71.94	28.38	42.46
La Rioja	67.68	93.69	38.60	55.67
Melilla	1.39	1.25	0.72	0.65
Ceuta	4.57	16.76	2.46	9.25

Table A18. Regional weighted specific demand for heating [kWh/(m^2 year)] using 16°C as baseline temperature (minimum healthy-temperature heating demand) per aggregated construction period and dwelling type

Region	≥ 25 years ago		< 25 years ago	
	Block dwelling	Single-family house	Block dwelling	Single-family house
Andalucía	-78%	-74%	-78%	-73%
Aragón	-50%	-47%	-50%	-47%
Asturias	-55%	-51%	-55%	-51%
Baleares	-92%	-80%	-92%	-80%
Canarias	-95%	-95%	-95%	-94%
Cantabria	-61%	-56%	-61%	-56%
Castilla y León	-46%	-44%	-46%	-44%
Castilla - La Mancha	-50%	-48%	-50%	-48%
Cataluña	-60%	-56%	-60%	-56%
C. Valenciana	-82%	-73%	-82%	-72%
Extremadura	-60%	-55%	-60%	-55%
Galicia	-58%	-54%	-58%	-54%
Madrid	-50%	-47%	-50%	-47%
Murcia	-79%	-70%	-78%	-70%
Navarra	-50%	-47%	-50%	-47%
País Vasco	-55%	-52%	-55%	-52%
La Rioja	-50%	-47%	-50%	-47%
Melilla	-97%	-98%	-97%	-98%
Ceuta	-92%	-80%	-92%	-80%

Table A19. Relative difference [%] between the regional weighted values of the minimum healthy-temperature heating demand (16°C as baseline temperature) and the required heating demand (20°C as baseline temperature), per aggregated construction period and dwelling type

Appendix E – 'Low absolute energy expenditure' indicator disaggregated by equivalised income deciles

Table A20 shows the results of the 'Low absolute energy expenditure' indicator (RENE/2) disaggregated by equivalised income deciles in each year of the analysed series.

	1st	**2nd**	**3rd**	**4th**	**5th**	**6th**	**7th**	**8th**	**9th**	**10th**
2016	66.6%	58.0%	53.3%	50.6%	46.8%	43.2%	43.6%	42.1%	40.6%	36.4%
2017	69.0%	61.4%	56.5%	54.7%	53.4%	47.7%	47.6%	45.1%	43.0%	41.9%
2018	69.6%	56.9%	55.3%	50.9%	52.0%	46.9%	46.4%	42.1%	44.0%	43.2%
2019	62.9%	52.1%	48.4%	45.9%	42.8%	38.9%	41.0%	40.7%	40.1%	39.0%

Table A20. 'Low absolute energy expenditure' indicator disaggregated by equivalised income deciles in each analysed year

On the other hand, Fig. A3-A5 show the RENE/2 indicator's values in 2019 for each equivalised income decile in three sensitivity analysis' scenarios, i.e. HDD_18, HDD_16 and the 'adjusted to reality' scenario.

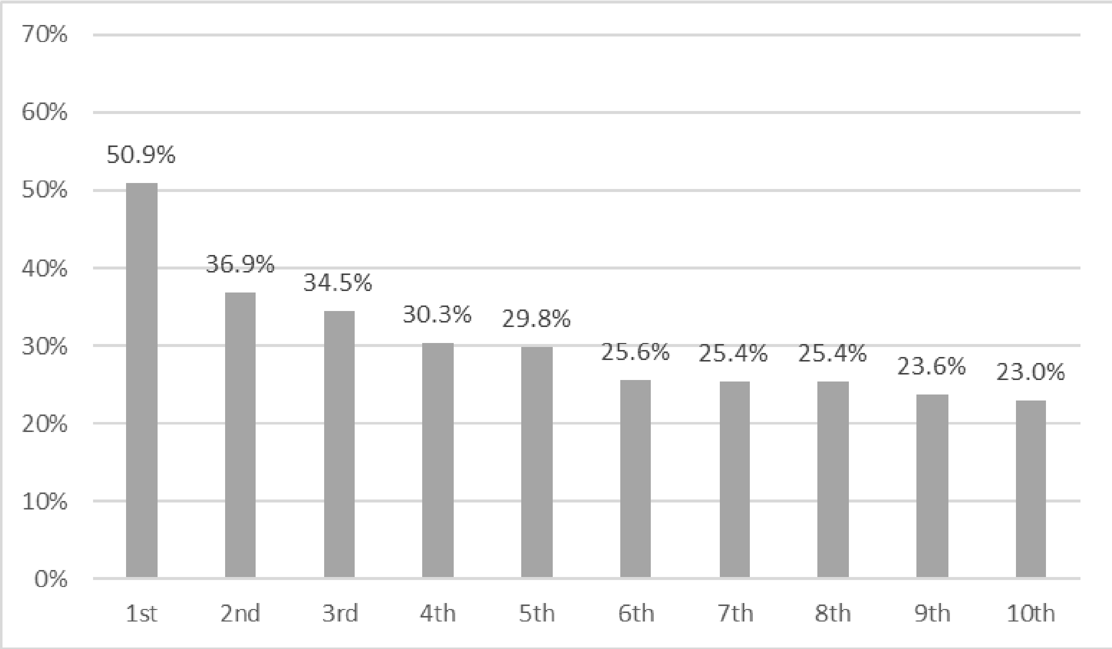

Fig. A3. RENE/2 indicator's values in 2019 for each equivalised income decile in the HDD_18 scenario

