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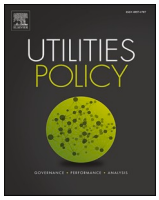

Full-length article

Comparative analysis of energy poverty definition and measurement in Portugal and Spain

Pedro Palma [a,*], Roberto Barrella [b,c], João Pedro Gouveia [a], José Carlos Romero [b,c]

[a] CENSE, Center for Environmental and Sustainability Research & CHANGE, Global Change and Sustainability Institute, NOVA School of Science and Technology, NOVA University Lisbon, Campus de Caparica, 2829-516 Caparica, Portugal
[b] Energy and Poverty, ICAI School of Engineering, Comillas Pontifical University, Alberto Aguilera, 25, 28015, Madrid, Spain
[c] Institute for Research in Technology (IIT), ICAI School of Engineering, Comillas Pontifical University, Alberto Aguilera, 25, 28015 Madrid, Spain

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ABSTRACT

This paper aims to critically analyse and compare the definition and measurement of energy poverty reflected in the national policy strategies in Portugal and Spain and propose recommendations for their enhancement. The analysis is supported by a systematic literature review of indicators in the Iberian context. Results highlight that both definitions can benefit from broadening the scope and increasing the representativeness of energy services and types of vulnerability. Measurement can be enhanced using available data and indicators for increasing comprehensiveness, reducing redundancy, and considering depth and persistence. Higher effectiveness in energy-poor households' identification requires increased indicator intersectionality and alternative indicators.

1. Introduction

Over the last few years, efforts to address energy poverty (EP) have multiplied in the European Union (EU), aiming to tackle this severe problem currently affecting over 69 million people in the EU (Eurostat, 2023a). Policy strategies such as the European Green Deal and the Renovation Wave (EC, 2019; EC, 2020c), and legislative acts such as the Energy Performance of Buildings (EPBD) and the Energy Efficiency (EED) directives (EPCEU, 2018a; EPCEU, 2023) bring EP to the forefront, stressing the need for mitigation efforts across the EU. Via the regulation (EU) 2018/1999 (EPCEU, 2018b), the Member States (MS) were mandated to assess the number of households in EP and set reduction goals and a strategic plan for addressing EP in their national energy and climate plans (NECP). MSs have addressed EP with varying levels of commitment and recognition, from agreeing on a definition and setting assessment frameworks and concrete measures to providing limited information on EP in their territories (EPAH, 2023a). Nine out of 27 MSs have provided an official definition, and half have set specific indicators to assess EP (Odyssee-Mure, 2021). Only four MSs (Ireland, Greece, Spain, and Portugal) have gone as far as developing dedicated national strategies for EP mitigation (EPAH, 2023a). Diagnosis is a major cornerstone of a strategy to face EP and can be regarded as the foundation of policy design.

A robust diagnosis sheds light on the root causes and characteristics of EP, as well as the challenges and effects that it produces (EPAH, 2023b). It encompasses a comprehensive definition and measurement framework that captures its complexity and multidimensionality and the diversity of its manifestations and affected groups. Several EP definitions have been advanced in research (Bouzarovski, 2014; Charlier and Legendre, 2021) and also at the policy level (Odyssee-Mure, 2022), stemming from distinct origins. In the EU, definitions have been previously proposed (EC, 2020a), and the EED recast and EPBD recast proposal also advance definitions to identify people in EP, with similarities but relevant distinctions (Martini, 2022). Although clear and working definitions are necessary, a one-fits-all definition can prevent targeted policymaking and may overlook the diversity of situations across the EU (EC, 2020b; Odyssee-Mure, 2021). A broader definition may capture a more diverse range of EP profiles but can be more complex to operationalise. Through the Electricity and Gas Directives (Directive, 2009/72/EC; Directive, 2009/73/EC), the EC also mandated MS to define the concept of vulnerable consumer (VC), which has been used interchangeably with EP occasionally. However, it is argued that these concepts do not fully overlap and should be distinguished (Pye et al., 2015a).

Regarding measurement, experts have defended the use of multiple indicators to comprehensively measure EP and capture its nuance using the broader concept of vulnerability (Baker et al., 2018; Thomson and Bouzarovski, 2019; Castaño-Rosa et al., 2019; Jiglau et al., 2023). The Commission's Recommendation 2020/1563 on EP states that no single

* Corresponding author.
E-mail address: p.palma@campus.fct.unl.pt (P. Palma).

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Abbreviations

2 M	"High share of energy expenditure in income" indicator
CDD	Cooling Degree-Days
EC	European Commission
EE	Energy Efficiency
EED	Energy Efficiency Directive
EP	Energy Poverty
EPAH	Energy Poverty Advisory Hub
EPBD	Energy Performance of Buildings Directive
EU	European Union
Eurostat	Statistical office of the European Union
HBS	Household Budget Survey
HDD	Heating Degree-Days
HEP	Hidden Energy Poverty
INE-ES	Spanish National Institute of Statistics
INE-PT	Portuguese National Institute of Statistics
ICT	Information and Communication Technology
LPG	Liquified Petroleum Gas
M/2	"Low absolute energy expenditure" indicator
MIS	Minimum Income Standard
MS	Member State
NCEP	National Energy and Climate Plan
PPS	Purchasing Power Standard
SILC	Survey on Income and Living Conditions
VC	Vulnerable Consumer

indicator can fully capture EP, outlining a set of indicators available for use at the national level (EC, 2020a). The importance of regional and local EP assessment has been thoroughly pointed out, including in the abovementioned Recommendation (EC, 2020a; Global Covenant of Mayors, 2022; EPAH, 2023b), but diagnosis also plays a relevant role at the national scale, to measure the problem's dimension and serve as a guideline for subnational and bottom-up frameworks and assessments. A vast set of indicators has been proposed to assess EP and estimate the number of individuals who suffer from this problem around the globe (Siksnelyte-Butkiene et al., 2021). The Energy Poverty Advisory Hub (EPAH) centralises knowledge on diagnosis and indicators, also proposing a group of indicators to measure EP based on data from the Household Budget Survey (HBS) and the Survey on Income and Living Conditions (SILC). These indicators represent energy prices, energy expenditure, thermal comfort, and dwelling energy efficiency (EE). EPAH aims to connect research and local policy practice (Palma and Gouveia, 2022) while enhancing measurement at different spatial scales (Gouveia et al., 2022, 2023).

There is potential to leverage the acquired intelligence and resources of different MS to support and co-create more comprehensive and accurate EP measurement approaches across the EU. Complex problems such as EP require multi-level coordination and cooperation between stakeholders. Territorial cooperation at cross-border, transnational, and interregional levels is central to the EU's cohesion policy for solving common problems and inequalities (European Parliament, 2022). In the EP Recommendations, the EC reiterates its support for sharing sound practices between MS to address identified challenges (EC, 2020a; EC, 023a). Analysis and comparison of the different efforts and approaches in distinct contexts is arguably the first step towards fruitful interchange and collaboration. Several authors have focused on this subject, namely Kyprianou et al. (2022), comparing Spain with other Mediterranean countries; Kyprianou et al. (2019), contrasting EP policies in five EU countries; and Kerr et al. (2019), comparing EP approaches in England, Ireland, and France. Other authors have discussed EP efforts across EU Member States (Bouzarovski et al., 2020; Heeman et al., 2022). Bardazzi et al. (2023) characterised EP in four Mediterranean countries (Greece, Spain, Italy, France, and Portugal).

Neighbouring countries often share common EP manifestations and challenges. Thus, there are added potential benefits from knowledge exchange and cooperation for improving strategies and actions. Portugal and Spain are two examples of neighbouring nations in the European context, bonded by history and geography, whose populations face a severe EP problem determined by similar causes. They share identical socioeconomic, climatic, and infrastructural characteristics, have significant integration of energy systems and markets, and lack a shared understanding and regulatory framework, supporting the case for comparative analysis. Metrics and measures implemented in one country are more likely to be suitable and directly transferable to the other.

Moreover, the peer effect between geographic neighbour countries can drive policy diffusion (Mistur et al., 2022). The two countries have a relatively recent background of scientific knowledge but have developed a national strategy for addressing EP in their territories, demonstrating the increasing recognition and concern over this issue. Moreover, Portugal and Spain are among the few countries in the EU that have adopted an EP strategy, following research developments in later years. Thus, there is value in comprehensive research that investigates EP measurement in the Iberian Peninsula, aiming to channel existing knowledge and scholarship toward informing and improving policy.

This paper aims to critically analyse and compare the EP definition and measurement framework proposed in both national contexts. It draws on state-of-art literature to identify similarities, shortcomings, and best practices in each approach, aiming to contribute to the enhancement of both countries' diagnosis strategies. It provides direct contributions to support the upgrade of current EP mitigation strategies. The outcomes of this study have a direct link to utilities' policy, as official EP diagnosis can shape and influence policy regarding energy provision. The definition of energy-poor and vulnerable consumers is essential for designing and implementing consumer protection measures and financial interventions that significantly impact utilities, determining which households are supported and the necessary investment. It can help transform energy demand and supply in the domestic sector by promoting renewable energy, consumption electrification, building energy renovation and EE, and grid upgrades.

EP-dedicated strategic policies are still scarce in the European context, and studies that bring state-of-the-art knowledge from research for developing a direct science-based critique and proposing direct recommendations for its future revisions are lacking. The value of the insights for both contexts taken from this comparative analysis is twofold. Firstly, critically comparing the implemented diagnosis in the light of the existing indicators and available data resources in each context, both on the policy and academic sides, enables an informed revision in the short term using the existing resources and scholarship. Secondly, integrating learnings from other geographical contexts can contribute to setting the scene for a deeper revision and a potentially more comprehensive upgrade, proposing the integration of new datasets and indicators. Additionally, it may also inspire the design or revision process of other strategies across the EU. The main research question addressed by this paper is synthesised as: "*How can official EP Diagnosis presented in the national strategies be improved by drawing on the available knowledge and resources in the two contexts but also from international literature and practice?*" This analysis is focused both on definition and measurement indicators. The article is organised as follows. Section 2 introduces the case studies. Section 3 describes the methods. Section 4 presents the results and discussion. Section 5 identifies the conclusions.

2. Case studies

Portugal and Spain are the westernmost countries of Europe, forming

jointly the Iberian Peninsula. Both countries have a considerable percentage of the older population (65 years old and older), about 23.4% in Portugal and 20% in Spain. On the other hand, the population under 15 years old is 12.9% and 14%, respectively (INE-PT, 2021; INE-ES, 2022). These population groups are particularly vulnerable to EP (Eisfeld, 2023). Examining the economic dimension, Portuguese and Spanish households have lower purchasing power than the average European citizen, with potential repercussions on energy purchases, as the adjusted gross disposable income per capita in purchasing power standard (PPS) was 21,032 and €21,382 in 2022, below the EU average of 25,786 (Eurostat, 2023b). Income distribution inequality is also high in both countries (32%), above the EU average of 29.6% (Eurostat, 2023c). Portugal also presents a high share of the population at risk of poverty in 2022, 20.4%, above the EU's 16.5% and Spain's 16.4% (Eurostat, 2023d, e), an indicator of difficulty in accessing basic needs.

Regarding the building stock, 65.5% of Portuguese residential buildings were built before 1990, when the first energy performance regulation was adopted. It reflects on the EE: from 2014 to 2021, approximately 68% of all the energy-certified residential buildings (about 1.43 million) had an energy performance rating equal to or below C, below the standard for new buildings (ADENE, 2023). In Spain, about 55% of buildings were constructed before the first building standard in 1981 (INE-ES, 2011), and around 97% of certified dwellings at the end of 2021 had a grade equal to or lower than C (MITECO and IDAE 2021). As for domestic energy consumption in Portugal, around 41% of the final energy consumption is electricity, and approximately 26% and 23% are, respectively, biomass and gas (Liquified petroleum gas (LPG) and natural gas) (DGEG, 2023). In Spain, electricity also represents the highest share of final energy consumption (43%). Still, there is a higher dependency on fossil fuels, about 37% (LPG, 6%, heating gasoil, 10%, natural gas, 21%) (MITERD and IDAE, 2022). Both countries report high energy prices, which is considered one of the leading causes of EP. Electricity prices in PPS, with all taxes and levies included for the second semester of 2022, were 0.26 and 0.35 for Portugal and Spain, respectively, the 15th and 8th highest in the EU, whereas gas prices reached values of 0.15 and 0.17, 7th and 4th highest in the EU for the same period (Eurostat, 2023g, 2023h).

Regarding climate, whose interaction with buildings' thermal performance impacts indoor temperatures and energy needs, both countries share similarities despite a higher diversity of climate types in Spain varying across the territory (AEMETInstituto de Meteorologia - PT, 2011). They are two of the warmest countries in the EU, with the 6th and 4th highest average number of cooling degree days (CDD) between 1979 and 2021 (approximately 182 for Portugal and slightly over 200 for Spain). On the other hand, both have two of the mildest winters, respectively, the 3rd and 5th lower heating average degree-days (i.e., 1239 in Portugal and 1880 in Spain) for the same period (Eurostat, 2023f).

The EU-SILC indicators can also provide insight into potential EP vulnerability in the populations. Both countries reported high levels of inability to keep their home adequately warm, respectively 17.5% and 17.1% (Eurostat, 2023a), a direct effect of EP. There is a higher incidence of inability to pay utility bills (including energy bills) in Spain, 9.2%, against 4.7% in Portugal (Eurostat, 2023j). In the summer, the last time data was collected for both countries (in 2012) showed a deeper problem in Portugal, with 35.7% of the population reporting not having their home comfortably cool during the summer, while in Spain, the share amounted to 25.6% for the same indicator (Eurostat, 2023i). A recent ad-hoc module survey shows an increase in 2023 to 38.3% (INE, 2023). In 2015, a considerable part of the population in both countries (15.1% in Portugal and 14.2% in Spain) had an energy expenditure proportion in the income higher than twice the median, a symptom of energy overspending. Self-restriction to abnormally low levels of energy consumption is also an EP effect, and a higher incidence of this problem is found in Spanish households, 13% compared to 6.8% in Portugal (EPAH, 2023c).

