NOVA SCHOOL OF SCIENCE & TECHNOLOGY
DEPARTAMENT OF ENVIRONMENTAL SCIENCES AND ENGINEERING

EXPLORING ENERGY POVERTY MEASUREMENT ACROSS SPATIAL AND TEMPORAL SCALES

INSIGHTS FOR MULTILEVEL FUTURE POLICY-MAKING IN PORTUGAL

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Master in Environmental Engineering

DOCTORATE IN ENVIRONMENT AND SUSTAINABILITY
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Abstract

Energy is a vital element for human welfare and quality of life and a main driver of societal progress and development. Access to sufficient energy is a fundamental human right that should be guaranteed to everyone. However, hundreds of millions of people live in energy poverty across the globe without access to adequate energy services for a decent standard of living. In Europe, the populations in periphery countries like Portugal are the most affected, as inefficient homes, high energy prices and low wages result in energy deprivation for many families, further exacerbated by the energy crisis. As funding is increasingly deployed at the EU level to tackle energy poverty, a large part is mobilised to untargeted measures and short-term consumption subsidies that do not address the structural causes. One of the potential reasons for this limited policy impact is the lack of appropriate energy poverty diagnosis and measure impact analysis at the different scales to inform and shape policy design.

Drawing on international knowledge and focusing on Portugal as the case study, this thesis sets out to further explore energy poverty diagnosis and mitigation action across different spatial scales, producing learnings for future problem definition, measurement, and policy design, targeting and monitoring. The approach aims to bridge the gap between scientific knowledge on energy poverty measurement, mitigation measures impact assessment, and national policy formulation dedicated to eradicating this issue. For this purpose, it conducts narrative and structured literature reviews of energy poverty measurement approaches, indicators, and data on national and subnational scales. Building on this knowledge and previous work developed in the country, it develops a local-scale building energy performance assessment to further explore high-resolution energy poverty analysis for a historic neighbourhood. It explores *ex-ante* regionally disaggregated impact assessments of building energy renovation and energy equipment replacement on the energy performance and energy poverty levels for the whole country. The economic dimension is also examined to assess necessary long-term investments. Finally, drawing on the knowledge produced in the previous assessments, it develops a critical analysis of the diagnosis and monitoring framework of the recent national policy strategy on energy poverty mitigation in Portugal, which guides the planned future action.

This research highlights the best practices, shortcomings, and gaps in current energy poverty indicators and discusses underexplored aspects that can lead to the improvement of energy poverty diagnosis at national and subnational levels. It takes the first steps into local-level assessment in Portugal within the broader context of energy transition and energy use decarbonisation, pointing out priority areas for building energy efficiency intervention in a historic neighbourhood. The whole-country energy efficiency measure rollout analysis provides regionally-disaggregated results on the most cost-effective measures, the regions and dwelling types with the highest energy needs reduction potential, and the necessary investments to conduct a deep transformation of the domestic sector, considering energy justice issues across the territory. It also draws a direct link between energy efficiency measures and energy poverty reduction, estimating the impact of measures on energy poverty vulnerability reduction. It finally provides direct inputs towards the improvement of energy poverty definition and measurement in the current national policy. These results can support national and local policymakers and practitioners in the country and across Europe in their energy poverty reduction efforts while contributing to the theory and scientific literature on this topic. The outcomes of this study can support a paradigm shift towards more nuanced, science-based, effective policy action and a faster and wider energy poverty eradication, granted that there is the necessary political commitment to drive this transformation.

Keywords: Energy Poverty; Indicators; Diagnosis; Mitigation measures; Energy Efficiency; Decarbonisation; Cost Assessment; Policy Analysis

RESUMO

A energia é vital para o bem-estar e a qualidade de vida das populações e é um dos principais determinantes de progresso e desenvolvimento da sociedade. O acesso a energia suficiente é um direito humano que deve ser garantido a todos. No entanto, centenas de milhões de pessoas vivem em situação de pobreza energética em todo o mundo, sem acesso a níveis adequados de serviços energéticos necessários a um nível de vida adequado. Na Europa, as populações dos países periféricos como Portugal são as mais afetadas. As habitações com baixa eficiência energética, os preços elevados da energia e os baixos salários resultam na privação de energia para muitas famílias, agravada pela crise energética. Com o aumento do financiamento ao nível da UE para combater a pobreza energética, uma parte significativa é mobilizada para medidas não direcionadas e subsídios ao consumo com efeitos a curto prazo, não atuando sobre as causas estruturais que perpetuam este problema social. Uma das razões potenciais para o impacto limitado das políticas é a falta de um diagnóstico adequado da pobreza energética e de uma análise do impacto das medidas a diferentes escalas que informem e apoio o desenvolvimento de políticas de mitigação.

Com base no conhecimento internacional e centrando-se em Portugal como estudo de caso, esta tese pretende explorar o diagnóstico da pobreza energética e a análise de medidas de mitigação a diferentes escalas espaciais, contribuindo com novos conhecimentos para uma melhor definição e avaliação deste problema. A abordagem visa colmatar a lacuna entre o conhecimento científico sobre a medição da pobreza energética e a avaliação do impacto das medidas de mitigação e a formulação de políticas nacionais dedicadas à erradicação desta questão. Para o efeito, realiza revisões da literatura narrativas e sistemáticas sobre abordagens de medição da pobreza energética, indicadores e dados às escalas nacional e subnacional. Com base neste conhecimento e em trabalhos anteriores desenvolvidos no país, esta investigação desenvolve uma avaliação do desempenho energético dos edifícios à escala local para explorar a análise da pobreza energética à escala local, nomeadamente num bairro histórico. Explora avaliações *ex-ante* do impacto da renovação energética de edifícios e da substituição de equipamento energético no desempenho energético e nos níveis de pobreza energética em todo o país à escala regional. A dimensão económica é também examinada, com o objetivo

de estimar os investimentos necessários. Finalmente, com base no conhecimento produzido nas avaliações anteriores, desenvolve uma análise crítica da metodologia de diagnóstico e monitorização da estratégia política nacional de mitigação da pobreza energética em Portugal, que orienta a ação planeada.

Esta investigação destaca as melhores práticas, limitações e lacunas dos atuais indicadores de pobreza energética e identifica aspetos pouco explorados que podem levar à melhoria do diagnóstico da pobreza energética a nível nacional e subnacional. Dá os primeiros passos na avaliação a nível local em Portugal, no contexto mais alargado da transição energética e da descarbonização do uso da energia, apontando áreas prioritárias para a intervenção na eficiência energética de edifícios num bairro histórico. A análise da implementação de medidas de eficiência energética produz resultados desagregados por região sobre as medidas mais rentáveis, as regiões e os tipos de habitações com maior potencial de redução das necessidades energéticas, e os investimentos necessários para realizar uma transformação profunda do sector doméstico, tendo em conta questões de justiça energética relevantes no contexto português. Estabelece igualmente uma ligação direta entre as medidas de eficiência energética e a redução da pobreza energética, estimando o impacto das medidas na redução da vulnerabilidade à pobreza energética. Finalmente, fornece contributos diretos para a melhoria da definição e medição da pobreza energética na política nacional do país. Estes resultados podem apoiar os decisores políticos nacionais e locais e técnicos do país e de toda a Europa nos seus esforços de redução da pobreza energética, contribuindo simultaneamente para a teoria e a literatura científica sobre este tema. Os resultados deste estudo podem contribuir uma mudança de paradigma no sentido de políticas públicas mais diferenciadas e suportados em conhecimento científico e de um processo de erradicação de pobreza energética mais célere e global, desde que haja o compromisso político necessário para impulsionar esta transformação.