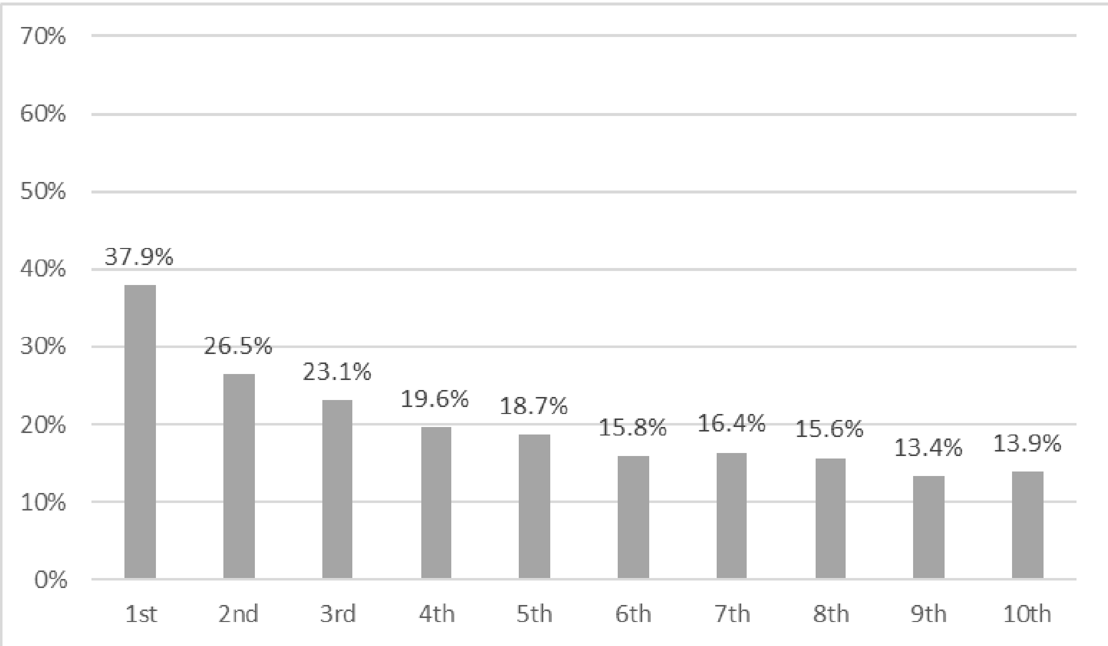

Fig. A4. RENE/2 indicator's values in 2019 for each equivalised income decile in the HDD_16 scenario

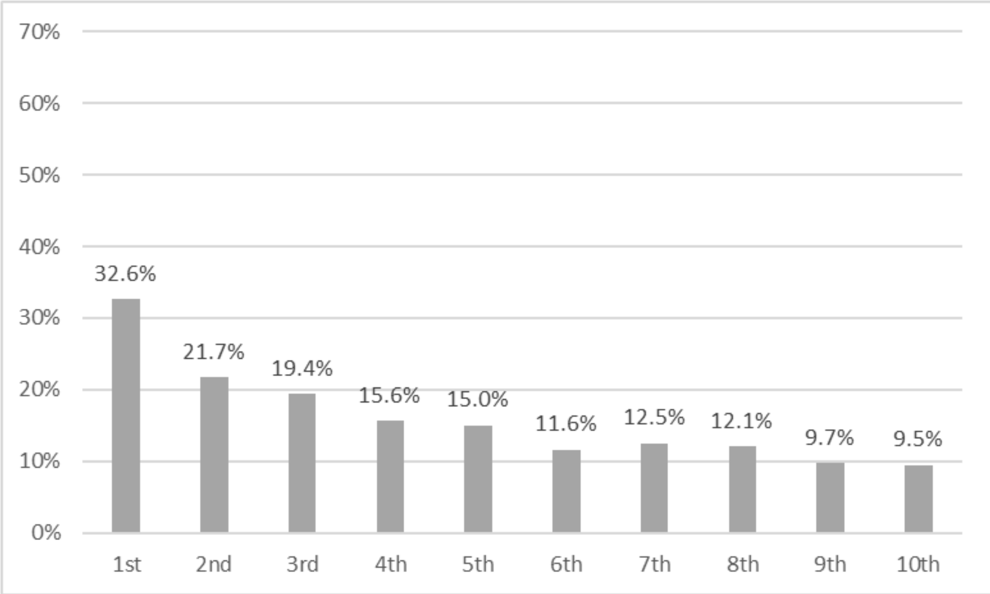

Fig. A5. RENE/2 indicator's values in 2019 for each equivalised income decile in the 'adjusted to reality' scenario

	2016	**2017**	**2018**	**2019**
Average energy poverty gap	€349	€399	€408	€374
National annual budget	€1,701m	€2,086m	€2,079m	€1,692m

Table A21. Average annual energy poverty gap and national annual budget needed for a hypothetical hidden energy poverty mitigation policy