EP recognition and attention in Portugal have risen in the policy arena in the last five years. It has been highlighted as a priority in several policy strategies, such as the National Energy and Climate Plan (NECP) 2030 (Portuguese Republic, 2019a), the Roadmap for Carbon Neutrality for 2050 (Portuguese Republic, 2019b), and the Portuguese Building Long-Term Renovation Strategy (Portuguese Republic, 2021). In Spain, awareness and attention have grown in Spanish society, from governmental entities to the general population, since the first report on EP (Tirado-Herrero et al., 2012). The electricity and natural gas social tariffs, implemented in 2010 and 2011, stemming from the directives on the internal EU energy market, were the first policy initiatives to address EP in Portugal. Currently, two buildings' EE improvement programs based on non-refundable subsidies are implemented, one directed to VCs, including energy-poor households (Fundo Ambiental, 2023). A social electricity tariff, thermal social allowances to support electricity and thermal energy services consumption, and EE measures have been adopted in Spain. In 2019, the Spanish EP roadmap for 2019–2024 was approved, setting the policy framework to tackle this issue (Ministerio para la Transición Ecológica, 2019). In Portugal, the Long-term National Strategy for EP Mitigation 2023–2050 was published at the beginning of 2024 (Portuguese Republic, 2023).

3. Methodology

The methodology is divided into four different steps. First, European EP definitions and measurement approaches in scientific literature and national policies were reviewed. Secondly, drawing from the countries' characterisation and the review of definitions and measurement approaches, the official EP diagnosis proposed in the national EP strategies of Portugal and Spain are compared and contrasted, aiming to identify sound practices and shortcomings. Thirdly, a dedicated systematic literature review of indicators for each case-study country is conducted to investigate existing data resources and scholarship regarding EP measurement in the two contexts. Finally, building on the outcomes of the previous steps, potential changes in the approaches are proposed and discussed, aiming to contribute to the enhancement of EP diagnosis in the Iberian Peninsula. The methodologic framework is displayed in Fig. 1.

3.1. Literature review of international definitions and indicators

A literature review of definitions and indicators was conducted to identify the existing approaches and best practices in EP diagnosis. EP definitions proposed in scientific literature and policy instruments, namely MS's adopted EP strategies and NECPs, were identified and analysed. VC definitions were also considered in the analysis. The policy and research relevance of EP has prompted multiple literature review studies, which synthesise key aspects of EP research. A review of eighteen scientific articles that developed a literature review or critical analysis of EP indicators was conducted to identify the most used approaches, their strengths and limitations, challenges to be addressed, and practices to be followed.

3.2. Analysing and comparing the official definition and indicators

Drawing from the review of definitions and measurement approaches in scientific literature and policy, the diagnosis components of the national strategies for combating EP proposed in each country are critically compared and contrasted. The definitions presented in the national strategies are analysed regarding their ability to capture the multidimensional nature of EP and its diverse manifestations and affected groups. The EP causes and consequences identified in the definitions or within the strategies were reviewed to compare their inclusion, positioning, and adequacy levels. The same exercise is conducted with the definition of VC introduced by the strategies, which are compared considering its role in EP diagnosis.

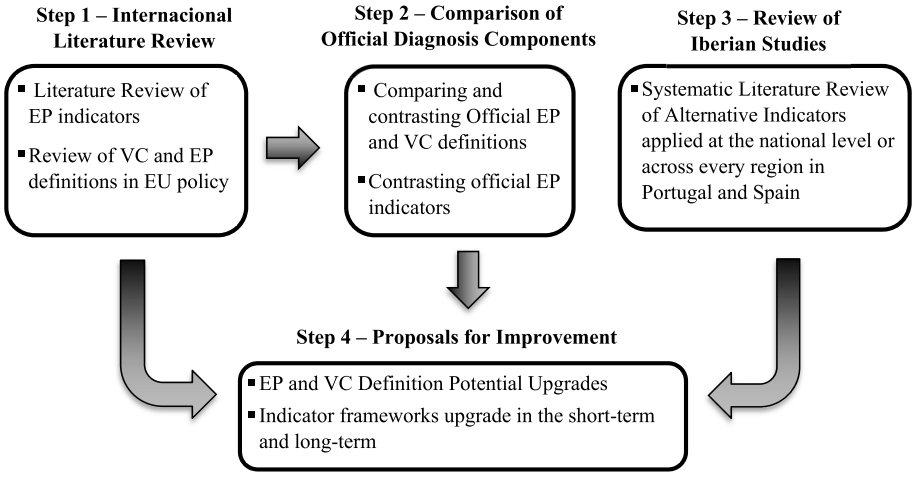

Fig. 1. Methodologic framework.

The indicators and data used to identify energy-poor households and assess EP in the national strategies ('official indicators') are also analysed and compared on the following characteristics: *approach, object of measurement, dimensions, outcome, and type of EP depicted*. The selection of these aspects is informed by the work of Pye et al. (2015b), Rademaekers et al. (2016), Thomson et al. (2017), Meyer et al. (2018), and Gouveia et al. (2022) reviewed in the previous chapter. The *approach* refers to how the indicator captures EP using numerical data from statistics (quantitative) or descriptive non-numerical data (qualitative). The *object of measurement* represents what is being measured: causes, like income or building and equipment EE; drivers, such as age, literacy, or housing ownership; or consequences (or effects), which can be direct, like thermal discomfort and high energy spending, or indirect, such as health issues or social stigma and isolation. The *dimension* indicates what aspect of the problem is being represented, which can be: (a) economic, such as income, energy prices, or expenditure; (b) infrastructural, such as energy network or buildings' characteristics and energy performance; (c) climatic, such as temperature or humidity; (d) sociodemographic such as age, unemployment, or education level. The *outcome* provides information on what is being measured, the extent (number of people/households in EP) or depth, *i.e.*, the intensity level of EP. Finally, the *type of EP depicted* was classified as in Meyer et al. (2018), *i.e.*, defined as 'measured', estimating energy overspending, 'hidden', capturing energy underspending, and 'perceived' representing self-reported difficulties. An extra type is considered: the 'vulnerability level', when EP is evaluated with a magnitude scale. The indicators' adequacy and effectiveness in identifying energy-poor households, incorporating enough nuance, and monitoring its evolution amidst potential data constraints are also discussed.

3.3. Systematic review of alternative indicators

A systematic literature review of alternative indicators proposed in scientific peer-reviewed articles was also conducted using the search engine Web of Science and the keywords "energy poverty" or "fuel poverty", together with "Spain" or "Spanish", to search for articles focusing on the Spanish context and "Portugal" or "Portuguese" searching for the Portuguese ones. The search was conducted using the title, abstract, and author keywords, following the PRISMA framework (Page et al., 2021). A total of 120 and 45 peer-reviewed articles were found in the initial search, considering the title, abstract, and keywords for Spain and Portugal, respectively. The screening process was conducted by revising the title and abstract and skimming through the main body of text of each article, excluding articles according to the following criteria: 1) articles (N = 7) that focused on case studies outside the two countries; 2) articles (N = 107) that do not advance an EP measurement approach; 3) articles (N = 26) that developed/proposed subnational indicators focusing on specific areas or regions within the countries.

Only national-level indicators and subnational indicators used for assessing EP across all country regions were considered in the review. This criterion guarantees that the data used for this indicator is available for the whole country and has been tested at the national level, enabling its use for the short-term update of national-level strategies. Finally, one study known by the authors (Palma et al., 2022) that was not captured in the search was included in the review as it fulfilled all the criteria. A total of 26 articles (21 for Spain and 5 for Portugal) were selected for the analysis. After the selection, these indicators were analysed according to the characteristics mentioned above and other key features, such as *Geographic scope, Population, Method,* and *Data source*, aiming to identify sound practices in scientific literature and unveil data sources and datasets that can strengthen the current official frameworks. The flow diagram is presented in Fig. 2. By focusing on existing data and expertise in the Iberian context, this systematic review aims to contribute to drawing policy recommendations that can be adopted in the shorter term.

3.4. Proposals for enhancing the official diagnosis in both countries

The last step aims to identify potential improvements in EP definition and measurement in both countries. The proposed improvements for the strategies' definitions and indicators stem from identifying each approach's strengths, the sound practices from European scientific literature and policy, and the existing resources and knowledge within the Iberian context. Regarding the indicator frameworks, two different types of proposals are discussed: long-term, stemming from the broader review of existing international indicators, which may require the use of data and indicators that may not be available in the two countries, and short-term, informed by the dedicated systematic literature review in both countries, which can potentially be implemented in the present moment, since the necessary resources and expertise are already available. The goal is ultimately to contribute to more comprehensive and nuanced diagnosis approaches in the two countries, accounting for justice and inclusiveness in identifying vulnerable groups.

4. Results and discussion

4.1. Literature review

4.1.1. Energy Poverty Definitions across the EU

The first definitions of EP in the literature date back to the 1970s in the UK and were tailored specifically to the British context, still referring to this issue as fuel poverty, focusing only on heating and mostly on fuel.

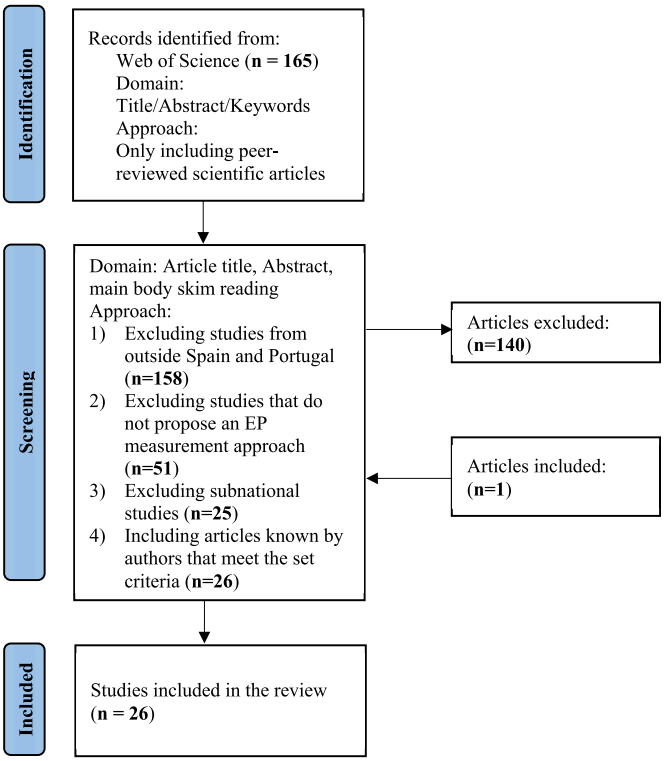

Fig. 2. Systematic literature review framework.

Isherwood and Hancock (1979) defined fuel-poor as 'households with high fuel expenditure as those spending more than twice the median (i.e. 12%) on fuel, light and power", and the median was based on the 1977 UK Family Expenditure Survey. This approach followed Townsend's (1979) definition of relative poverty as not bound to a fixed condition. Subsequently, Bradshaw and Hutton (1983) stated that individuals, families, and groups are in fuel poverty "when they lack the resources to obtain the reasonably warm and well-lit homes which are customary, or at least widely encouraged or approved in the societies to which they belong'. Boardman (1991) popularised the term as households who "are unable to obtain an adequate level of energy services, particularly warmth, for 10% of its income". Disproportionately high energy expenditure was the first metric to identify energy-poor households, albeit with slightly different threshold levels, leaving out households that self-restricted their consumption.

It is possible to distinguish two different categories of definitions. One type of definition, such as those by Isherwood and Hancock (1979) and Boardman, 1991), blends the concept with the measurement, as the definition of the problem integrates a specific indicator. This approach is more practical and operational but risks narrowing the problem to a limited range of dimensions or aspects. The other type is a more conceptual definition that does not integrate a concrete metric but qualitatively describes the concept and the underpinnings of being energy-poor, as in Bradshaw and Hutton (1983). Other authors have proposed definitions that follow one of these two approaches. While the 10% indicator has been transferred to different contexts and is widely used (Thomson et al., 2017), other authors proposed definitions based on other metrics, often composite ones. Hills (2011) introduced an income condition to the expenditure indicator, considering that a household is in EP if it has an income lower than the poverty line and the energy cost exceeds the national average (median) fuel cost. The author states that expenditure is not the exclusive requirement for a household to be considered energy-poor and that income levels should be considered.

More on the conceptual side, Bouzarovski (2014) defined EP as the inability of a household to access socially and materially necessitated levels of energy services in the home. The author follows a similar approach to Bradshaw and Hutton (1983) by focusing on energy services rather than energy expenditure. However, the latter especially mentions warmth and lighting, whereas Bouzarovski (2014) does not specify the energy services. The author defines the level of energy services qualitatively rather than quantitatively, introducing a component of social costume to qualify the need for energy. In subsequent work, he proposed an amended definition, stating that "a household is unable to secure a level and quality of domestic energy services—space cooling and heating, cooking, appliances, information technology—sufficient for its social and material needs" (Bouzarovski, 2017). It further defines the needed energy services in terms of quality, as energy service provision may be more or less clean, safe, and efficient. This detail is also stressed in the 7th SDG, Affordable and Clean Energy (UN, 2015).