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ACRONYMS AND UNITS

2M – “High share of energy expenditure in income” indicator

BIPV - Building-integrated photovoltaic

BPIE - Building Performance Institute Europe

CDD – Cooling Degree-Days

COVID-19 - Coronavirus disease 2019

DHW - Domestic Hot Water

DGEG - Direcção Geral de Energia e Geologia [Directorate General for Energy and Geology]

EC - European Commission

ECS - Energy Consumption Survey

EE – Energy Efficiency

EED – Energy Efficiency Directive

EP - Energy Poverty

EPAH - Energy Poverty Advisory Hub

EPBD – Energy Performance of Buildings Directive

EPC - Energy Performance Certificate

ETIC - External Thermal Insulation Composite System

EU – European Union

EPS - Expanded Polystyrene

EPVI - Energy Poverty Vulnerability Index

ETS - Emissions Trading System

Eurostat - Statistical office of the European Union

EN ISO - European Standard International Organisation for Standardisation

GHG - Greenhouse gases

GIS - Geographic information system

HBS - Household Budget Survey

HDD – Heating Degree-Days

HVAC - Heating, Ventilation, and Air-Conditioning

HEP – Hidden Energy Poverty

IEA - International Energy Agency

INE – Instituto Nacional de Estatística [Portugal Statistics]

INSA - Instituto Nacional de Saúde Doutor Ricardo Jorge

LED - Light-emitting diode

LIHC - Low Income High Cost indicator

ICT – Information and Communication Technology

IPCC - Intergovernmental Panel on Climate Change

LCCA - Life-Cycle Cost Analysis

LILEE - Low Income Low Energy Efficiency indicator

LPG - Liquified Petroleum Gas

LTRS - Long-term renovation strategy

M/2 – "Low absolute energy expenditure" indicator

MIS – Minimum Income Standard

MS - Member State

NCEP - National Energy and Climate Plan

NGO - Non-governmental Organisations

NUTS - Nomenclature of Territorial Units for Statistics

NZEB - Nearly Zero-energy Buildings

PED - Positive Energy District

PPS - Purchasing Power Standard

PRR - Recovery and Resilience Plan

PV - Photovoltaic

PVC - Polyvinyl chloride

PVGIS - Photovoltaic Geographical Information System

RES - Renewable Energy Sources

RM - Renovation Measure

RQ - Research Question

SDG - Sustainable Development Goal

SILC - Survey on Income and Living Conditions

ICESD - Inquérito ao Consumo de Energia no Setor Domestico [Survey on Energy Consumption in the Domestic Sector]

UK - United Kingdom

UN - United Nations

VAT - Value Added Tax

VC – Vulnerable Consumer

WHO - World Health Organisation

°C – degree Celsius

GJ - gigajoule

GW - gigawatt

GWh - gigawatt-hour

K – Kelvin

kVA - kilovolt-ampere

kWh - kilowatt-hour

MW - megawatt

MWh - megawatt-hour

1

INTRODUCTION

1.1 The fundamental role of energy in societal development and well-being

Energy has always been a vital element of human survival and activity and a significant driver of societal progress and development. Energy access and consumption are one of the main determinants of quality of life (Brand-Correa and Steinberger, 2017). Day *et al.* (2016) assert that most attempts to specify the basis of a good life include, explicitly or implicitly, some form of energy access as a requirement. Energy provides necessary domestic energy services, such as cooking, heating, cooling, and lighting, enabling capabilities such as preparing food, keeping thermal comfort, and accessing information. These capabilities are essential for maintaining good health, social relations and participation, work, and education (Day *et al.*, 2016). In fact, energy is a fundamental enabler of social expression and reproduction. It is also closely linked to economic output, driving economic growth and productivity (Smith *et al.*, 2013; Tran *et al.*, 2019). Warmth (or thermal comfort) is one of the basic physiological needs of humankind, as previously described by Maslow (1943). In its 2030 Agenda, the United Nations (UN) General Assembly defined 17 sustainable development goals (SDGs) and 169 targets, addressing current global challenges to transform the world and achieve a "better and more sustainable future" (UN, 2015). The 7th SDG highlights the role of energy, as it aims to ensure that clean and affordable energy is available to all. It is intrinsically connected to the first UN's SDG, which refers to the end of poverty in "all its forms and everywhere" worldwide. The 3rd SDG - guarantees health and well-being for the whole population at all ages.

The first era of humankind's relationship to energy is described as the organic energy economy (Fouquet, 2011), with an economy based on land use and biomass consumption, which developed at the rate of solar energy conversion to resources that were turned into goods and services, with land availability and population growth limiting economic output (Bithas and Kalimeris, 2016). The transition to the new energy era came with the industrial revolution and the invention of the steam engine, which converted chemical energy into mechanical energy (McNeil, 2000). This marked a shift from muscle-based source of mechanical energy, which depended on biomass, to fossil fuel-powered machines (Huber, 2009), a mineral-based energy economy (Wrigley, 1988). This new socio-natural metabolism led to the reconfiguration of economic geographies of power (Huber, 2009) and the continued exploitation of fossil resources. These energy resources have become central to the capitalist mode of production, whose ecological contradictions and biospheric rifts have been thoroughly discussed (O'Connor, 1988; Foster, 1999; Clark and York, 2005)

Its expansive nature has transformed the human relationship with nature towards increased objectification and commodification of the resource-based natural world (Matthews, 2011), which is perceived to be endless and limitless. Industrial capitalism has a global impact on the natural world, outgrowing its limits and destroying the resources and the entire biosphere, with civilisational collapse looming large (Matthews, 2011). This insatiable pursuit of growth and capital accumulation is dependent and has been fuelled by the energy sector, and the fossil fuel industry in particular, with significant impacts on our planet. It is currently the major driver of global warming, responsible for around 75% of total greenhouse gas emissions (IEA, 2024a). Anthropogenic activity is estimated to have caused between 0.8°C to 1.2°C of global warming above pre-industrial levels, and it is likely to reach 1.5°C between 2030 and 2052 at the current rate of increase. Anthropogenic emissions have a long-lasting effect and continue to significantly change the climate system for centuries, but climate risks are proportional to the rate, peak, and duration of warming; thus, impacts to natural systems at 1.5° are lower than at 2°C (IPCC, 2018). The achievement of the 2015 Paris Agreement target of limiting global temperature increase to a maximum of 2°C and even below 1.5° depends on the transformation of the energy sector and its ability to reach net zero emissions by 2050 (IEA, 2024a). As displayed in Figure 1.1, electricity and heat production are the main emitting sectors. Still, several other energy-consuming sectors are also a considerable part of the problem, hence the need to transform the whole energy system from production to consumption.