Furthermore, the authors enumerate the energy services considered, namely space cooling, which is increasingly a priority in EP studies (Thomson et al., 2019). Access is also mentioned as a broader term, not limited to affordability, which presupposes that access is not just dependent on financial resources. Other authors, such as Dobbins et al. (2019), define EP as "a situation where households are unable to adequately meet their energy needs at an affordable cost", including the causes of the problem in the definition "(…) caused by a combination of interrelated factors including low-income, high-energy prices, poorly insulated buildings, inefficient technologies and sometimes limited access to clean and affordable energy sources." It provides more information about the causes behind the inability and can help direct policy design. On the other hand, it can also generalise a problem with different possible configurations and combinations of aspects within the same geographies. Day et al. (2016) propose a definition tailored to the capabilities approach, defining EP as the "inability to realise essential capabilities as a direct or indirect result of insufficient access to affordable, reliable, and safe energy services". Energy services guarantee secondary capabilities such as heating or cooling homes, washing clothes, or cooking healthy meals, and ensure basic capabilities such as physical and mental well-being, social respect, education, and maintaining relationships. This approach can help define broader and subjective concepts, such as "adequate" or "basic levels" of energy services. Finally, the

European Commission proposed a broader and more conceptual definition, declaring that "energy poverty is a situation in which households are unable to access essential energy services" (EC, 2020a). A new definition was recently advanced in the revised EE directive, stating that EP "means a household's lack of access to essential energy services, where such services provide basic levels and decent standards of living and health, including adequate heating, hot water, cooling, lighting, and energy to power appliances, in the relevant national context, existing national social policy and other relevant national policies, caused by a combination of factors, including at least non-affordability, insufficient disposable income, high energy expenditure and poor EE of homes". (EPCEU, 2023). It is still a conceptual approach but a more comprehensive one, referencing the different energy services, the importance of the national context, and the leading causes.

Several European countries have proposed an official definition in a policy instrument or state document. The definitions that have been collected can be consulted in Table A1 in the appendix. The UK nations based their definitions on energy expenditure thresholds, such as Boardman's 10% indicator, still used in Northern Ireland, Wales, and Scotland. The three nations only focus on indoor temperature and heating regimes, dismissing other energy services in EP considerations. Wales defined a second threshold (20%) for a second level of severe EP, distinguishing different levels of vulnerability. Scotland and England introduced an income threshold in the definition based on Hills' work. Slovakia's definition of energy poverty also relies on energy expenditures in the different energy carriers over income but mentions a "substantial" share without quantifying the threshold, which is not operational, hence requiring the use of indicators to proceed with the identification of households.

France also opted for the conceptual definition approach, mentioning the satisfaction of "elementary needs" and underlining the causes of "inadequacy of financial resources" or "housing conditions". The French definition mentions "difficulties" in contrast to "inability", potentially widening household identification. Finland has a similar approach to France and Romania, pointing to minimum energy needs, focusing solely on the cold season but mentioning the provision of optimal heating. Lithuania adds two valuable aspects, mentioning both the difficulty and impossibility of guaranteeing heating and transport, which has been considered a relevant part of EP, highlighting the nexus between domestic and transport EP (Openexp, 2019). Austria introduced consumption restriction, stating that EP is defined by high cost and a forced reduction of consumption due to low income, enabling the identification of a different kind of vulnerability. Poland states that not only the three leading causes must be observed but the existing social support programs' criteria as well, possibly to rule out non-low-income households.

4.1.2. Vulnerable consumers definitions

The VC definition is distinct from the general definition of EP, but there can be partial overlap between the two concepts, and income represents the connection (EC, 2015). As asserted by Pye et al. (2015b), in the European context, vulnerable energy consumers cannot access the more competitive prices and market conditions or require additional safeguards and protection due to their income, age, health, disability, or other reasons. A household can be energy-poor and not a VC, and vice versa. On the other hand, the EP intensity can be magnified if a person is a VC and adequate support is not provided. The MSs have different approaches to the definition in their legislation, translating into support allocation to different population groups. Pye et al. (2015b) identified four definitions: receipt of social welfare, energy affordability, low income/high expenditure, health and disability, and other socioeconomic groups. Often, these aspects are intrinsically intertwined, and in some cases, broader definitions explicitly consider several aspects within the definition. The most common definition is based on social welfare recipiency (14 MSs), mainly attributed to low-income households. It is arguably the more accessible strategy to identify this group, addressing an often-relevant factor of vulnerability, the reduced purchasing power resulting in affordability issues.

Nevertheless, it is a limited representation of vulnerability, as income is only one component of a diverse and complex problem. Several MSs do not draw such a clear line between EP and VC, proposing a definition analogous to the EP based on energy affordability and income. Other MSs base their VC definition on health and disability conditions, such as Slovakia and Czechia, and even a diverse set of socio-economic aspects, including income, age, retirement, number of children, and social exclusion from energy supply, such as Cyprus and Bulgaria (Kyprianou et al., 2019). Most MSs address the issue from an affordability perspective, supporting vulnerable consumers via income or price support schemes. However, a stronger EU endorsement for disconnection protection is on the horizon (EC, 2023b). Other factors not considered in these definitions are also emerging as potential vulnerability drivers, such as gender and ethnicity, which may call for revising the concept in the MSs. However, as Pye et al. (2015b) state, there is a trade-off between a definition that is so wide that it creates a complex challenge to translate into practical action and one that is so narrow that it disregards relevant vulnerable groups.

4.1.3. International indicators

Indicators are often grouped into three main categories: expenditure-based, consensual-based, and direct measurement (Thomson et al., 2017; Tirado-Herrero, 2017; EPAH, 2023c). In some instances, a fourth category of indirect or supporting indicators that depict associated factors has also been considered (Rademaekers et al., 2016; EC, 2020a). The review of scientific articles focusing on EP meaurement is displayed in Table A2. The use and advantages of the different types have been thoroughly discussed (Rademaekers et al., 2016; Thomson et al., 2017b; Tirado-Herrero, 2017). The consensual-based approach consists of self-reported experiences and assessments by households on thermal comfort, ability to afford basic energy services, housing conditions inside their homes, or other relevant aspects of EP. Known examples are the EU SILC proxy indicators presented by EPAH, such as the "Share of the population not able to keep their home adequately warm" and the "Share of the population having arrears on utility bills" (EPAH, 2023c). Thomson et al. (2017) state that these indicators are intelligible and result from a bottom-up approach, capturing the lived experience of the household and potential vulnerability, which statistics may not depict. However, they are intrinsically subjective – concepts such as thermal comfort represent different meanings and expectations, and households may provide skewed representations of their situation (Boardman, 2011; Thomson et al., 2017). Countries like Czechia (Government of Czechia, 2023), Latvia (Government of Latvia, 2020), Malta (Government of Malta, 2019), Romania (Government of Romania, 2020) or Denmark (Government of Denmark, 2019) rely on the EU-SILC indicators to report EP levels in their population despite not having a legal definition or indicators established.

Expenditure-based indicators compare domestic energy expenditure to income, defining an expenditure threshold above or below which a household is considered in EP. These are objective and comparable across regions despite being sensitive and unable to capture the more subjective aspects of EP (Rademaekers et al., 2016; Thomson et al., 2017). The first EP definitions brought forward the first expenditure-based indicators, such as Isherwood and Hancock's double the median or Boardman's 10% of income expenditure, depicting high energy expenditures. Wales, Northern Ireland, as seen in their definition, and Ireland (Government of Ireland, 2022) still mostly rely on the 10% indicator to identify energy-poor households, while Poland uses it to monitor national levels (Government of Poland, 2019). This indicator is easy to communicate and apply but specific to the English context (Liddell et al., 2012). However, Romero et al. (2018) highlight its high sensitivity to fuel price changes. It does apply an income threshold, so it can wrongly identify high-income households as energy-poor (Hills, 2011; Moore, 2012). It also does not capture cases of high energy inefficiency, energy behaviour (namely self-restriction), or high energy needs related to large households, older, or occupants with disabilities that require more energy (Hills, 2011; Moore, 2012; Legendre and Ricci

2015). EPAH proposes the expenditure-based "High share of energy expenditure in income" (2 M) indicator, which has been used with variations, namely considering double the mean or median absolute values or double the mean or median share of income (Castaño-Rosa et al., 2019). Depending on the distribution of population expenditures, one of these options may be more effective in identifying energy-poor households. Using the absolute values of expenditure instead of the shares removes income from the equation, giving it an absolute interpretation as an independent variable from earnings. Moore (2012) defend using median energy expenditure values instead of the mean because they are more representative of typical use and less affected by outliers. EPAH also proposes the indicator M/2 (half the median share), which captures abnormally low energy expenditure. It is a dimension of EP highlighted by several authors as a relevant aspect, often defined as "hidden energy poverty" (Meyer et al., 2018; Barrella et al., 2022a).

Another example of a commonly used expenditure-based indicator is the "Low-Income High Costs" (LIHC), proposed by Hills (2012) and, up until recently, the official EP in England. Similar approaches are currently used in other contexts, such as Greece (Government of Greece, 2021). It aimed to overcome the mentioned shortcomings of the 10% indicator. It is a double objective indicator, combining an income threshold, 60% of median adjusted income after housing costs plus modelled energy expenditure, and an expenditure threshold, based on modelled median energy consumption, above which costs are considered "high". This indicator captures those households that are pushed into EP by their energy costs while excluding households that are not income-poor (Hills, 2011). It also measures the extent and depth of the problem, which is a relevant addition for a more comprehensive understanding. However, it does not consider the hidden EP and EE of the dwellings. The English government (Government of the UK, 2023) replaced the LIHC with an upgraded expenditure-based metric, the Low Income Low (LILEE), that adds EE as a criterion for identifying energy-poor households, namely those living in a dwelling with an energy rating D or below, while maintaining the income threshold as before. It replaces the previous energy costs, an arguably less effective indicator of poor EE since it depends on energy prices. Moreover, the indicator already includes energy costs, as residual income is compared to the poverty threshold after subtracting housing and energy costs.

Proposed by Moore (2012), the "Minimum Income Standard" is another indicator that has gained traction, having been transferred and adapted to other contexts (Romero et al., 2018; Panão, 2021) . It establishes a minimum income level after deducting all living costs, including housing costs, that enables households to afford their required energy costs. The selection and estimation of different items or living costs varies, leading to underestimating the number of people in EP (Barrella et al., 2022b). Despite the inherent difficulty of estimating all the necessary expenditures, MIS is seen by some authors as an adequate alternative in this indicator typology. Moore (2012) defends that it is a more direct measure of need and more transparent in accounting for housing needs and household income adjustments. Romero et al. (2018) mention the difficulty in determining minimum income but state that the indicator is one of the most robust. The authors defend that EP is a normative problem and of absolute limits, not directly dependent on the aggregate situation of society; thus, an absolute indicator such as the MIS, considering the household's specific needs and situation, is more appropriate for identifying energy-poor households. Scotland has established a hybrid official indicator, adopting the LIHC approach while integrating Boardman's and Moore's approaches. The energy cost threshold is defined as 10% of net income, and the income level after energy costs is defined as 90% of MIS.

There are important considerations when using income and expenditure as an EP indicator. Income can be applied in its generic form or be adjusted to household type and size (equivalisation) due to economies of scale within the household, which provides a more realistic depiction of household needs. However, the geographical and temporally rigid equivalisation scales will likely lose effectiveness in capturing existing variability (Tirado-Herrero, 2017). Income can also be considered gross or net and before or after housing costs, which yields different results. Deducting housing costs is appropriate for estimating household disposable income (Tirado-Herrero, 2017). Expenditure can be relative to actual consumption or modelled consumption. Actual consumption can be more realistic, but it may hide underconsumption cases, not capturing energy-poor households that restrict their consumption, where modelled consumption can result in overestimations. Lowans et al. (2021) state that actual and required consumption are rarely the same.

Direct measurements compare domestic energy services consumption with a required set value, often using temperature as a proxy for assessing if the household maintains comfortable temperatures. Difficulties involving conducting measurements in homes (Thomson et al., 2017) may explain the meagre number of studies employing this approach in Europe. As an example, Cong et al. (2022) investigated the indoor temperature that prompts households to turn on their space cooling systems, noticing a difference that an EP situation may justify; and Okushima (2019) and Kahouli and Okushima (2021) used an energy use threshold, instead of an expenditure threshold, to identify energy-poor households.

Authors show that there is no total overlap between the population groups captured by the different types of indicators (Rademaekers et al., 2016; Karpinska and Śmiech, 2021; Deller et al., 2021); thus, diverse and comprehensive frameworks are required to capture the complexity and broad nature of this issue.

Several authors also propose and defend using composite indexes, integrating several indicators in one single metric (Walker et al., 2012; Fabbri, 2015; Castaño-Rosa et al., 2018; Karpinska et al., 2021; Barrella and Blas-Álvarez, 2024). These are considerably comprehensive approaches but context-specific and more challenging to transfer and operationalise in other contexts, often requiring several specific datasets. Sareen et al. (2020) point to difficulties regarding its transparency, commensurability, and effectiveness across different contexts. However, there are various levels of complexity depending on the method and number of indicators. Some expenditure-based indicators already covered can be considered composite as they encompass different indicators.

Regarding the metrics adopted by the EU MSs, Austria defines two official EP indicators: income below the risk-of-poverty threshold and higher-than-average expenses for energy ((Republic of Austria, 2019), identifying low-income households' high energy expenditure as the sign of EP. Lithuania applies the same expenditure indicator together with the inability to keep homes adequately warm indicator to monitor EP levels (Government of Lithuania, 2019), operationalising a mixed framework that captures the objective and subjective dimensions of the problem, an advantage of composite approaches. France has a similar but more complex approach with two leading indicators: the energy effort rate, with a threshold of 8% of income, and an income per consumption unit (UC) of less than three decimal numbers of total income (to capture hidden EP) and an indicator regarding feeling too cold or too hot at home (Government of France, 2023; ONPE, 2023). In their NECP draft (Government of Netherlands, 2023), the Netherlands proposes four indicators: 10% for high energy quote, low income (up to 130% of low-income standard) and high energy bills, low income and low EE, and low income, low EE and low investment capacity (under 40 thousand euros including excess value of property). The latter indicator measures the household's ability to participate actively in the energy transition, an often-overlooked aspect.