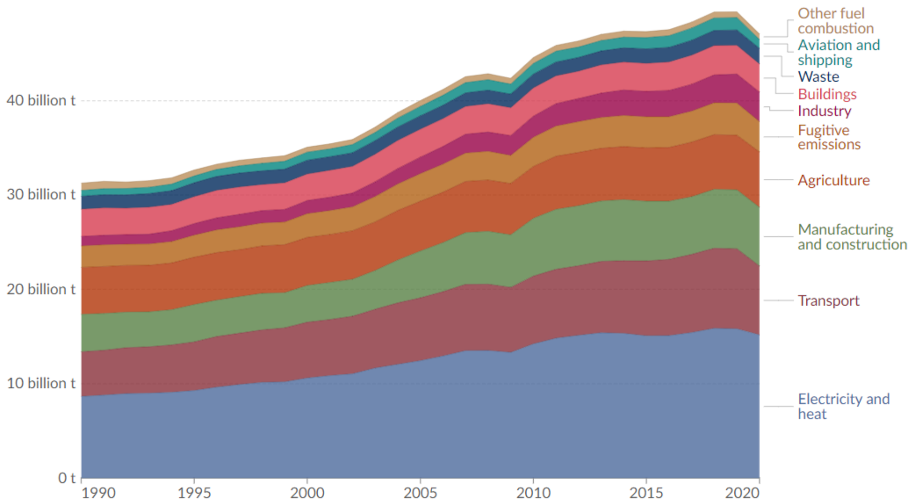

Figure 1.1 - Greenhouse gas emissions by sector, from 1990 to 2020 (Our World in Data, 2024a)

Despite ongoing efforts across the globe to develop renewable energy technology, fossil fuels continue to be the main energy source of the world's economy. After a dip in 2020 due to the Coronavirus disease 2019 (COVID-19) pandemic, the recovery of consumption levels was accompanied by an increase in energy demand and fossil fuel use levels to pre-pandemic levels or even above, as displayed in Figure 1.2. Despite their significant impacts, the dependence on these energy sources is perpetuated partly due to governmental support and subsidisation. Global fossil fuel subsidies amounted to 7 trillion or 7.1 per cent of gross domestic product in 2022, a $2 trillion increase since 2020 and are expected to rise to $8.2 trillion by 2030 (IMF, 2024). The largest part of subsidies is a consequence of underpricing local air pollution costs and climate damages, representing 30 per cent of the total global subsidies each (IMF, 2024).

These subsidies distort markets, increase fiscal deficits in Global South countries, and discourage the investment and adoption of renewable energy technologies at a time when the efficient use of energy resources and a clean energy transition should be urgent priorities (IEA, 2024b).

On the other hand, in 2023, the oil and gas industry earned a record-high net income of over $2.6 trillion, investing just 4% of capital expenditure on clean energy, while climate-related extreme events such as the Pakistan floods devastate the most unprivileged and poor communities, costing the country up to $40 billion (Energy Profits, 2024). On the back of the Russian invasion of Ukraine, which made the already high wholesale gas prices and household bills soar, the oil and gas companies made historic record income gains, profiteering from the war. At the same time, millions struggle to heat their homes and pay their energy bills (Galey, 2024). Retracting from pledges of oil production cuts, profits are spent on investor handouts and ever more oil and gas production (Sweney, 2024).

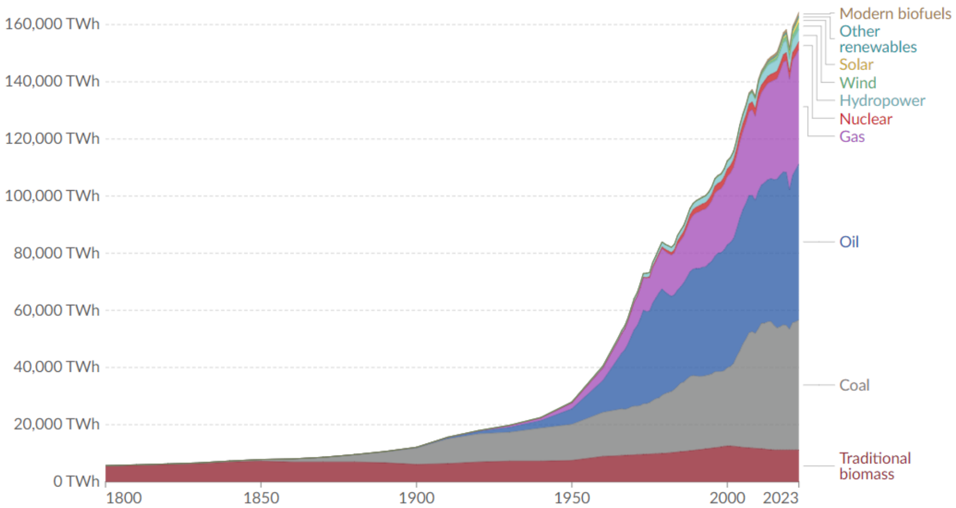

Figure 1.2 - Global direct primary energy consumption per energy source (Our World in Data, 2024b)

The building sector is a significant driver of material consumption and environmental impacts during its construction or off-site production of electricity and heat (indirectly) and operation (directly) (Zhong *et al.*, 2021). In the operational phase, buildings still represent around 30% of global final energy consumption. This number rises to 34% if the energy used for construction materials is considered (IEA, 2024c). In the past decades, energy demand has had an average annual increase of around 1%, and despite the increase of electricity in the energy share and the shift to renewable energy, fossil fuel use has risen since 2010 at an average annual rate of 0.5% (IEA, 2024c). Buildings accounted for 26% of global energy-related emissions in 2022, decreasing for the first time since 2015. Residential buildings are the most impactful of the whole stock, being responsible for 62% of total CO_2 emissions (Figure 1.3). They also represent 21% of the total final energy consumption, including all sectors, compared to 8.8% of non-residential buildings.

The whole sector has considerable potential for climate change mitigation action and for meeting Paris Agreement goals and SDGs, which can be realised through the decarbonisation of global and regional energy systems (IPCC, 2018; Cabeza *et al.*, 2022). As energy performance and efficiency standards and renewable energy technologies are increasingly rolled out, a faster rate of transformation is needed for all new buildings and 20% of the existing building stock to be zero-carbon ready by 2030 (IEA, 2024c).

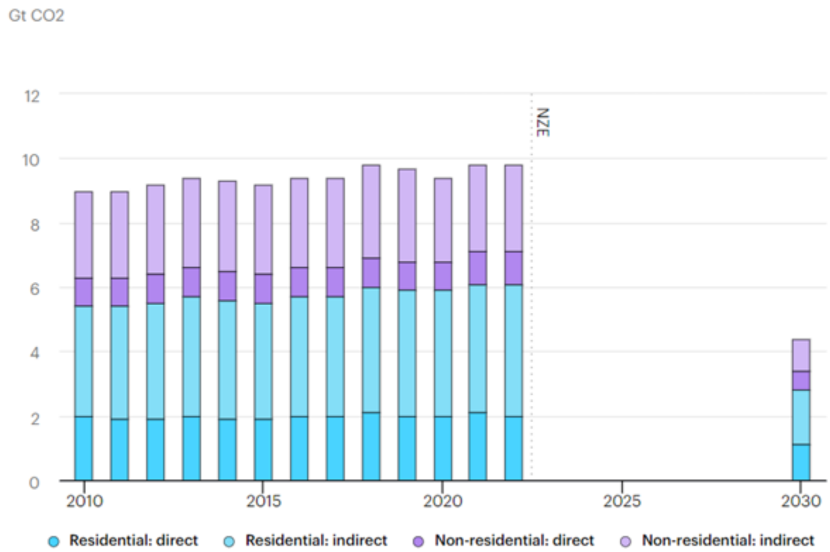

Figure 1.3 - Global CO_2 emissions from the operation of buildings in the Net Zero Scenario, 2010-2030 (adapted from IEA, 2024c)

However, the global capitalist political economy has produced considerable asymmetries in resources and consumption distribution. The gap between the Global South and the Global North deepens, and inequality grows as income and wealth increase in the Global North (Lawrence, 2021). Inequality is also a reality within countries, with the rich increasing their wealth at a higher rate than the poor. Globally, the top 10 per cent of consumers consume approximately 30 times more energy than the bottom 10 per cent (Millward-Hopkins, 2023). Human well-being and climate protection would require a gap reduction between the world's highest and lowest energy consumers of about eight-fold by 2050. There is a close relationship between energy and income inequality, thus a significant decrease in income inequality levels would be necessary to address this energy gap (Millward-Hopkins, 2023). These disparities are heightened by crises such as the COVID-19 pandemic, especially in Global South countries (Lawrence, 2021). Millward-Hopkins *et al.* (2020) estimated that 40% of global energy use could provide universal decent living standards in 2050. Inequality can increase energy demand and costs to double the current values (Millward-Hopkins, 2022). The asymmetric distribution of energy resources is accompanied by unequal effects of climate change. Global warming is greater in several land regions and seasons than the global annual average, and the associated risks depend not only on the magnitude and rate of warming but also on levels of vulnerability, development, and mitigation and adaptation strategies (IPCC, 2018). The existing asymmetries in energy provision are well reflected in the domestic sector.