4.1.4. Practices and challenges identified in measurement

Several authors have dedicated their research to the study of EP indicators and have uncovered important aspects and challenges regarding EP measurement. Culver (2017) mentions the trade-offs in indicator design between accuracy, comprehensiveness, consistency, and simplicity for communication, highlighting the difficulty and

importance of balancing these aspects. Pelz et al. (2018) see multidimensional approaches as advancement compared to binary approaches in policy discourse and national energy planning. However, they mention the challenge of operationalisation, its over-prescriptive nature, and the needed separation between measurements at different scales. Adapting measurement dimensions and thresholds may be necessary to simplify these metrics and retain meaningfulness. The authors state that the value of a metric pertains to the ability to inform policy, assist those in need whose vulnerabilities are often masked (mentioning age and gender), and reap the greatest welfare benefits. Brabo-Catala et al. (2024) defend that novel indicators adapted to each specific case are necessary, while a combination of household, dwelling, and economic indicators that can assess the severity and remain effective through changes should be prioritised. These aspects are corroborated by Pelz et al. (2018), who mention the depth and dynamics of in and out of EP as potential enhancements. Thomson et al. (2017) and Tirado-Herrero (2017) also agree that a set of indicators would arguably provide a more detailed depiction of EP, while a single indicator simplifies the determinants at play and excludes vulnerable households from receiving support. Thomson et al. (2017) propose a distinction between priority and non-priority indicators, representing internal and external factors and a vulnerability framework with different factors such as access, needs, practices, affordability, flexibility, and EE, each encompassing different indicators with separate results or combined in a multidimensional index. Castaño-Rosa et al., 2019 also used a four-area vulnerability framework: available infrastructures, energy efficiency, monetary and social poverty, and well-being and health, requiring the combination of several indicators. The authors defend the inclusion of vulnerable groups (children, older adults, people with disabilities), the impact of other basic needs, e.g. "heating or eating", and thermal comfort assessments. The latter aims to overcome the subjectivity of other EP indicators, namely subjective EU SILC indicators and EE indicators, considering they cannot be interlinked with other EP indicators. The authors suggested that indicators should be analysed independently to avoid exclusion or inclusion inaccuracies. Rademaekers et al. (2016) also support a multidimensional approach, combining quantitative and qualitative indicators portraying causes and consequences in four indicators that measure the hidden, measured, and perceived EP, minding aspects of data availability, simplicity, and implantation. The authors mention the importance of thresholds and how small changes can lead to considerably different results, namely the identification or exclusion of different households.

This aspect was also highlighted by Fizaine and Kahouli (2018), who recommend combining indicators with a sensitivity analysis, omitting thresholds from expenditure-based indicators, assessing the distribution of the data, and using new indicators in multidimensional frameworks. The authors also defend analysing the duration of EP, distinguishing endogenous and exogenous determinants, and linking EP with other social vulnerabilities such as monetary poverty, health, and social exclusion. Deller et al. (2021) reiterate the lack of overlap between measures, with varying levels and types of households identified, and the problem of excluding specific households when using only one indicator. The authors suggest complementing the indicators with in-home temperature measurements and occupants' preferences, which are increasingly feasible with the rollout of smart thermostats.

Besides supporting a multiple indicator approach, Lowans et al. (2021) emphasise the importance of the definition, as it determines the problem's scale while arguing for the cross-analysis between health indicators and debt measures with EP metrics to assess the impact of solutions on different groups. The authors mention the lack of standards for appliance use and the often arbitrary nature of EP thresholds. Lowans et al. (2021) also pinpoint space cooling as an overlooked issue that is bound to be more problematic in the future. The authors highlight data availability as a limitation that shapes indicator selection, resulting in neglected population groups such as the travelling community, and defend the intersection between energy and transport. Thomson and Bouzarovski (2018) identified other measurement gaps or untapped aspects such as electrical safety, economic impacts of poor-quality energy supply, health and wellbeing impacts, energy consumption data of information and communication technology (ICT), regionally specific data, and household behaviour.

After a review of a diverse set of indicators, Siksnelyte-Butkiene (2021) argued for a more sustainability-based approach following the United Nations' modern concept of EP. The author proposes a set of indicators divided into economic, social, and environmental categories for household-level assessments. They include thermal comfort, indoor and outdoor pollution, and accessibility to renewable energy, which are not often prioritised in EP measurements. Siksnelyte-Butkiene et al. (2021) further developed the analysis, proposing indicators within the same categories for meso-level, aggregating household level data, and macro level, depicting the major EP trends. The authors evaluate whether indicators reflect the objectives of sustainable development, defining criteria that include the economic, social, and environmental dimensions, as well as transparency in data and method, practicability and flexibility, and stakeholders' participation in the indicators' selection and weighting. The authors found that most analysed studies rarely covered the environmental dimension and the participation criteria.

Sareen et al. (2020) assert that measurement defines the problem, so EP becomes what is measured, and reduction efforts are tailored according to the constructed representation, which is bound to be flawed or limited. The authors argue for bottom-up public engagement and direct inputs. Subjective indicators, collected directly from the population regarding their condition, can be seen as a step towards this intent.

4.2. National strategy diagnosis

4.2.1. Official definitions

The long-term national strategy for EP mitigation in Portugal proposed the first-ever official definition of EP in the country, which copies the definition proposed in the EE directive (EU) 2023/1791, previously described. The Spanish Government officially defined EP as "the situation in which a household cannot meet its energy needs due to insufficient income and which, in some cases, may be aggravated by energy inefficient housing".

The definitions hold some differences and similarities. Both strategies propose a more conceptual definition without integrating a specific indicator, thus not being operable frameworks for direct and objective identification of the affected households and subsequent prescription of mitigation policies. The general term 'energy services/needs' is mentioned in both definitions, but only the Portuguese specifies the different energy services. However, it leaves out the energy from information and communication technologies, which are increasingly relevant energy services. Both also encompass directly or indirectly the notion of "need", and this concept is not detailed. The Spanish definition introduces the term directly, whereas the Portuguese refer to "essential energy services", which intrinsically holds the same notion with analogous interpretation. In the latter, the qualification "adequate" is included without quantification, only mentioning the need to establish the threshold to what constitutes essential levels. Nevertheless, it is referred to as being dependent on the national context, namely the implemented policy. Although the policy environment is an important aspect, the social norm is another attribute missing in either strategy, despite also being a determining factor in defining an adequate level.

Both strategies define EP as an inability or lack of access without highlighting that situations of difficulty in accessing those energy services can also reflect a problem of EP impacting the number and type of households that fit these criteria. The Portuguese EP definition identifies three leading causes and considers them on a similar level of importance, including them but not limiting the causes to only the three. On the other hand, the Spanish EP definition underlines low income as the leading cause and buildings' energy efficiency as the secondary one, more as a driver than a structural cause, not leaving space for

considering other causes. Unlike the Portuguese definition, 'energy prices' are not identified as a primary determinant of this social issue in the Spanish definition, as they are not mentioned directly. However, its consideration is implied when insufficient income is mentioned, as insufficiency refers to the ability to afford energy services based on prices. The recorded values for national indicators show that all three factors are likely to contribute to higher vulnerability in both countries than most EU MS.

Neither definition highlights the adverse effects of EP on the population, but these are mentioned in other sections of the strategies. The Portuguese strategy only briefly addresses them further in the document, mentioning respiratory, cardiovascular, and mental health issues. The Spanish strategy provides a more complete description of the potential consequences of a situation of EP, not only regarding health but also underlining impacts on education and social and work life.

Arising from the Directive 2009/73/EC, the definitions of VCs in Portugal and Spain have been used as the eligibility criterion for the current social tariff's attribution, relying solely on income poverty and welfare support recipiency in different population groups, depicting income poverty more than EP (see Barrella et al., 2021). The Spanish strategy defined the figure of the VC as 'the consumer of electricity or thermal utility who is in a situation of EP, being able to benefit from support measures established by the administrations'. Its Portuguese counterpart describes the VC as a "domestic energy consumer in economic and/or social hardship and potentially in energy poverty". Both strategies provide an updated definition of VC, establishing a direct link between the concept of VCs and EP for the first time. The concept is expanded in both strategies to encompass income and EP, but with a slight difference. In the Spanish strategy, the VC is necessarily in EP, whereas in the Portuguese, it may or may not be, meaning not every VC identified is in EP.

Both definitions propose a relevant upgrade: including social vulnerability in the criteria for identifying vulnerable consumers. The Spanish strategy identifies groups that are potentially more vulnerable to EP and require special protection: migrants, pregnant women, people with health problems or disability, children, older adults, dependent people, people with low levels of literacy, single-parent households, and people living in informal dwellings. The Portuguese strategy provides a less extensive list, mentioning info-exclusion, diseases, or disability, leaving out several other groups that may be more vulnerable.

4.2.2. *Official indicators*

The Spanish Government chose four indicators to analyse and monitor the phenomenon's evolution. The two expenditure quantitative indicators (the 2 M and M/2) are calculated using the national median value and the mean of the last five years' national median values as the threshold. The strategy in Portugal proposes a varied set of indicators and defines two types of indicators to evaluate EP: primary and complementary. The diversity in the Portuguese approach translates into a broader representation of EP dimensions, exploring energy expenditure, inability to heat and cool the home and pay bills, income, buildings' energy efficiency, state of conservation, energy access, and energy literacy. Two levels of EP are defined: "general" EP and severe EP, where the first group encompasses the second. The households in a situation of income poverty who cannot keep their home adequately warm or spend more than 10% of their income on energy are considered to be in severe EP. This approach captures and combines objective and subjective aspects of EP, linking causes, drivers, and effects of EP, enabling the critical distinction of different levels of severity. Other primary indicators are presented but not used to estimate EP incidence, such as the intersection of income poverty and building state of conservation, and a rationale is not provided to justify this decision. The inability to keep home adequately warm and 10% of energy expenditure indicators, excluding the intersection with the income poverty indicator, are used to calculate the total population in EP (general EP). Several primary indicators are presented individually. The complementary indicators are not used to compute the number of people in EP but rather to describe the impact of the different action measures, some being used to set the goals to achieve in 2030, 2040, and 2050, together with some primary indicators. Tables 1 and 2 display the official indicators chosen in the two countries.

On the other hand, Spain's strategy proposes a more straightforward measurement framework, focusing mainly on the dimension of energy expenditure. It proposes four individual indicators, all used directly to measure EP levels. It identifies energy-poor households through the direct consequences, namely the level of energy expenditure, arrears, and inability to heat their home. The primary indicators are presented for specific household groups according to characteristics such as heating system ownership, winter climate zone, region, household size, composition, members' occupation, dwelling tenure status, and income quintiles. This analysis provides a more detailed depiction, highlighting the possible intersection of EP with other vulnerabilities. The strategy also intersects the primary indicators from the same survey: the two expenditure-based indicators from the HBS and the two consensual-based indicators from the SILC.

Both strategies focus on measuring the number of households in EP (extent of the problem). Still, only the Portuguese approach evaluates the magnitude level (depth), reflected in this severity assessment, by intersecting these indicators with an income level. Despite intersecting EP indicators from the same survey and with a broader range of population characterisation variables, the Spanish approach does not use these results to estimate EP, only framing them as an auxiliary analysis. In the Portuguese approach, general EP is calculated using an individual expenditure-based indicator (10%) and the inability to heat indicator. Especially for the expenditure-based, the individual use of the indicator results in a misrepresentation of specific households as energy-poor, rendering them arguably insufficient to determine with certainty if there is an EP situation. Other primary indicators are also presented individually; thus, their inclusion does not necessarily translate into a more comprehensive identification of households in EP. Examples are the EPC level of the dwellings, which alone cannot be used to identify energy-poor households. The same problem was also identified for Spain, as individual indicators were used to estimate the EP levels.

Both strategies computed "measured EP", using expenditure-based indicators to calculate the number of households with disproportionate expenditure and the perceived type using consensual-based subjective indicators. This practice is highlighted in the literature as helpful in identifying different household profiles, as there is limited overlap between these two EP manifestations (Rademaekers et al., 2016; Drescher and Janzen, 2021). Neither strategy links the two dimensions to estimate the number of people suffering from these two types of EP. Moreover, both strategies estimate a range of EP incidence using two separate indicators without cross-analysing them, which implies that households captured by one are the same households captured by the other, potentially leading to an underestimation of EP levels.

Several primary indicators in the Portuguese strategy are outdated or infrequently collected and are not used to measure the EP levels. An example is the ability to keep the home cool in the summer indicator, which is included in the Portuguese approach as a primary indicator. It was collected in 2012 and 2023 in the SILC ad-hoc module. Another example is the "Presence of leak, damp, rot in dwellings" indicator, for which no data was available since 2020 until the same ad-hoc module. Other indicators, such as the global energy literacy or the 10% indicator, are also not collected regularly. The strategy mentions that data will start to be collected at the national level, but there is no information on whether the necessary data will be collected for these indicators periodically, considering they are not updated annually. Conversely, the Spanish strategy only uses annually updated indicators, guaranteeing that EP-level monitoring can be periodically performed.

Regarding expenditure indicators, Spain assesses energy underspending as an expression of EP using the M/2 indicator, which is absent in the Portuguese strategy. Moreover, the Portuguese strategy defines

Table 1
Official energy poverty indicators in Spain.

Importance	Approach	Indicator	Object of measurement	Dimensions	Type of Energy Poverty	Outcome	Annual update
Primary	Quantitative	2 M	Consequences	Economic	Measured	Extent	Yes
		M/2	Consequences	Economic	Hidden	Extent	Yes
	Qualitative	Arrears on utility bills	Consequences	Economic	Perceived	Extent	Yes
		Inability to keep home adequately warm	Consequences	Economic, climatic	Perceived	Extent	Yes

Table 2
Official energy poverty indicators in Portugal.