In 2022, around 760 million people still lacked electricity access (IEA, 2024d). Virtually all this population resides in the Global South, especially in Sub-Saharan Africa. About 2.1 billion people still rely on damaging cooking fuels, which negatively affect health and well-being, preventing social progress (IEA, 2024e; Pesch *et al.*, 2023). Access to adequate levels of reliable and clean energy services improves healthcare and education, empowering individuals and communities (UN, 2021). About 660 million people are projected to remain without access to electricity in 2030, 85% in Sub-Saharan Africa, and around 110 million new connections per year would need to be established to reach SDG 7.1.1 (IEA. 2024d). It is worth pointing out that access does not necessarily mean that energy is being used, not translating into tangible benefits for the population. Min *et al.* (2024) estimate that at least 1.8 billion people live in dark areas, with no statistical evidence of electricity use, a number considerably higher (60 per cent) than the International Energy Agency (IEA) estimative. Energy vulnerability is not restricted to access. Energy provision can be unreliable, insufficient, polluting, or too expensive. These are all signs of a problem often designated as energy poverty (EP).

In the most affluent nations of the Global North, unsustainable amounts of energy are consumed to sustain lifestyles that vastly surpass the necessary levels for decent living standards, translating into significant environmental degradation and resource consumption (Pesch *et al.*, 2023). Nevertheless, energy resource distribution is still a concern in these societies, as a part of the population still experiences EP, generally defined as a household's lack of access to essential energy services (Directive (EU) 2023/1791)

In the EU, 16.2% of the population were at risk of poverty and 10.6% of the population reported not to be able to keep their homes adequately warm in 2023, amounting to a total of at least 47.5 million people in EP (Eurostat, 2024a, Eurostat, 2024b). In Portugal, this condition is a daily reality for an even greater share of the population (20.8%), affecting over 2.1 million people. EP is not only manifested as the inability to keep the home warm, so it is likely that the number of affected surpasses the number of reported people using this indicator. Tackling EP requires effective measures and policies that address the core aspects of this multidimensional scourge. The deployment of varied impactful mitigation actions across the spatial scale, from national to local, is paramount to broaden the impact of the mitigation strategies, reaching a higher number of people and account for its diverse regional expressions and configurations. In collaboration with the Covenant of Mayors Europe (CoM), the Energy Poverty Advisory Hub (EPAH) places a strong emphasis on local-level action, having supported multiple local-level projects and employing innovative solutions to target the energy-poor and reduce their vulnerability (EPAH, 2024a). The Hub also highlights the importance of diagnosis in designing and targeting mitigation actions. Diagnosis should be the foundation of every mitigation intervention, as it is fundamental to understanding how this issue is shaped in each particular territory, and which are the important aspects and challenges that need to be addressed in the mitigation process (EPAH, 2024b). Like the mitigation interventions, EP measurement should be conducted at different scales. National scale assessment is essential for problem-setting and defining wider targets and policy frameworks.

On the other hand, several of the causes and effects of EP are more visible at the household level and local scales. Thus, disaggregated measurements are essential to identify those specific features and expressions of the problem and detect energy-poor households with higher. Despite ongoing efforts to develop diagnoses and implement mitigation measures and the increasing EU funds recently made available for governments to implement support schemes, EP levels have been on the rise in Portugal and the EU since 2021, a period marked by the energy crisis resulting from the Russo-Ukraine war. There is evidence that the dimension and structure of available public funding may be a significant part of the problem, as it is mostly distributed through non-targeted price mitigation and income support measures with limited effectiveness (Galgóczi, 2023; Cornago and Springford, 2023).

1.2 Problem definition

Appropriate indicators and measurements are essential for assessing the dimension, severity and configuration of EP, identifying affected groups, assessing trends and changes, and monitoring the impact of mitigation actions across different geographies and spatial scales (Hills, 2011). An indicator can be defined broadly as a measure from which conclusions on a phenomenon can be inferred (Heink and Kowarik, 2010). Choosing adequate methodologies and indicators for diagnosis and monitoring is not straightforward, especially for EP.

There is not one common measure of EP in the EU. EPAH identifies twenty-eight proxy indicators to contextualise and measure EP at the country level (EPAH, 2024c). National scale measurement approaches and understanding of the issue at this level have historically been based on proxy indicators, especially the consensual-based indicators provided in the EU SILC (Pye *et al.*, 2015). As researchers started to access other databases, such as the Household Budget Surveys (HBS), the available income and expenditure data prompted the use of expenditure-based measurements (Romero *et al.*, 2018; Panão, 2021; Bardazzi *et al.*, 2021). The EU generally appraises indicators according to their suitability for a systematic transversal approach across the Member states, favouring the current national-scale approaches (Rademaekers *et al.*, 2016; Bouzarovski and Thomson, 2019). Whilst simplified metrics seem to be preferred at the European policy level, current datasets are not comprehensive, only enabling generic and limited country comparisons between Member states (Sébastian and Bauler, 2013; Sareen *et al.*, 2020). Moreover, most national-level indicators and data have arguably not been designed and collected to measure EP, thus having inherent limitations regarding their ability to provide comprehensive assessments and contextually relevant interpretations

(Rademaekers *et al.*, 2016; Kashour and Jaber, 2024). Therefore, there is extensive room for exploration regarding the use of the existing national data resources and indicators and for directing future developments towards more comprehensive and insightful national assessments.

At the regional and local scales, a great diversity of approaches has been proposed to measure EP (*e.g.* Walker *et al.,* 2012, Sanchez-Guevara *et al.*, 2019 or Martín-Consuegra *et al.*, 2020), employing the mentioned indicators but also developing alternative composite metrics based on different conceptual frameworks and perspectives of the problem. Researchers defend the development of this type of metrics; ENGAGER (2018) pointed out the need for regional vulnerability assessment, and Gouveia *et al.* (2019) emphasised the importance of bridging the gap between generic country assessments and case study approaches at the local level. Data availability is often a major driver and limitation of these subnational studies, as authors recognise the importance of measuring EP at lower scales while dealing with scarce data on these levels, making the most out of what is available to them. Therefore, these metrics are often very context-specific, and transparency and commensurability across Member-States is a difficult challenge to overcome (Espeland and Stevens, 1998; Sareen *et al.*, 2020). They do not point to a "one size fits all" solution. Instead, they uncover specificities and nuances that may help but also hinder the detection of energy-poor in some cases, as they may involuntarily disregard several aspects of the issue.

Nevertheless, while ensuring its effectiveness across different contexts is indeed difficult, they form a pool of different alternative methods and approaches that can still prove useful to other contexts, advancing valuable theory that can enhance local scale measurement. Several authors have conducted literature reviews of EP indicators focusing mostly on the measurement method without a particular concern over the spatial dimension (such as Castaño-Rosa *et al.*, 2019 and Siksnelyte-Butkiene *et al.*, 2021). As the rollout of subnational approaches continues, an analysis focusing on EP metrics at this scale could provide important insight into what are the most effective measurement approaches, most used indicators, and available datasets to further increase the understanding of this problem and identification of vulnerable households in regions and populations with such varying characteristics. Simultaneously, it would contribute to signalling policymakers of the existing needs regarding data resources to improve measurement at the local level, which in turn would provide a better service to local government in their mitigation efforts. The knowledge gathered on EP metrology at subnational scales can help enhance already existing metrics in different contexts, uncovering possibilities related to indicators and data, and move towards a more inclusive and nuanced identification of vulnerable population groups. In Portugal, this knowledge can support the development of more spatially disaggregated assessments, zooming in as far as the neighbourhood unit, which has not yet been explored in the country. Higher spatial scale resolution analysis can contribute to enhancing the work of local governments.

Buildings' energy efficiency (EE) increase and renewable energy promotion measures are regarded as key solutions to mitigate EP (Widuko, 2023), with research showcasing their potential impact (Boemi and Papadopoulos, 2019; Zhao *et al.*, 2022). On the EE front, progress has been slower than desirable, as building renovation rates in the EU are still significantly low, with the annual weighted energy renovation rate estimated at 1.0% and deep renovation rate at around 0.2%, with southern European countries lagging. Portugal had the lowest values for energy savings generated from all three levels of energy-related renovations (Zangheri *et al.*, 2021). While policy strategies and roadmaps to boost EE and decarbonisation have multiplied in the last few years, dedicated programs have had a limited impact in addressing this problem. Taking the example of Portugal, previous and current programs have resulted in regional disparities in support allocation, issues in the program design resulting in poor targeting of vulnerable consumers, inadequate scope of support to address decarbonisation and EP, and low adoption from the more vulnerable segments of the population. One of the causes is arguably a discernible knowledge gap regarding the identification of the most effective measures and priority regions to address EP from policymakers at the national and local level, but also citizens, which results in ineffective and inefficient funding use and support instruments. The considerable spending of EU's energy crisis funds on untargeted support is symptomatic of this policy ineffectiveness.

Metrics should assume a more prominent role in policymaking, not only in assessing the scale and nature of the problem but also in the design and monitoring the impact of policies and measures dedicated to EP alleviation. Assessment should be conducted at the design stage so that the connection between resources, tools, and impacts is transparent and well understood, and planning can be more thorough and efficient. *Ex-ante* impact analysis guarantees that the intervention is planned with the most effective solutions focusing on the most vulnerable regions and populations, establishing a connection between resources and policies produced at the national level and interventions conducted at the regional and local levels. It can enable more knowledge-based and tailor-made policy design that addresses the needs of the population. With the potentially highest-ever amount of funding from the European Social Climate Fund (EC, 2024a) to be deployed for EP mitigation in the next years, the use of EP metrics to develop *ex-ante* impact analysis of EE measures constitutes an essential tool to guarantee that these resources are used efficiently and to the benefit of those who need support the most. For supporting long-term strategies and planning, *ex-ante* analysis could incorporate future scenario analysis, considering future policy targets and investigating how measures allocation can impact different EP systemic determinants and EP levels. Analyses focusing on country-wide policy and intervention roll-out, disaggregated per region and linking the national to the regional scale, could produce relevant results for planning and tailoring more detailed and regionally specific national strategies, policies and funding schemes. The study of future scenarios to assess the impact of different interventions on EP is still an underexplored field, as only a few authors have focused on the direct impact of country-level EE scenarios on future EP levels. Barrella *et al.* (2023) is the exception, having assessed the impact of EE interventions on the households' affordability and EP in 2030. Alba-Rodriguez *et al.* (2021) also investigated the relationship between EE measures and EP for social housing homes in Seville, using a composite EP index to assess the impact of building retrofitting projects on future EP levels. Pérez-Fargallo *et al.* (2018) also delved into future EP measurement, developing an index to assess the potential risk of social housing households being in fuel poverty in the future in Chile, using the forecast evolution of incomes, energy prices and weather data to assess future fuel poverty risk probabilities. Dedicated regionally-specific studies focusing on the connection between EE measures and EP levels in country-scale scenarios are still scarce despite their potential value for policymaking. This holds particularly true for Portugal, where the high potential for EE improvement of the ageing building stock across regions can significantly reduce the persistent EP problem afflicting the country if adequate interventions are planned.

Post-implementation monitoring and assessment of strategies and policies is also a key step towards identifying potential shortcomings and enhancing future policymaking. As EU countries start to develop EP mitigation national strategies and are still required to continue reporting on EP levels in their National Energy and Climate Plans (NECP), it becomes increasingly relevant to interrogate how EP diagnosis is framed and conducted in these instruments, especially considering the diversity of possible approaches. The EP definition and measurement constitute the basis for the mitigation action plan to be deployed across the whole country. Thus, they are paramount to ensure that the planned interventions effectively target the energy-poor population and address all relevant aspects that determine this condition at different scales. As implemented national EP strategies are still rare, dedicated critical analysis confronting the state-of-art scientific literature with current policy strategies to assess their scientific soundness has not yet been explored.

1.3 Objective and Research Questions

This research aims to increase knowledge of EP diagnosis and mitigation across different spatial scales in Portugal, producing learnings for future problem definition, measurement, and policy design and monitoring. More specifically, the main goal can be divided into four specific objectives: 1) to analyse EP measurement approaches across the spatial scale and identify best practices; 2) to improve and expand EP measurement in Portugal at the local scale drawing from the national and international literature and existing data; 3) to assess the potential impact and cost of EE and decarbonisation solutions and macro scenarios in the energy performance of the building stock and future EP levels in the country, and 4) to propose improvements in public EP policy, namely regarding EP definition and measurement. This approach aims to draw a connecting thread between scientific knowledge on EP diagnosis, further explorations of EP measurement at subnational spatial scales, and the impact assessment of potential cross-country mitigation actions while transferring the gained insights and knowledge into a critical analysis of existing EP policy strategy. It aims to bring EP metrology and *ex-ante* impact assessment of mitigation measures into the policymaking drawing board and contribute to a paradigm shift towards more nuanced, accurate, science-based, and effective policy action. To guide this study towards the achievement of the set objectives, four research questions (RQs) were formulated:

- RQ1: What are the most adequate indicators to describe the impact of the different causes and drivers of energy poverty from national to local scale?
- RQ2: How can existing data resources be integrated to develop energy poverty measurements at the neighbourhood level?
- RQ3: What is the potential impact and cost of different measures for future energy efficiency improvement and energy poverty mitigation?
- RQ4: How can energy poverty diagnosis in public policy be improved?

The approach to effectively answering these questions builds on previous work and methods developed in the Portuguese context. It integrates a varied set of new data and methods towards a holistic and comprehensive outlook of the issues at play. It aims to advance state-of-the-art knowledge of the subject while guiding and improving multilevel policymaking in the country. Several learnings can be transferred to other contexts and help shape European EP mitigation policy strategies.

1.4 Thesis Research Approach

The philosophical stance or research paradigm is essential for a research design since it provides it with its methodological context (Morais, 2010). Each stance implies a set of ontological assumptions (beliefs about the nature of social reality, including political, social, and physical points of view), epistemological assumptions (beliefs about how we know the world and the nature of knowledge), and assumptions on human nature and how we interact and relate to the environment (Sikes, 2004, Bahari, 2010, Scotland, 2012, Ormston *et al.*, 2014, Marsh *et al.*, 2017), which contextualise and shape the research. The philosophical stance derives from the author's positionality, which describes the individual's worldview and position regarding the different tasks and their social and political contexts (Foote and Bartell, 2011; Savin-Baden and Major, 2013; Rowe, 2014). These ontological, epistemological, and methodological assumptions stem from the individual's values and beliefs, which are shaped by several aspects, inter alia, such as faith, gender, sexuality, historical and geographical location, and political allegiance (Sikes, 2004, Wellington *et al.,* 2005 and Marsh *et al.*, 2017, Holmes, 2020). It is, therefore, relevant to briefly articulate the author's positionality. The worldview or research paradigm of this research can be described as Postpositivist. It is different from positivism because it moves away from the notion of the absolute truth of knowledge (Phillips and Burbules, 2000), acknowledging that it is not possible to be completely positive about our claims of knowledge regarding the actions and behaviour of humans (Creswell, 2018).