Importance	Approach	Indicator	Object of measurement	Dimensions	Type of Energy Poverty	Outcome	Annual update
Primary	Quantitative	10% of income spend on energy	Consequences	Economic	Measured	Extent	No
		Population in a situation of poverty that spend 10% of their income on energy	Causes	Economic	Measured	Extent	Yes
		Buildings Energy Performance Class (A-F)	Causes	Infrastructural	Measured	Extent	Yes
	Qualitative	Inability to keep home adequately warm	Consequences	Economic, infrastructural	Perceived	Extent	Yes
		Population living in a home with leakage, dampness, and rot	Consequences	Infrastructural	Perceived	Extent	Yes
		Inability to keep home comfortably cool	Consequences	Economic; Infrastructural	Perceived	Extent	No
	Mixed	Population in a situation of poverty unable to maintain their home adequately warm	Consequences	Economic, infrastructural	Measured and Perceived	Extent	Yes
		Population in a situation of poverty living in a home with leakage, dampness, and rot	Consequences	Economic, infrastructural	Measured and Perceived	Extent	Yes
Complementary	Quantitative	Percentage of domestic energy consumption provided by local renewable energy production	Causes	Economic	Measured	Extent	Yes
		Population at risk of poverty	Causes	Economic	Measured	Extent	Yes
		Number of energy cuts imputable to the consumer	Consequences	Economic	Measured	Extent	Yes
		Global energy literacy of private consumers (1–100)	Causes and Drivers	Sociodemographic	Vulnerability level	Magnitude	No
	Qualitative	Arrears on utility bills	Consequences	Economic	Perceived	Extent	Yes
	Mixed	Population in a situation of poverty with arrears on utility bills	Causes and Consequences	Economic	Measured and Perceived	Extent	Yes

10% of income as the absolute threshold for expenditure, a metric taken from the British context in the 1990s, which is not representative nor adequate for the Portuguese context. The Spanish strategy uses relative thresholds (for the M/2 and 2 M), defined according to the population's economic situation and thus more representative of the country's context, although framing EP as relative to the population's situation.

Another relevant difference between the two approaches is scale. The Spanish strategy focuses solely on the household level. In contrast, the Portuguese strategy introduces aggregate indicators to be used at the country level, such as the percentage of local renewable energy or the energy literacy rate, that characterise the population and the context but are difficult to relate to the household.

4.3. Alternative indicators and data in Spain and Portugal

Several methods and indicators proposed in the scientific literature may provide valuable insights into how EP measurement can be potentially integrated into policy instruments. Table A3 presents the analysed selection of studies conducted in both countries.

In Spain, several authors have focused on EP diagnosis at the national scale. Aristondo and Onaindia (2018a) considered three qualitative metrics, *i.e.*, the two considered in the Spanish strategy and the 'Presence of leak, damp, rot in the dwelling' indicator, and counted as energy-poor each individual deprived in one, two, or three dimensions between 2004 and 2015. This method employs the yearly SILC indicators to depict the potential EP effects based on households' self-reports. It adds the dwelling state of conservation indicator to assess the building EE dimension, which is not addressed in the Spanish strategy. Furthermore, it distinguishes different EP levels determined by the number of indicators identifying a household as deprived. Taltavull de La Paz et al. (2022), Aristondo and Onaindia (2018b), Aristondo and Onaindia (2023), and Cadaval et al. (2022) have relied on the most used three SILC subjective indicators, as well.

Llorca et al. (2020) compared quantitative and qualitative metrics. They proposed a latent class-ordered probit model to analyse the effect of EP on self-reported health, finding that there is a detrimental effect of EP in the households' health condition and defending the use of both types of metrics to capture objectivity and subjectivity. The subjective indicator is also a SILC analogue (inability to keep home warm in the winter), and the objective indicator is the Fuel Poverty Index, integrating regionally specific Minimum Income Standard Indicator (MIS), energy expenditure values, and disposable income.

Several other authors have used the MIS. Romero et al. (2023) assessed the evolution of the EP indicators during the COVID-19 lockdown year using the most recent Spanish HBS. The authors used the indicators arrears on utility bills and inability to heat, the 2 M and M/2 indicators, and two additional objective indicators: the Minimum Income Standard Indicator (MIS) to measure disproportionate expenditure and the Hidden Energy Poverty (HEP) an alternative indicator to capture underspending due to lack of affordability. The former was based on Romero et al. (2018), which considers households as energy-poor when having a net income that, after deducting actual housing costs and the minimum income standard, is insufficient to cover the total energy costs that meet their energy needs. The authors defend that an estimated expenditure can better capture EP since it considers the households' basic needs despite the more complex calculation. The MIS was also used

by Rodriguez-Alvarez et al. (2019) to assess EP and the well-being of the Spanish population, Aguilar et al. (2019) to compare it to other objective indicators, aiming to evaluate EP in Spain and the Canary Islands, and by Cadaval et al. (2022), to assess the effectiveness of a subsidy in reducing EP in Spain. Barrella et al. (2022b) proposed improving the MIS methodology using alternative minimum income thresholds based on the reference budgets approach. All these studies show that there is publicly available data in the country to calculate absolute indicators that provide a less volatile and population-dependent perspective on households' EP condition.

Bienvenido-Huertas (2021) and Barrella et al. (2021) proposed metrics to investigate underconsumption based on the 2 M approach but using an absolute threshold (required or modelled energy expenditure) instead of a relative one (median or mean energy expenditure). Barrella (2022a) proposed an index to measure the extent and depth of hidden EP, considering only the first five deciles (income threshold). The extent is captured by estimating the share of households whose actual energy expenditure is lower than half their required energy expenditure, and depth is the difference between the expenditure and the threshold. This index provides a more complete picture of the household vulnerability since it enables a depth measurement, which can be interpreted as the effort or difficulty to alleviate their situation. Romero et al. (2023) calculated the HEP indicator using the Barrella et al. (2022a) method for the 2020 Spanish HBS. Regarding other expenditure-based indicators, Costa-Campi et al., 2020 proposed using the Low-Income High-Cost metric (LIHC) instead of the 2 M, following the methodology used in the UK Hills (2012).

Shifting the focus to Portugal, a smaller pool of studies was found. Inspired by Simoes et al., (2016) and Palma et al. (2019), Gouveia et al. (2019) developed the Energy Poverty Vulnerability Index (EPVI) to estimate and map EP vulnerability for all 3092 Portuguese civil parishes. This multidimensional area-based metric combined different indicators, such as building stock envelope and equipment, climate variables, and actual energy consumption levels, to calculate regional thermal comfort energy gaps for heating and cooling and socioeconomic indicators to assess the population's ability to implement coping measures. It combines several datasets, from national statistics on socioeconomic indicators, municipal statistics on energy consumption, and energy performance certificates for building characteristics. It is a comprehensive area-based approach that enables comparison between regions and identifying key drivers. However, it has some inherent subjectivity as it requires indicator weighting from expert consultation and does not identify the number and type of households in EP.

Horta et al. (2019) used the EPVI to select 10 of the most vulnerable civil parishes and conduct interviews with 100 households within the selected regions, combining a quantitative with a qualitative evaluation of the problem on a small scale. It collects relevant information regarding the occupants' behaviour and coping strategies. Still, it requires presential interviews to collect this data, which have additional costs and present confidentiality, trust, and engagement challenges. Palma et al. (2022) estimated future EP vulnerability variation in future scenarios of HVAC equipment ownership also using EPVI. Future estimations may be helpful for long-term strategies to predict evolving vulnerabilities.

Panão (2021) used the Portuguese HBS microdata to calculate various expenditure-based indicators (the 2 M, LIHC, and MIS) to estimate the energy-poor population in Portugal for the different NUTS3 regions, demonstrating that existing data offers several possibilities to calculate a more diverse set of expenditure-based indicators.

4.4. Proposals for enhancing the official energy poverty diagnosis in both countries

This section presents and discusses several proposals for enhancing EP diagnosis in both countries by unpacking the two main aspects of this approach: EP definition and indicators. Although this discussion is separated into two components, definition and measurement should be regarded not as a dichotomy of independent dimensions but as interrelated, co-dependent, self-consistent, and equally essential parts of the unity that is an EP diagnosis. The goal of enhancing these national approaches reflects a search for practices that increase comprehensiveness, inclusiveness, conciseness, and operability for more robust diagnoses that can effectively be put into practice through policy.

4.4.1. Definitions

EP is a problem that can have multiple causes and expressions across territories, and its definition should be broad enough to encapsulate, directly or indirectly, all the relevant aspects that determine or are determined by this issue while still retaining the conciseness that enables its operationalisation. Both Iberian definitions follow the conceptual approach, existing separately from the indicators, which enables a broader perspective of the problem. More practical definitions are narrowed by the limits immediately imposed by the one indicator, which tends to be too simple for better communicability, generally resulting in relevant omissions.

Nevertheless, there are points for improvement in both definitions, which can be implemented in the short term. Both highlight that EP is a situation of inability or lack of access to energy, which is even more accurate than the inability to afford since there may be cases of households that can access fuel or energy at no cost. However, they do not consider the notion of "difficulty", as proposed in France's and Cyprus's definitions. Including the term "difficult" is relevant as it broadens the range of households that fall under the definition, including energy-poor households that maintain regular levels of energy services but at the cost of other essential goods needs or services (see Burlinson et al., 2022); restrict their consumption; or have excessive burden that leads to arrears or debt. This notion can be linked to intensity or magnitude, as households suffering from EP can have different levels of hardship.

The inclusion of causes in the definition should be discussed because the definition is one of the first sources for understanding the problem. How the definition is shaped can impact the selection of assessment and monitoring indicators, target setting, and public recognition. It might also lead to the design and prioritisation of a particular type of policy. The Portuguese definition includes the three leading causes of the problem, which can help shift public policy. Although it can be argued that EP is ultimately an affordability issue, housing energy inefficiency, which also impacts affordability, is a structural cause of the problem in both countries. Adequate housing would be an effective solution for many households to achieve higher thermal comfort and potentially lower energy expenditures. Buildings' energy renovation is a more targetable and structural approach to reduce EP, addressing the demand side of the problem, which is its foundation. Energy prices generally depend on international markets and utilities, and efforts to decrease the burden on final consumers typically materialise in financial bill support, which is a short-term solution (Kyprianou et al., 2019).

Nevertheless, if addressed more effectively, energy supply can be part of the solution. Promoting wholesale or retail energy price caps or the ownership of local energy means of production can significantly reduce prices, constituting a more enduring solution. Still, there are limited cases where energy communities have been tailored to support energy-poor households and often struggle to reach the most vulnerable energy consumers (Hanke and Guyet, 2023). Income depends on several complex dynamics and actors. There is an argument for including the leading causes in the definition according to each context to prompt policy that targets these aspects. The Spanish definition mentions energy-inefficient housing as an aggravating factor, even though it is widely considered a fundamental cause. Placing the focus solely on insufficient income may direct policymakers towards short-term financial support measures that do not address the root of the problem.

Nevertheless, the three leading causes may only explain part of the problem. Although not direct causes, other factors such as local climate and climate change, access to energy infrastructure and fuels, public

support policy, and sociodemographic characteristics (e.g., age, education, ethnicity, and disability) significantly impact the potential EP vulnerability. These drivers can even assume higher preponderance than one of the identified causes in a given geographical context. The definition should not lock EP to the three leading causes; instead, it should be open to including these factors to enhance the understanding of EP, opening other avenues that can lead to more comprehensive assessment studies of EP across regions within the country. These drivers, if not described in detail, are worth mentioning by the dimension they represent (e.g., climate, sociodemographic). The potential changing dynamics of the causal connections should also be highlighted, as causes and drivers could transform and have distinct impacts on the population through time.

Both definitions allude to an energy need, using the same term or referring to it as "essential energy services". An EP definition should further describe this rather vague and subjective concept. The Portuguese strategy goes further in detail, enumerating the different energy services but still qualifying the needed level as "adequate". Several official definitions (Wales, Slovakia, Ireland, Belgium, and Scotland) link it to a metric, relying on the share of expenditure on income to define a level of adequate energy services or combining income and expenditure thresholds. This approach to energy needs quantification may enable faster identification of a household in EP. Still, it is recognised to fall short of adequately and thoroughly representing adequate levels of energy services and will likely render several households facing hardship as non-energy poor. Although also focusing on a share of income, the Scottish definition mentions the maintenance of a "satisfactory heating regime" instead of "adequate energy services". It is defined as maintaining a determined temperature daily, according to the room type, with special conditions for households with older adults or people with disabilities or chronic illness, as set by the World Health Organization. This description is a step in the right direction, as it links the necessary level of space heating, in this particular case, to ensure thermal comfort instead of a simple quantification of expenditure that is often arbitrary.

Furthermore, it recognises and describes the different needs of vulnerable occupants, which is essential for a more inclusive definition, particularly in these countries where the share of the older population, a particularly vulnerable group to EP from a physiological, health, and economic point of view (Vandentorren et al., 2006; Polimeni et al., 2022), is considerably high. This approach links the energy service to the aimed outcome instead of focusing solely on the aimed output, which is a particular level of energy consumption. Despite this phenomenon's subjective and personal nature, it is still an example of a more scientifically based alternative, focusing on obtaining temperatures that will most result in the aimed outcome, thermal comfort. Day et al. (2016) follow a similar approach, drawing the link between energy consumption and supply, secondary capabilities such as heating or cooling homes, washing clothes, or cooking healthy meals, and basic capabilities such as physical and mental well-being, social respect, education, and maintaining relationships. These direct effects could be included in the definition, as they attribute real-life meaning to the problem of insufficient energy in the domestic sector. Therefore, taking this example, this approach could be expanded to energy services other than space heating. The Portuguese strategy highlights cooling, lighting, and electrical appliances. The focus on cooling is paramount for both countries, as a considerable share of the population claims not to have thermal comfort in the summer (Eurostat, 2023j), and the increasing need for space cooling in the summertime due to climate change impact, electrification of domestic consumption resulting from consumption decarbonisation and increasing digitalisation. Lack of thermal comfort is, in fact, the most direct effect of EP in European and Iberian households, but other energy services must be included. Adequate cooling should provide thermal comfort, and proper lighting should ensure the home is well-lit. As supported by Bouzarovski (2017), ICTs should also be considered as an essential energy service, as it is becoming increasingly demanding and relevant in people's lives. It is more challenging to qualify or link to a determined outcome for energy services other than space heating and cooling, and lighting. Still, the basic capabilities Day et al. (2016) described, namely health, interpersonal relationships, social respect, and education, can be considered. This way, the outcomes are more detailed than those of "dignified levels of life and health" described in the Portuguese strategy, which can be applied to all energy services. The Portuguese definition also mentions the national contexts, namely the national social policy, which can impact the situation of lack of access to energy and thus must be considered in the definition. Although causality is not straightforward, studies have linked EP to health issues and stigma (Ballesteros-Arjona et al., 2022; Davillas et al., 2022). The potential contribution of EP to creating and magnifying these issues, even if indirectly, should be included in the definition, as it can help illustrate the genuine impact it can produce in people's lives.