Embedded in the methodologies is the deterministic philosophy that causes (probably) determine outcomes. A reductionistic approach is also implicit in this research, as problems are reduced into a discrete set of variables selected to study the problem and test hypotheses (Creswell, 2018). Theory that explains the problem is used, tested and refined to conduct new experiments. Objectivity is vital to a postpositivist research approach as it searches for empirical evidence that helps explain the object of study and causal relationships (Morais, 2010; Creswell, 2018). However, contrarily to positivism, it recognises that knowledge is influenced by the researcher's interpretations and perspective (Creswell, 2018), acknowledging the importance of context, reflexivity and subjectivity in understanding EP. More specifically, this doctoral thesis was developed through an approach that relies mostly on quantitative methods. This research is built on the use of a deterministic physics-based model to calculate thermal energy needs using quantitative data on building physical characteristics and thermal behaviour parameters. It also employs a composite index combining quantitative and qualitative indicators that are transformed into numerical results. Finally, theory stemming from quantitative and qualitative research is used to develop a critical analysis of a policy strategy, which can be perceived as an exercise of qualitative research with an objective philosophical stance underneath. Following Mintzberg's (2005) distinction between qualitative and quantitative based on the nature of data, this research is quantitative for the most part, although the use of qualitative strategies to develop theory about facts (such as content, hermeneutical, and logical analysis, as well as taxonomy) can lead to the perspective that the thesis research strategy is of the mixed-method type. The scientific quality criteria of this research are objectivistic (Guba and Lincoln, 2005), assured by external validation in the form of analytical generalisation, as the developed models focus on making projections based on a theoretical evaluation of the determining factors selected and prioritised according to current theory.

Moreover, as Yin (2009) stated, previously developed theory is used as the background to compare the research results. It is considered a generalisation to theory, the appropriate form of generalisation for a case study analysis. The aim and main innovation of this thesis are not methodological *per se*. It does not propose a new methodology; it instead uses, refines and combines previously developed and validated methodologies from the literature, building energy simulation and regional EP assessment, and applies them to the study of underexplored aspects relating to subnational EP measurements, the potential and cost of energy performance and EE measures, and the link with EP mitigation and policy analysis focusing on recent and under scrutinised EP strategies.

As Varpio (2018) pointed out, scientific research is often seen as an exercise of rationality. However, for the researcher's propositions and solutions to be accepted, arguments must be constructed to convey the meaning of the research and for the reader to take the "rationality" presented. Thus, it is relevant to reflect on the three acts of rhetoric advanced by Aristotle that embed this research: *ethos*, *logos*, and *pathos*. The *ethos* refers to the credibility and trustworthiness of the researchers, which are related to using sound and justified research methodologies. This research is built on scientifically peer-reviewed validated methods and reliable data from official sources. It also integrated a thorough literature review process, which enabled the identification of the most adequate practices and methodologies. The credibility of the research is also strengthened by a discussion of its limitations. This discussion is presented in the General Discussion section (chapter 8). The *logos* focuses on the argument given to the reader; it refers to the logic and clarity of the argument, which is rooted in reasoning. The *logos* of this research is hypothetic-deductive (Yin, 2009), as it draws on knowledge and theory from previous literature to develop sound approaches to test EP solutions and zoom the EP measurement on the spatial scale. The hypothesis advanced by this research is the transfer of measurement practices to more disaggregated spatial scales and the regionally specific analysis of EE measures' potential effect on the energy performance of the entire building stock and regional EP levels. The *pathos* refers to the emotions of the research, connected to political and ethical aspects (Punch, 2006). The emotions are connected to the author's position regarding the research study. They can be positive or negative. From an ontological point of view, aiming to be transparent on the author's beliefs regarding social and political reality and respective emotions, this research stands on the conviction that access to adequate housing and a level of clean energy services that guarantee the secondary capabilities necessary for an adequate standard of living is an inalienable universal human right and should be guaranteed to everyone regardless of their socioeconomic condition. It is the author's belief that essential energy services are a public service rather than a commodity to be traded. I believe this research can make a small contribution to the envisaged reality of energy access to all, as it provides policymakers at different levels of governance with valuable information on EP measurement and the potential of different measures to mitigate it, enabling more tailormade action to eradicate this social condition. However, this research's potential lack of traction and subsequent low impact at the policy level is a concern. It depends on political action, so the potential lack of political commitment, other policy priorities, or even the inability of this research to produce sufficiently interesting and valuable results that could be used practically can be important barriers. I believe the connection between research and policymaking is not straightforward because languages and needs are often misaligned, and collaboration and synergetic action between both sides require more than a written academic document.

1.5 Foundational work

The research developed in this doctoral thesis was built on the vast body of work and literature published on this subject matter internationally. However, some previous research carried out in Portugal on this topic was particularly seminal to this work. It is then important to revisit the small history of research focusing specifically on EP measurement. The existing literature examined EP focusing on space heating and cooling to analyse thermal comfort or lack thereof and energy performance and EE of buildings.

Building on previous research that combines socio-economic variables with electricity smart meters data to identify and characterise potentially vulnerable consumer groups through energy consumption patterns (Gouveia *et al.*, 2012; Gouveia and Seixas, 2016; Gouveia *et al.* 2017), Gouveia *et al.* (2018) combined daily smart meter data for 265 houses from 2011 to 2014 with household door-to-door surveys and energy simulations of building typologies to identify energy-poor consumers. Using electricity smart meters and household survey datasets, the authors applied a clustering analysis to detect different yearly electricity consumption profiles, daily consumption levels, and distinct groups of electricity consumers. The authors used a building energy model to predict space heating and cooling energy needs for the building typologies where the identified groups of people were living to cross-reference with the electricity consumption profiles. For this purpose, the authors compared daily electricity consumption with final energy consumption calculated from the estimated energy needs to calculate an energy gap. Two groups of households were identified: the EP group and the energy obesity group.

In previous work on thermal comfort and climate vulnerability, Simoes *et al.* (2016) created a methodology to assess the potential EP of residential dwellings at the regional level, combining data on income, level of education, unemployment rate, and number of inhabitants above 65 years old, and a space heating and cooling gap estimated per household typology in a weighted vulnerability index. The study was conducted for 29 municipalities across the country. Results show that an average of 22% of the inhabitants are potentially energy-poor regarding their dwellings' space heating and 29% regarding space cooling.