It is also helpful to consider the energy source and how the energy services are provided, as the focus on renewable energy and decarbonisation should be integrated into EP mitigation efforts. This way, the qualification of energy services as clean, sustainable, and safe, following Day et al. (2016) proposed definition and the UN's 7th sustainable development goal, should be considered. The qualification of safe and clean should be integrated immediately into the definitions, as energy service provision should not harm consumers. Moreover, they should not have to face the choice between energy and health, to the image of the "heat or eat" dilemma, where a household must forego a basic need for another. This choice can be controversial considering that a substantial percentage of households in Portugal and Spain still use inefficient equipment, such as open fireplaces, which are detrimental to indoor air quality and the health of occupants (Stojilovska et al., 2023). These consumers may be in a technological or fuel lock-in situation and do not have the option to shift away due to economic hardship, rendering households energy-poor.

Regarding the sustainability and environmental dimension of energy service provision, a similar logic could be applied, as consumers should not be placed in a position of choosing between energy provision and not harming the environment or living in a healthy environment, a human right recognised by the United Nations. Similar lock-in situations could happen where a consumer cannot shift from fossil fuel consumption to renewable energy despite not having an energy affordability problem regarding daily fuel acquisition. Mulder et al. (2023) corroborate this position, including the indicator "inability to participate in the energy transition" as a relevant dimension of EP. This alteration would render a considerable share of the population energy-poor, as fossil fuel use is still common in both countries despite strong efforts toward electrification and renewable energy integration. It can be argued that environmental protection transcends the boundaries of the EP concept as in the current definitions. Nevertheless, it is a critical reflection that binds together cross-generational basic needs and human rights in a more integrative and holistic perspective, thus should be considered in future updates.

The updated VC definitions in both strategies contribute to more clearly distinguishing the frontier and overlap between energy vulnerability and EP and simultaneously identifying households in EP or in compound hardship, both in income, social, and EP. The Portuguese proposed definition enables more nuance and variety of possible vulnerabilities by stating that VCs are "potentially" in EP, considering the real possibility that there are VCs, *i.e.*, who may not be in EP. Therefore, the vulnerabilities of an energy consumer can exacerbate an EP problem (*e.g.*, income hardship) but can also occur when there is no case of EP (e.g., physical disability). While the execution of this definition in policy, such as the social tariff, still relies mainly on income in the two countries, an expansion of the concept is due. Some cases of vulnerability, such as extreme situations related to health and disability, can create added difficulties in accessing the needed energy services for some non-low-income households, pushing them to a situation of EP. This situation illustrates the importance of going beyond vulnerability solely based on income poverty.

Both definitions identify different important vulnerable groups, although Spain provides a more comprehensive list. The Spanish definition could include the information-excluded population as a

vulnerable group, as in the Portuguese definition. Inversely, Portuguese should consider migrants, pregnant women, children, older adults, dependent people, people with low literacy levels, single-parent households, and people living in informal dwellings, as in the Spanish example. Both definitions should include other potential vulnerability drivers, such as gender and ethnicity. Ethnic minorities and migrants are more likely to experience a higher degree of vulnerability, similar to income-poor groups (Bouzarovski et al., 2022; Middlemiss, 2022). It would be beneficial to specify in the VC definition the aspects that characterise these groups and drive their vulnerability, as its omission may lead to their exclusion. In Portugal and Spain, the utilities are responsible for financing the social tariff, attributed to vulnerable consumers according to the existing definition. If this change in the VC definition would materialise in new legislation, increasing support and resources would need to be harnessed, either from the utilities or the public sector, depending on the regulatory framework and potential changes. Recognising different vulnerabilities would call for other support measures, going beyond the historic bill support in the form of social tariffs and introducing new measures such as disconnection protection, which would also significantly impact utilities. Both definitions should make clear that vulnerability can aggravate EP and vice versa, and the compound vulnerability of suffering from the two conditions elicits the need for special support measures. A summary of potential upgrades in the official EP definitions is displayed in Table 3.

Table 3
Potential improvements in EP and VC official definitions.

Potential Improvements	Portugal	Spain
Including the notion of "difficulty" in accessing energy services	x	x
Broadening representation of EP causes	–	x
Identifying the diverse range of needed energy services	–	x
Defining adequate energy needs with more detail concerning the aimed outcomes	x	x
Including the environmental dimension (quality and safety) of energy provision	x	x
Acknowledging the right to access sustainable energy sources	x	x
Establishing more clearly the difference between EP and VC	–	x
Identifying a comprehensive set of vulnerable groups	x	–
Referring to the different energy needs of VC in the EP definition	x	x
Considering gender and ethnicity in the VC definition	x	x

4.4.2. Measurement and indicators

Building an improved EP measurement framework is an exercise prone to subjectivity and bias. Just as for the definition, the aim is to propose enhancements that contribute to a more comprehensive and inclusive framework of indicators that simultaneously maintains robustness and conciseness, following the upgrades proposed for the definitions for a coherent diagnosis approach. The proposed enhancements can be implemented in the short term or long term, depending on the availability of data and resources in each country.

Following the discussion on the definition, the indicators framework should be able to capture the different expressions of EP, both the inability and the difficulty to access a needed level of energy services. These can reflect high energy expenditure, abnormally low energy consumption due to self-restriction, and the trade-off between access to different basic needs. The Spanish Strategy proposes indicators that assess over-expenditure (measured EP) and abnormally low energy consumption (hidden EP), whereas the Portuguese only directly considered energy over expenditure. This shortcoming could be addressed with publicly available data, such as the HBS, to implement a hidden EP indicator, as shown by Panão (2021). The problem may lie in monitoring, as the HBS is only conducted every five years in the country. Spain proposes the M/2 indicator to assess this aspect. Still, it does not propose a cross-analysis with other indicators to estimate EP levels, which renders this indicator ineffective for EP measurement. The cross-analysis with the 2 M indicator, as conducted in the auxiliary analysis, is also not helpful, considering they portray opposite phenomena. Implementing an income threshold to rule out high-income households would be a beneficial short-term upgrade. The same metric could be easily applied to the Portuguese strategy. The double threshold of expenditure and income implemented in the Portuguese framework for assessing overexpenditure would be an accessible upgrade in Spain, enabling a more nuanced identification. More frequent data collection of expenditure-based indicators would be a relevant aspect to address in the longer term via increasing the time periodicity of existing surveys or conducting a dedicated survey yearly.

Nevertheless, the Portuguese framework still applies the 10% threshold, an arguably inadequate expenditure threshold that does not represent the Portuguese context, and following the Spanish example and implementing the 2 M indicator would be a short-term step towards a more representative diagnosis. Using disposable income instead of gross income would also be beneficial, as it better represents the available income for basic needs such as energy. The Spanish framework uses net equivalised income, which is already a better option than gross income. Both the 2 M and the M/2 are relative thresholds, meaning they are more capable of measuring inequality than poverty (Romero et al., 2018). Moreover, these indicators are calculated using actual energy expenditure, which is likely not representative of the required energy needs of households, especially in countries such as Portugal and Spain where building inefficiency, income inequality, and energy consumption variability are high and hidden EP is not a negligible phenomenon. A short-term solution could be the calculation of a modelled energy consumption, as in Gouveia et al. (2019), Bienvenido-Huertas (2021), and Barrella et al. (2021). The modelled energy expenditure estimated from this estimated consumption would be used as the expenditure threshold, instead of the population's median and mean consumption, to identify abnormally high and low expenditures while keeping the income threshold. This approach would provide an indicator that could capture the absolute nature of EP, particularly the needed energy levels of households, more rigorously, which does not depend on the state of the population. As mentioned in the discussion on the definitions, it would be paramount that modelled energy expenditure would consider the characteristics of the dwelling and the household as well as the need for adequate levels for every energy service, based on the aimed outcome (thermal comfort, well-lit home, available ICT). This method would enable a shift from more arbitrary thresholds towards a more sufficiency-based option. The considerable number of older adults in both countries calls for a more inclusive metric that considers their specific needs, applying different criteria for vulnerable consumers as proposed in the Scottish definition. A more complex and comprehensive solution would be the MIS, which integrates modelled energy expenditure to identify disproportionate expenditure. Although it represents a more challenging calculation method, this metric has been computed in both contexts; hence, there is the necessary data and expertise to test its implementation. It provides a more comprehensive measurement since it considers not only modelled energy expenditure but also the costs of housing and all the other basic needs. It also enables the assessment of potential trade-offs between basic domestic needs.

The complete set of energy needs and other basic needs must be considered, such as healthy food, potable water, adequate indoor air quality, transport, ability to shift away from fossil fuels, and others, guaranteeing the household's safety and well-being and environmental protection. This approach would require further development of the indicator and data resources. It is challenging to operationalise as it depends on several estimates of representative energy expenditure levels and other basic needs, which vary at the regional level. It could represent an opportunity to involve stakeholders and energy-poor households in tailoring the diagnosis framework, improving the critical aspect of transparency, as asserted by Siksnelyte-Butkiene et al. (2021), considering geographical variabilities in the cost of living.

Regarding the trade-off between basic needs or similar "heat or eat" dilemmas, a swifter alternative to the more complex option of

quantifying expenditure for all the basic needs, and as a complement to income levels and thresholds, is the subjective indicator "inability to make ends meet" (Eurostat, 2023k). It is available for both countries and disaggregated in different subjective levels, and it has the advantage of providing a scale of difficulty instead of a binary response. It can help identify these trade-offs or hardships in general if they intersect with the expenditure and consensual-based indicators, such as the inability to heat the home indicator. The indicator of arrears on utility bills can be combined with other indicators and used for the same purpose. However, it bundles all utilities and may only reflect a circumstantial situation instead of a symptom of EP or general hardship.

Regardless of the absolute measure selected, combining relative and absolute expenditure metrics would strengthen the analysis of EP, considering both poverty and inequality. It would simultaneously consider both the characteristics of the dwelling and the household, namely the financial situation, energy services, and cost of living, as well as the population's situation, customs, and societal underpinnings.

Both strategies integrate objective expenditure-based and consensual-based indicators, which enables the identification of a broader range of EP expressions. Nevertheless, they propose these indicators as separate units, despite arguments supporting the interlink between these two types of indicators. Boardman (2011) describes a situation of "denial of reality" where households claim to be warm when they are, in fact, cold. For Portugal, Horta et al. (2019) state that despite feeling cold, a thermally comfortable home is not a priority for some households, highlighting the cultural component of this issue. A household might not portray its situation rigorously, either because it does not recognise its hardship or because its standards for energy services surpass the levels that would be characterised as essential. Thus, intersecting the two types of indicators can yield more reliable assessments, discerning the underpinnings of the problem. Moreover, it can help improve the estimation of EP incidence range, which might suffer from misrepresentation in both strategies.

An improved framework should focus on measuring EP extent and its depth, as Meyer et al. (2018) defended. This parameter assesses the magnitude of EP or the level of effort necessary to lift the identified households out of EP. The Portuguese strategy already introduces two levels of EP severity through the combination of indicators, which is a step in the right direction. Nevertheless, the calculation should be improved, as general EP is calculated using the 10% and the inability to heat indicators individually, potentially resulting in the mentioned misrepresentation of higher-income households as energy-poor. It is necessary to exclude high-income households, while not overlooking households above the income poverty threshold (defined for severe EP), who may be in EP. Most approaches in the literature assess depth or distance to the threshold using income or energy expenditure. It can be computed either with relative measures, such as the 2 M and M/2, or absolute thresholds, such as the MIS, and it would be a valuable addition to the diagnosis in both cases. It could also be applied to consensual-based indicators such as the inability to keep the home adequately warm. However, this would require a change in the SILC, using a qualitative scale response instead of a binary response, to the image of the "inability to make ends meet" indicator. Depth analysis should enable the distinction of several degrees of magnitude for different types of EP vulnerability, depending on different causes and manifestations being measured.

Furthermore, it is also relevant to measure its persistence, as defended by Hills (2011) and Fizaine and Kahouli (2018), by revisiting the selected indicators in past years to understand if the problem is intermittent or has persisted despite mitigation efforts. It is crucial to monitor EP levels and understand the policies' impact. Integrating this dimension in the frameworks can be a short-term step using the HBS and EU SILC data.

Both countries have high EP vulnerability in the summer, which is bound to increase due to climate change, resulting in a higher projected frequency of heat waves. Only the Portuguese strategy addresses this aspect in their measurement framework via "the inability to cool" indicator, which currently is collected at a decadal pace through ad-hoc modules, prompting the government to ensure that it will continue to be collected in the future in dedicated surveys, with unknown periodicity. Considering the relevance of summer EP, despite mentioning it in an auxiliary analysis, Spain could also include this indicator in the strategy's framework, increasing the commitment to tackling this issue. Both strategies should adopt a procedure of frequent, dedicated data collection and cross-analysis with expenditure indicators as proposed for the inability to keep the home adequately warm indicator.

As thoroughly highlighted in literature and policy, namely by the European Commission (EC, 2020a; EC, 2023a), addressing the key dimensions that compose its multidimensional nature is a general sound practice in EP diagnosis. It implies analysing the causes, drivers, and consequences characterising EP, which can lead to more targeted policy measures. As a considerably influential cause in both contexts, building energy efficiency should be a key component of the diagnosis. It can provide valuable input in the direct identification of energy-poor households. It can help uncover additional potential EP situations, namely households with average income and typical energy consumption and expenditures who do not report an inability to heat their home adequately but reside in inefficient dwellings requiring considerably higher consumption for healthy and comfortable indoor living. As with the previous indicators, it should be cross-analysed with expenditure-based or with another consensual-based indicator, such as the inability to heat, as building energy inefficiency alone is not a sufficient criterion to disclose a situation of EP. This dimension is absent in the Spanish framework, at least in a direct form, and the Portuguese strategy integrates the indicator 'Presence of leak, damp, rot' as a primary indicator, individually and intersected with income poverty, but does not use it to estimate EP levels. This indicator was collected yearly at the household level and for both countries until 2020. If data collection is resumed, it can be a short-term solution for both strategies. Marks of a deteriorated dwelling are a proxy of low energy efficiency. Still, the EPC level is arguably a more adequate indicator of low energy performance and efficiency and would enable an in-depth analysis based on the EPC rates. Data are available for both countries, and the Portuguese strategy integrates them as a primary indicator. However, it is not possible to cross-reference this indicator with others due to data constraints, hindering its potential as an EP indicator at the household level. Other possible indicators for both countries are "buildings with dilapidated, bad, or deficient maintenance conditions" and "buildings age". However, they might pose the same issue and constitute less effective proxies. Research studies in the two contexts have proposed more detailed indicators that could provide further insights, such as the thermal comfort gap. However, these would require several data sources and further statistical work.

Accurately identifying energy-poor households requires comprehensive cross-analysis of indicators, coalescing the dimensions of energy expenditure, income, thermal comfort, and building energy efficiency to reduce the exclusion or misrepresentation of these vulnerable households significantly. This shortcoming is identified in both countries' frameworks. The lack of intersectional datasets can be partially due to EU and national data protection regulations, and access to EU SILC microdata could potentially enable further developments in the diagnosis. Indicators used individually fall short in identifying specific households but can still be used in another capacity. Organising the indicators into main and complementary (or primary and secondary) indicators, as conducted in the Portuguese strategy, can be an effective way of separating them according to the scale of analysis and their level of importance. The Portuguese approach proposes indicators at household and aggregate scale, even though it does not link the scale to the category of primary or complementary, which results in the selection of several primary indicators that alone are ineffective for identifying energy-poor households. As highlighted by Thomson et al. (2017), setting apart indicators by level of priority or importance can be

beneficial. However, a rationale that justifies this distinction should be set to avoid redundancy, clarify the goal, and increase operability. In this sense, the primary indicators could focus on the household scale and be apt to identify energy-poor households.

In contrast, at an aggregate scale, complementary indicators could depict the causes, drivers, and consequences of EP, not requiring a connection to others, as they paint the contextual picture of vulnerability that causes EP. Literature shows that publicly available data and indicators in both countries can be used to depict various causes and drivers of EP and expand EP measurement in the two countries. Median income and climate indicators are available annually for both countries and can contribute to a broader understanding of the country's contexts and how vulnerability is shaped. Drivers, such as energy literacy, included in the Portuguese strategy, could also be helpful to include as it depicts a critical EP determinant. The strategy also proposes a relevant indicator of "domestic energy consumption provided by local renewable energy production", which signals higher energy autonomy, reduced energy dependence, and lower environmentally impactful electricity production, factors that contribute to facing vulnerability (related, for instance, to dependence on volatile energy prices), and thus can be examined against EP levels. Energy price indicators are absent in both strategies, and data are available. In measurement approaches, mainly focusing on energy demand, the inclusion of price indicators prices, also places energy supply in the spotlight, potentially calling for energy price reduction measures and higher involvement and responsibility of utilities in the EP mitigation efforts.

Sociodemographic aspects of vulnerability factors, such as age, tenancy, education, and population with disability, should also be included in the frameworks as complementary (or secondary) indicators or intersected with the primary EP indicators. The Spanish strategy develops some of these intersections in an auxiliary analysis, whereas the Portuguese only focuses on income poverty. Thus, both strategies can be improved by linking EP to the vulnerable groups identified in the vulnerable consumer definition. They may call for dedicated assessments to assess EP in those groups.

Disaggregating the indicators at subnational scales would also be valuable for identifying regional variabilities and vulnerabilities. The Spanish strategy computed the EP indicators at the regional level using available HBS and SILC data. The Portuguese could follow a similar approach. Area-based approaches based on secondary or indirect indicators developed in both countries (in scientific studies) reveal available data across all regions. They are also a potential solution in the short term in case EP primary indicators are not available. These geographically disaggregated assessments identify the EP hotspot regions that should be investigated urgently, prompting further research and dedicated policy at the regional scale.

A summary of the potential short-term and longer-term improvements is displayed in Table 4 and Table 5.

Table 4
Potential short-term improvements for Portugal and Spain EP official diagnosis.

Potential short-term Improvements	Portugal	Spain	Data source
Increase accuracy of EP level range estimation	x	x	–
Consider hidden EP in the assessment	x	–	HBS
Implement income threshold to calculate EP levels	–	x	HBS
Replace the 10% indicator with a more contextually representative threshold	x	–	HBS
Implement income threshold in hidden EP indicator	x	x	HBS
Calculate depth levels for measured EP	–	x	HBS
Compute depth for hidden EP and broaden the scale of severity	x	x	HBS
Use disposable income instead of gross or net income	x	x	HBS
Calculate modelled energy consumption to compare to actual energy consumption and calculate expenditure indicators	x	x	Census, national statistics, EPCs
Differentiate necessary energy consumption levels for vulnerable groups	x	x	Census, national statistics, EPCs
Calculate EP persistence through the years using longitudinal data for the selected indicators	x	x	HBS; SILC;
Include the building EE dimension	–	x	SILC; EPCs
Focus on multi-scale household and country	–	x	HBS, SILC, Census
Include climate variability, energy prices, and people from vulnerable groups as contextual indicators	x	x	Census
Include regional variabilities in indicator estimation	x	–	Census, HBS, SILC, EPCs

Table 5
Potential Longer-term Improvements in both countries' official diagnosis.

Potential Longer-term Improvements	What would be necessary
Calculate MIS thresholds using modelled energy expenditure	Identify and estimate the cost of the basic needs using the HBS and SILC and extra data collection
Include stakeholders in the framework design and indicator selection	Promote participation in the revision phase of the strategies
Calculation of expenditure-income indicators with relative and absolute thresholds for comparison	Compute and analyse MIS with the different relative thresholds of income and expenditure
Change data collection to enable cross-reference expenditure-based indicators, consensual-based, and home EE	Change existing surveys design or design new surveys to enable the collection of these varied datasets for the same sample of households
Compute EP persistence, depth, and incidence for the intersection of different indicators	With the new intersectional data, analyse the relation between these different aspects for the combined indicators
Include thermal comfort indicators using indoor temperature and air quality data	Data collection in a sample of homes using sensors
Link energy literacy and consumer autonomy and empowering (e.g. ownership of means of production) with EP levels	Include a collection of ad-hoc indicators in existing surveys or design a new survey
Relate the heating or eating dilemma, including the indicator "inability to make ends meet" or an analogous indicator, with EP levels	Including indicators in the existing survey structure, namely the HBS and SILC
Intersect EP indicators with characterisation variables related to the VC definition	Linking HBS and Census data or including additional indicators in the HBS
Frequent updates of inability to keep home comfortably cool in the summer indicator and intersection with other indicators	Resume yearly collection of this indicator in integrated existing or dedicated survey
Include a qualitative scale-based response for consensual-based indicators	Change the current survey design
Increase the monitoring frequency	Additional resources to collect data for HBS or a new dedicated survey with intersectional indicators yearly

5. Conclusions

This paper explores the potential of improving EP diagnosis approaches in Portugal and Spain (Iberian Peninsula), which share climatic, social, and cultural similarities. A comparative analysis of EP definition and indicators framework was conducted, supported by a methodological framework combining a review of EP measurement case studies in the Iberian context, European policies, and international scientific literature on EP measurement. Drawing on existing knowledge and data from inside and outside the study's geographical context, it identifies short-term improvements and long-term prospects and needs to support current and future policymaking towards improving EP diagnosis. The results highlight the considerable potential for improvement in both approaches and opportunities for cross-learning.

The EP definition of official strategies can be revised to broaden their vulnerability spectrum and increase inclusiveness. There is potential to improve their capacity to capture the different expressions of EP while maintaining coherence and conciseness that enables the transfer of concepts to the indicators' framework. Including the leading causes and energy services while maintaining openness to the diversity of determinant factors are relevant points to consider. Further qualification of adequate energy needs, linking it to the aimed outcome, and considering quality criteria regarding safety and sustainability could reduce subjectivity. Differentiating vulnerable consumers from energy-poor consumers while recognising the reciprocal magnifying effects is paramount. Vulnerability is a complex phenomenon affecting various groups whose differing needs should be acknowledged in the strategies.

The two strategies have distinct approaches to the indicators' framework, with their strengths and shortcomings. Both frameworks employ multidimensional approaches, integrating the qualitative subjective and the quantitative objective indicators that capture a broad range of EP expressions. Further improvements could be undertaken to broaden this range, including hidden EP in the Portuguese Strategy, building dimension in the Spanish one, or the trade-off between basic needs in both strategies. The use of expenditure indicators can also be enhanced, replacing the current indicators with more representative and reliable alternatives in the short and long term. The selection of adequate thresholds is essential to increasing the effectiveness of these indicators in identifying energy-poor households. Using relative and absolute thresholds and conjugating different types of thresholds, such as expenditure and income, are key steps to avoid misrepresentation. The use of indicators individually and the lack of a broader intersection between them is a shortcoming that is common to both frameworks. The identification of energy-poor households could be significantly improved in both strategies by cross-referencing energy expenditure indicators, consensual-based indicators, and building energy efficiency metrics. Data protection and difficulties linking the data at the household level are considerable challenges. Still, the available SILC and national HBS microdata enable a more significant intersection between indicators that can improve the national diagnosis in both countries in the short term. Measurement approaches could also be strengthened by introducing (in the Spanish approach) or developing (for the Portuguese framework) the aspect of magnitude, which enables households to be distinguished according to the depth of vulnerability. This inclusion creates the opportunity to shift away from binary outcomes that risk oversimplifying the analysis. The persistence aspect would also deepen the understanding of households' difficulty combatting this social scourge. Distinguishing the types of indicators according to their use and relevance in the measurement frameworks can be helpful if applied to operationalise analysis at two spatial scales, household-level and country-level, to identify vulnerable households and depict the underlying background and driving forces of EP in the populations.

This work is a theoretical exercise grounded on the effort to base every enhancement proposal on the best scientific evidence and policy initiatives. However, it still faces a component of subjectivity and bias that must be mentioned. It does not aim to build a finished diagnosis framework but to discuss possible changes that could increase comprehensiveness and inclusiveness. Managing the trade-off between robustness, conciseness, and practicality is challenging, as some proposals may be difficult to operationalise. The fact that it is not possible to test every proposal herein with empirical data collected within the case studies is also a limitation. It can be further addressed in future research, especially concerning testing the combination of different indicators to specify the most encompassing and effective intersections. Furthermore, this study only focused on domestic EP. It did not delve into the connection with transport poverty, which can also be relevant to integrate into future research and policy agendas.

The analysis carried out in this paper points out the potential of unused available data sets at the national level and the need for a more regular collection of multidimensional data that enables indicator intersectionality. Further EP-focused regionally disaggregated data, through enhancements in existing data collection methods or newly tailored data collection initiatives, would allow experts to further delve into the complexity of EP across regions and conduct more accurate EP analyses, potentially leading to better-targeted policies.

By highlighting the potential for improvement and providing specific changes and recommendations, this work can significantly contribute to enhanced policymaking in the future revision of the Portuguese and Spanish strategies and even inspire efforts at subnational scales. Similarities in the vision and approach can be the seed for developing stronger cooperation and knowledge exchange between the nations towards improved identification, monitoring, and design of mitigation action. This study can also provide important insights into other EU MS, which still lack definitions, indicators, strategies, and dedicated action plans. It discusses critical issues that could be developed or improved on other EU MS strategies to address EP, minding each territory's different contexts and particularities.

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CRediT authorship contribution statement

Pedro Palma: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Roberto Barrella:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **João Pedro Gouveia:** Writing – review & editing, Supervision, Project administration, Methodology, Conceptualization. **José Carlos Romero:** Writing – review & editing, Validation, Project administration, Methodology, Conceptualization.

Declaration of competing interest

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

Data availability

Data will be made available on request.