Subsequently, building on the research conducted by Lopes (2010) and Simoes *et al.* (2016), two research studies developed in the Portuguese context are particularly relevant to this thesis, constituting its bedrock foundation - Palma *et al.* (2019) and Gouveia *et al.* (2019). It is important to briefly present these studies as their comprehension is required to fully grasp several of the tasks undertaken in this thesis. Palma *et al.* (2019) assessed the energy gap of the Portuguese residential dwelling stock for every civil parish of the country. The energy gap is the difference between the theoretical energy consumption required for indoor thermal comfort conditions in the heating and cooling seasons and the actual energy consumption of households. The theoretical energy consumption was calculated using a bottom-up building typology approach based on a set of key building characteristics (*e.g.* area, walls, bearing structure) identical to the method defined in the European Standard International Organisation for Standardisation (EN ISO) 13790, the heating and cooling equipment ownership split and efficiency ratios, and the number of dwellings and respective areas for each dwelling typology. The actual energy consumption was computed from municipal final energy consumption statistics for the residential sector provided by the national energy authority. It was disaggregated per civil parish according to regional energy matrixes or the national energy consumption survey, which provided the share of final energy consumption for every energy carrier and the number of dwellings and built area in each parish. Thermal comfort is a rather uncertain and subjective phenomenon, of personal nature since it varies from person to person (Tirado-Herrero, 2017). For instance, Magalhães and Leal (2014) state these conditions are probably too demanding as a standard to assess thermal comfort in Portugal, as some occupants can be comfortable only through adaptation measures without actively heat and cool their dwelling. Often, occupants only actively acclimate a part of their houses' area for a limited period, with different threshold temperatures (Gouveia *et al.*, 2017). Thus, three scenarios were tested, with varying space heating and cooling duration and dwelling area. The nominal scenario considers the full duration of heating and cooling seasons and the whole area of the dwellings. In contrast, the Conservative and Strict scenarios test increasing levels of reduction in these parameters in the energy gap. The methodological scheme is displayed in Figure 1.4.

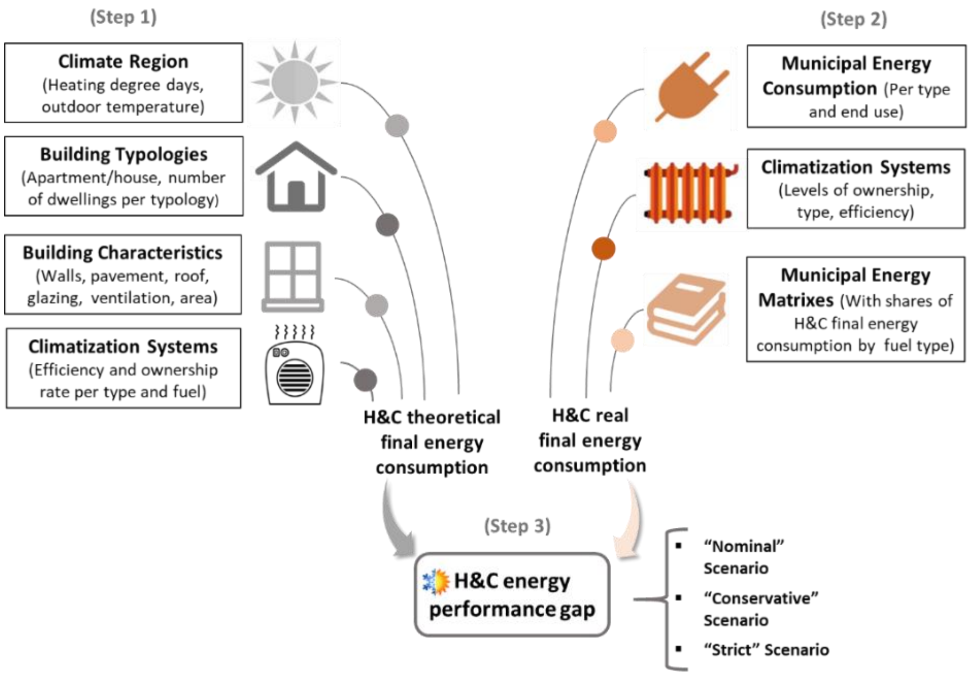

Figure 1.4 - Methodological scheme (from Palma *et al.*, 2019)

Results show that, at a national level, the country's aggregated space heating and cooling energy gap is 92% and 96%. The national space heating and cooling theoretical final energy consumption would need to increase to 12 and 26 times (respectively) the actual final energy consumption, with inevitable increases in GHG emissions. Every civil parish records a gap higher than 60% for space heating and cooling related to the poor EE of the building stock and low heating and cooling energy consumption. The energy gaps for space heating and cooling are displayed in Figure 1.5. However, the scenarios demonstrate that different temporal space climatisation patterns can significantly reduce or even erase the energy gap. High remaining

EP gaps in restricted scenarios identify parishes in the north and centre inland regions as the most vulnerable in the winter and summer seasons, likely due to significant EP levels.

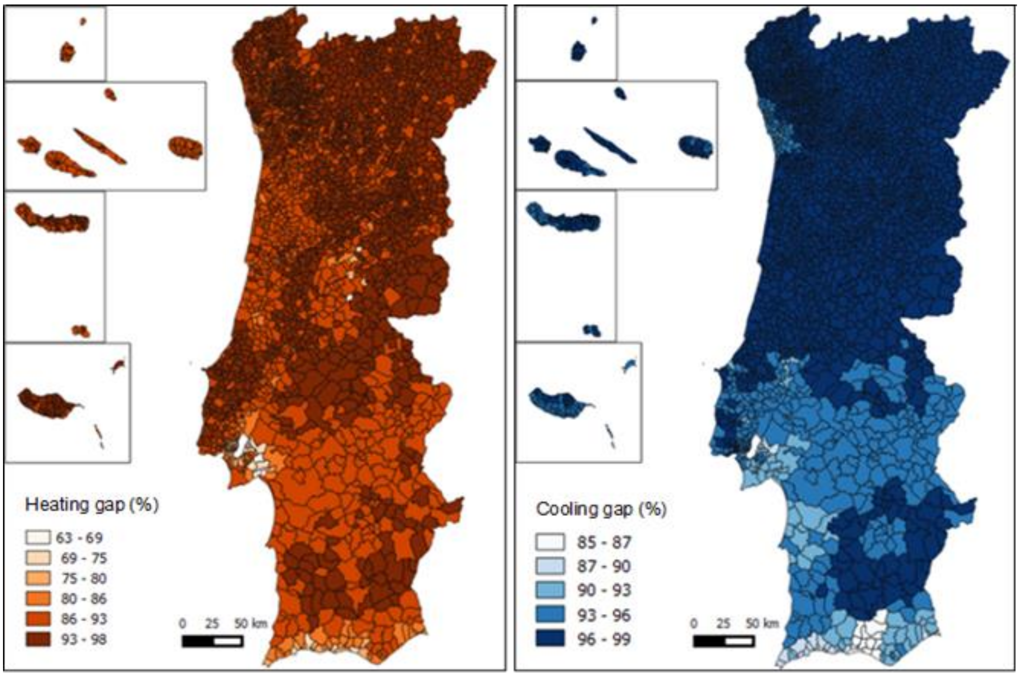

Figure 1.5 - Space heating and cooling energy gaps in Portugal (from Palma *et al.*, 2019)

Gouveia *et al.* (2019) integrated the energy gap model into the design of a novel EP composite index – the Energy Poverty Vulnerability Index (EPVI). This index was created to map and assess EP vulnerability at a very high-resolution spatial scale (all 3092 Portuguese civil parishes). It combines the energy gap calculation (conducted for 187 building typologies representing the whole dwelling stock) with a sub-index measuring the population's ability to implement thermal comfort measures. This sub-index joins seven socioeconomic indicators (elderly and young people; unemployed; tenancy; dwelling state of conservation; levels of income; education levels), weighted according to specialists' feedback. These two components are then combined into the EPVI. The methodological framework can be consulted in Figure 1.6.