Appendix

Table A1
Energy Poverty Definitions across Europe

Country	Definition	Reference
France (2010)	"A person who encounters difficulties in his/her accommodation in terms of energy supply related to the satisfaction of elementary needs. This is due to the inadequacy of financial resources or housing conditions."	ONPE (2014)
Northern Ireland (2011)	"A household is in fuel poverty if, in order to maintain an acceptable level of temperature throughout the home, the occupants would have to spend more than 10% of their income on all household fuel use."	DSDNI, 2011
Slovakia (2012)	"Status when average monthly expenditures of household on consumption of electricity, gas, heating and hot water production represent a substantial share of average monthly income of the household."	Law No. 250/2012 Coll (Strakova, 2014)
Cyprus (2014)	"The situation of customers who may be in a difficult position because of their low income as indicated by their tax statements in conjunction with their professional status, marital status, and specific health conditions and, therefore, are unable to respond to the costs for the reasonable needs of the supply of electricity, as these costs represent a significant proportion of their disposable income."	Government of Cyprus (2020)
Ireland (2016)	"…inability to heat or power a home to an adequate degree."	DCENR (2016)
Romania (2016)	"… impossibility of the vulnerable consumer to meet their minimum energy needs for the optimal heating of the home during the cold season."	Romanian Government (2016)
Italy (2019)	"… inability to purchase a minimum energy basket of goods and services, or, alternatively, in the sense of energy vulnerability, when the access to energy services entails a diversion of resources (in terms of expenditure or income) higher than a 'normal value'."	Government of Italy (2019)
Lithuania (2019)	"… difficult or impossible for residents to enjoy adequate heating of their homes or access to essential energy services such as lighting or transport."	Government of Lithuania (2019)
Finland (2019)	"… difficulty in maintaining or satisfying basic needs due to high energy costs."	Government of Finland (2019)
Austria (2019)	"A household is considered energy poor if its income is below the at-risk-of-poverty threshold and, at the same time, it has to cover above-average energy costs."	Republic of Austria, 2019
Wales (2021)	"Households needing to pay more than 10% of their full household income to maintain a satisfactory heating regime [fuel poverty]. Households needing to pay more than 20% of their full household income to maintain a satisfactory heating regime [severe fuel poverty]."	Welsh Government (2021)
England (2021)	"A household is energy poor if it is living in a property with an energy efficiency rating of band D or below and when they spend the required amount to heat their home, they are left with a residual income below the official poverty line."	Government of the UK (2024)
Scotland (2021)	"A household is defined as being in fuel poverty if, in order to maintain a satisfactory heating regime, total fuel costs necessary for the home are more than 10% of the household's adjusted net income (i.e. after housing costs), and if after deducting those fuel costs, benefits received for a care need or disability and childcare costs, the household's remaining adjusted net income is insufficient to maintain an acceptable standard of living. The remaining adjusted net income must be at least 90% of the UK Minimum Income Standard to be considered an acceptable standard of living with an additional	Scottish Government (2021)

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Table A1 (*continued*)

Country	Definition	Reference
	amount added for households in remote rural, remote small town and island areas. If more than 20% of net income is needed, the household is defined as being in extreme fuel poverty."	
Belgium (2023)	"… the inability of a household to access – in its home – the energy it needs, at an affordable income."	Belgium Government (2023)
Slovakia (2023)	"A household is at risk of energy poverty if, after subtracting its total energy and water costs from the total disposable household income, the financial resources of the household remain available at a specified level, for example against the universally accepted minimum subsistence value. In addition, a baseline energy standard (threshold energy and water consumption) may also be taken into account in the future when assessing the total cost of a household, and the future setting of this value should act as an incentive to adjust consumption habits in order to incentivise households to use energy and water more economically."	Government of Slovakia (2023)
Poland (2023)	"Energy poverty means a situation in which a household run by one person or by several people together living in a dwelling or in a single-family residential building, where no business activity is carried out, cannot secure sufficient levels of heat, cooling and electricity to power devices and for lighting where the household collectively meets the following conditions:1) has low income; 2) incurs high expenditure for energy purposes; 3) lives in a flat or building with low energy efficiency; 4) Energy poverty criteria to qualify for energy poverty reduction programs are defined each time when the instruments for reducing energy poverty are introduced."	Polish Government (2023)

Table A2
Literature review or critical analysis articles on EP indicators

Authors	Geographical scope	Object of analysis	Goal
Fizaine and Kahouli (2018)	Europe	EP indicators	Indicator analysis and proposal of a multidimensional approach
Pelz et al. (2018)	Global south	Multidimensional measurement approaches	Analysis of the indicators and discussion on their operationalisation
Thomson et al. (2017)	Europe	EU-available EP indicators	Critical analysis of indicators through the lens of the vulnerability framework and proposal of data improvement options
Siksnelyte-Butkiene et al. (2021)	Worldwide	Composite EP indicators	Analysis of EP indicators in the light of sustainability framework, aiming to identify better performing indicators and draw recommendations
Romero et al. (2018)	Europe	Expenditure-based EP indicators	Critically compare expenditure-based indicators using Spain as a case study
Castaño-Rosa et al., 2019	Europe	Expenditure-based and consensual-based EP indicators	Discussion of the intersection between EP and vulnerability factors to identify shortcomings and propose a multiple-indicator approach
Castaño-Rosa et al. (2020)	Europe	Expenditure-based and consensual-based EP indicators	Assess EP indicators' ability to identify those homes at risk according to a set of criteria
Tirado-Herrero (2017)	EU, Africa, and Latin America	Selected EP indicators in academic and policy literature	Classify and assess the most relevant issues in EP measurement
Rademaekers et al. (2016)	Europe	EP indicators	Assess indicators and test a selected group using household-level data to evaluate its appropriateness
Lowans et al. (2021)	Worldwide	EP and transport poverty metrics	Analyse key indicators and draw suggestions for uniting the measurements and arriving at a more comprehensive assessment
Culver (2017)	Worldwide	EP indicators	Conceptual discussion of EP types and analysis of strengths and limitations of their use
Deller et al. (2021)	England	EP indicators	Assess the intersection between indicators and the impact of determinants
Siksnelyte-Butkiene (2021)	Worldwide	Composite EP indicators	Analyse EP indicators and propose a selection to measure the most relevant dimensions that reflect the modern concept of EP
Brabo-Catala et al. (2024)	Worldwide	Definitions and indicators of EP	Identify the prevalence of relevant themes and discuss biases and priorities
Schuessler (2014)	OECD countries	Expenditure-based indicators	Critically discuss the use of EP measurement indicators
Guevara et al. (2023)	Worldwide	EP related terms	Analyse EP doctrines, trends, and insights, including measurement
Isazade and Altan (2023)	Worldwide	EP indicators	Evaluate different methods of measurement to propose recommendations
Sareen et al. (2020)	Europe	The concept of measurement, in general	Reflection on EP measurement and analytical framework for EP metrology

Table A3
Review of alternative indicators

Study	Country	Geographic scope	Population	Method	Data source	Approach	Object of measurement	EP dimensions	Type of EP depicted	Outcome
Gouveia et al. (2019)	Portugal	All 3092 parishes	Whole population	Area-based composite index (age, education income, unemployment, building characteristics, equipment, conservation state, dwelling ownership, and energy consumption)	Portugal Statistics; Directorate General for Energy and Geology; Energy Performance of Buildings regulation; National Energy Agency;	Quantitative	Causes and drivers	Economic, climatic, infrastructural, sociodemographic	Vulnerability level	Regional vulnerability to EP
Horta et al. (2019)	Portugal	all municipalities and ten parishes	Selected sample of households	Area-based composite index (same as Gouveia et al., 2019) plus qualitative characterisation of vulnerability and coping mechanisms	Portugal Statistics; Directorate General for Energy and Geology; Energy Performance of Buildings regulation; National Energy Agency; interviews	Mixed	Causes, drivers and consequences	Economic, climatic, infrastructural, sociodemographic	Vulnerability level	Regional vulnerability to EP and qualitative characterisation of deprivation
Palma et al. (2022)	Portugal	All municipalities	Whole population	Area-based composite index (same as Gouveia et al., 2019) plus projections of space heating and cooling equipment stock)	Portugal Statistics; Directorate General for Energy and Geology; Energy Performance of Buildings regulation; National Energy Agency; National Roadmap for Carbon Neutrality 2050	Quantitative	Causes and drivers	Economic, climatic, infrastructural, sociodemographic	Vulnerability level	Estimating vulnerability in future scenarios
Panão (2021)	Portugal	NUTS3 regions	Whole population	Expenditure-based indicators (LIHC, MIS, 2 M)	HBS	Quantitative	Consequences	Economic	Measured	Estimating the number of EP households
Matos et al. (2022)	Portugal	National level	Whole population	Qualitative (inability to heat; the presence of leakage, dampness, and rot; arrears on utility bills); quantitative (excess winter mortality; net income; electricity and natural gas prices)	Eurostat; academic literature	Quantitative	Causes, drivers, consequences	Economic, sociodemographic	perceived vulnerability level	analyse the effectiveness of EP policies
Aristondo and Onaindia (2018a)	Spain	Country level	Whole population and selected samples of household	Qualitative indicators (inadequate temperature – winter, arrears on bills, and presence of leakage, dampness, and rot)	SILC	Qualitative	Causes, drivers, and consequences	Climatic, Infrastructural	Perceived	Estimating the number of EP people (individuals)
Llorca et al. (2020)	Spain	Country level	Whole population and selected samples of household	Qualitative (Precarious health, Inadequate temperature – winter) and quantitative indicators (Fuel Poverty Index, MIS)	SILC	Mixed	Drivers and consequences	Economic, Climatic, Sociodemographic	Measured and Perceived	Estimating the number of EP people (individuals)
Aristondo and Onaindia (2018b)	Spain	Country level	Whole population and selected samples of household	Qualitative indicators (inadequate temperature – winter, arrears on bills, and presence of leakage, dampness, and rot)	SILC	Qualitative	Drivers and consequences	Sociodemographic	Perceived	Estimating the number of EP people (individuals) and EP inequality among groups
Romero et al. (2018)	Spain	Country and regional (NUTS2) level	Whole population and selected samples of household	Quantitative disproportionate expenditure indicators (10%, LIHC, MIS)	HBS	Quantitative	Consequences	Economic, Infrastructural, Sociodemographic	Measured	Estimating the number of EP households

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Table A3 (*continued*)

Study	Country	Geographic scope	Population	Method	Data source	Approach	Object of measurement	EP dimensions	Type of EP depicted	Outcome
Costa-Campi et al., 2020	Spain	Country and regional (NUTS2) level	Whole population and selected samples of household	Quantitative disproportionate expenditure indicator (LIHC)	HBS and extreme temperatures at NUTS2 level	Quantitative	Drivers and Consequences	Economic, Infrastructural, Sociodemographic, climatic	Measured	Estimating the number of EP households and the significance of each EP driver
Barrella et al. (2021)	Spain	Country and provincial (NUTS3) level	Vulnerable consumers	Quantitative disproportionate expenditure indicators (Absolute threshold 2 M)	Social tariff beneficiaries database	Quantitative	Consequences	Economic, Infrastructural, Sociodemographic, climatic	Measured	Estimating the number of EP households before and after heating allowances
García Alvarez & Tol (2021)	Spain	Country and regional (NUTS2) level	Whole population and selected samples of household	Qualitative indicators (inadequate temperature – winter, arrears on bills, and presence of leakage, dampness, and rot)	SILC	Qualitative	Consequences	Economic, Sociodemographic	Perceived	Estimating the number of EP households before and after social electricity tariff and Difference-in-differences assessment
Bagnoli and Bertoméu-Sánchez (2022)	Spain	Country and regional (NUTS2) level	Whole population and selected samples of household	Quantitative disproportionate expenditure indicators (2 M)	HBS	Quantitative	Drivers and Consequences	Economic, Sociodemographic	Measured	Estimating the number of EP households before and after social electricity tariff and Difference-in-differences assessment
Bienvenido-Huertas (2021)	Spain	Country and provincial (NUTS3) level	Vulnerable consumers	Quantitative disproportionate expenditure indicators (Absolute threshold 2M-10%)	Climate databases and social tariff income data	Quantitative	Consequences	Economic, Infrastructural, Sociodemographic, climatic	Measured	Estimating the number of EP households before and after social electricity tariff or unemployment benefits
Barrella et al. (2022b)	Spain	Country and regional (NUTS2) level	Whole population and selected samples of household	Quantitative disproportionate expenditure indicators (MIS)	HBS	Quantitative	Consequences	Economic, Sociodemographic, climatic	Measured	Estimating alternative minimum income thresholds and the number of EP households
Barrella et al. (2022a)	Spain	Country and regional (NUTS2) level	Whole population and selected samples of household	Quantitative underspending indicator (HEP)	HBS	Quantitative	Consequences	Economic, Infrastructural, Climatic, Sociodemographic	Hidden	Estimating the extent (number of energy-poor households) and depth (EP gap) of EP
Phimister et al. (2015)	Spain	Country level	Whole population and selected samples of household	Qualitative (inadequate temperature – winter, arrears on bills, and presence of leakage, dampness, and rot) and quantitative (10% and income poverty) indicators	SILC	Mixed	Consequences	Economic, Sociodemographic	Measured and Perceived	Estimating the number of EP households and EP persistence.
Taltavull de La Paz et al. (2022)	Spain	Country-level and regional disaggregation	Whole population sample	Qualitative (arrears on utility bills, inability to maintain a comfortable temperature in the winter, deteriorated dwellings, isolated large homes); quantitative (poverty line)	SILC	quantitative	Causes and consequences	economic, sociodemographic, infrastructural	Perceived, measured	study the link between energy poverty indicators and housing features

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Table A3 (*continued*)

Study	Country	Geographic scope	Population	Method	Data source	Approach	Object of measurement	EP dimensions	Type of EP depicted	Outcome
Arce (2019)	Spain	country level	whole population	ration of electricity expenditure and family income over 80% of the decile threshold	Household Budget Survey	quantitative	consequences	economic	measured	explore the causes of household electricity poverty
Murias et al. (2020)	Spain	country level and regions	whole population	electricity and natural gas tariff (euros/kWh); access to renewable energy; home ownership; new home; HDD; hours of sunshine; unemployed, under 16 and over 65; income	Ministry for Energy Transition data; INE-ES	quantitative	causes	economic, sociodemographic	vulnerability level	assess territorial differences in household EP
Rodriguez-Alvarez et al. (2019)	Spain	country level	whole population	MIS indicator	Spanish Life Condition Survey	quantitative	consequences	economic	measured	analyse EP and well-being
Aristondo and Onaindia (2023)	Spain	country level	whole population	the ability to keep the home adequately warm, the arrears on utility bills, deteriorating dwelling	SILC	quantitative	consequences	sociodemographic; infrastructural	perceived	decompose a family of energy poverty indices
Cadaval et al. (2022)	Spain	country level	whole population	qualitative: the ability to keep the home adequately warm; the arrears on utility bills; deteriorating dwelling; quantitative (MIS calculation)	Living Conditions Survey; Household Budget Survey	mixed	consequences	economic, sociodemographic	measured and perceived	analysing the effectiveness of subsidy in reducing EP
Aguilar et al. (2019)	Spain	country level and one region	whole population	10% Indicator; 2 M; LIHC; ADCP; MIS;	Household Budget Survey	quantitative	consequences	economic	measured	measure and compare EP in Spain and the Canary Islands
Sánchez-Torija et al. (2022)	Spain	country level	whole population	Maximum square metres of housing eligible without being in EP (calculated with 2 M)	Household Budget Survey; Living Conditions Survey	quantitative	consequences	economic	measured	proposing a new concept of energy solvency
Arsenopoulos et al. (2020)	Spain	country level	whole population	Average temperatures (winter-summer); Population growth; Unemployment; purchasing power; political will; average building age; persons per room, Number of tenants; electricity price; adoption of article 7 of obligation schemes; official definition	stakeholder consultation	mixed	causes, drivers	sociodemographic, political; economical; climatic	vulnerability level	assessing the resilience in the face of EP

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