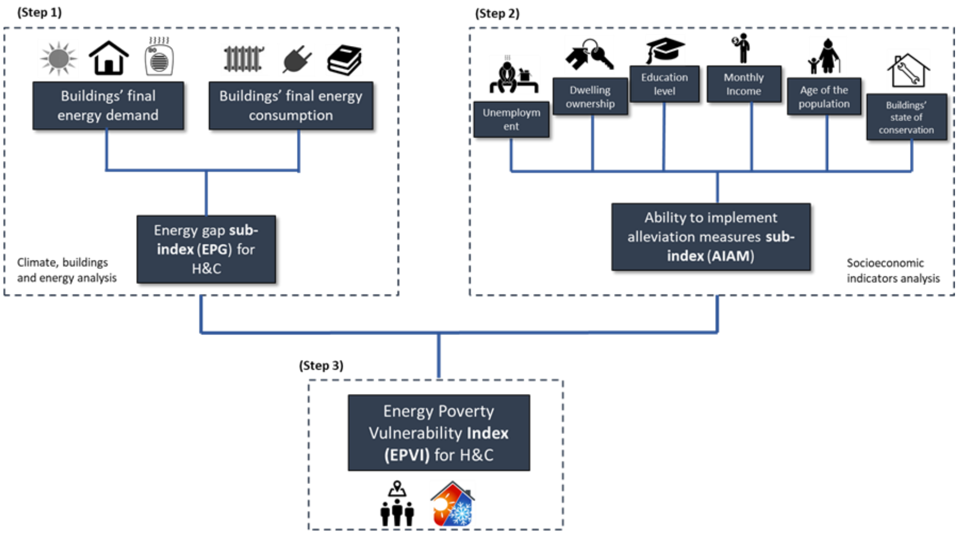

Figure 1.6 - EPVI methodological framework (from Gouveia *et al.*, 2019)

The EP space heating and cooling vulnerability maps are displayed in Figure 1.7. Results highlighted have a generally higher prevalence of significant EP vulnerability for both heating and cooling in the inland region and the islands, particularly in rural civil parishes in the north and inland centre continental regions. However, several south inland civil parishes also have a higher level of vulnerability. The high levels are determined by the conflation of more severe climate conditions, lower EE of the dwelling stock and energy consumption for space heating and cooling, and the lower ability of the population to implement thermal comfort improvement EE measures. Space cooling EPVIs are generally higher, although lack of adequate space heating may be more impactful in terms of energy demand and health effects.

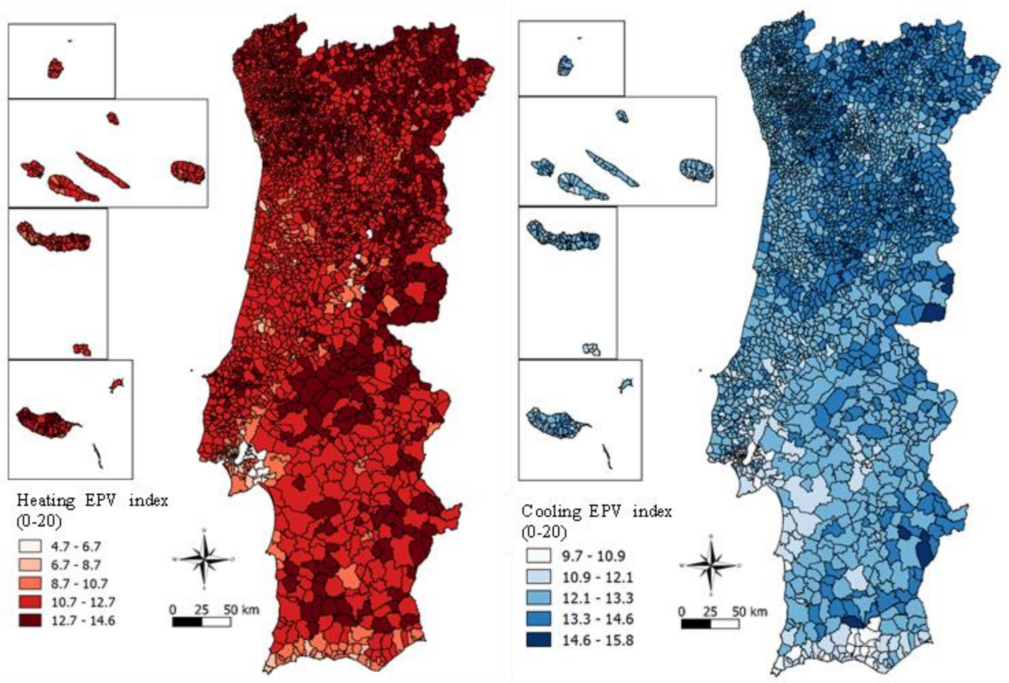

Figure 1.7 - Heating (left) and Cooling (right) Energy Poverty Vulnerability Index (from Gouveia *et al.*, 2019)

The analysis conducted by Gouveia *et al.* (2019) is based on the assumption put forward by building thermal regulations that thermal comfort is assured when the entire dwelling useful area is permanently heated/cooled for 24 hours a day within the heating/cooling season. This could mean overestimating the EP vulnerability indexes and, consequently, the potential for its reduction. However, this is the way to bypass the subjectivity, cover and compare all regions of a country with the same consistent methodological approach, and arguably include even the most thermal comfort-demanding people in the analysis. On the other hand, as seen in Palma *et al.* (2019), even with lower requirements, actual energy consumption is still insufficient to match the theoretical energy consumption in multiple parishes, suggesting EP vulnerability is a reality for a considerable part of the population. This could mean that increasing energy consumption to fulfil energy services demand would be necessary, conflicting with the energy consumption reduction policies and targets at the national and European level, as Gouveia (2017) described. This proportion-based index is used to characterise regions (area-based). Thus, it does not indicate the amount of energy-poor people but rather the likeliness of finding vulnerable populations in a particular region. EP vulnerability equates to a probability associated with that specific region, rendering it a useful tool for comparing regions and checking the probability potential of each region. As is, this index contributes to overcoming one of the potential shortcomings in policy, which is the difficulty in identifying and pinpointing the most vulnerable areas to address to EP.

Notwithstanding this fact, it is crucial that policymakers also consider the amount of population living in each civil parish and municipality when using these results to cover the greater number of households and people in potential EP. Horta *et al.* (2019) provided an additional perspective on using the index, contributing to a deeper understanding of EP by combining the index mapping with interviews conducted with 100 households in ten vulnerability hotspots nationwide. Findings denote an acceptance of households regarding feeling cold or hot in winter or summer, which is a normal situation. These results are indicative of a lack of social recognition of the EP issue, which can exacerbate negative effects on the quality of life and health of the occupants. The study collects important direct feedback from the inhabitants of the most vulnerable zones, adding a more participatory qualitative dimension to it, which enables a more thorough analysis and understanding of the impact of EP in the population's daily lives.

The methods developed in these two research studies are employed in this study with a few modifications. The number of representative typologies of the building stock was increased to a total of 264 using energy performance certificate (EPC) raw data from the Portuguese National Energy Agency; thus, the computation of the building stock energy needs (identical to Palma *et al.*, 2019) is based on a more representative sample of building types, accounting for higher degrees of variability. The energy matrixes were replaced by the most recent national energy consumption survey from 2020 to update the shares of final energy consumption for each energy service and to estimate actual energy consumption for space heating and cooling per civil parish. The municipal energy consumption was also updated with the most recent data. This method was used to calculate the energy needs of the building stock before and after simulating energy renovation solutions and scenarios. The updated version was also integrated into the EPVI to estimate the impact of EE measures on EP vulnerability at the regional level. The EPVI also underwent small amendments, namely the replacement of the income indicator. The average individual gross income indicator was replaced with the median gross household income after taxes, as it arguably represents the household purchasing power of the region more accurately than the previous indicator. No significant changes in its structure were conducted, as it could jeopardise the scientific soundness and the meaning of the stakeholder participation process performed in the design phase.

1.6 Thesis Outline

This thesis is developed in eight chapters, including the Introduction, State of Art, Case-study description, and General Discussion and Conclusions. Figure 1.8 presents a schematic of the research and the thesis organisation. It describes the chapters (Chapters 4-7) that depict the different scientific publications and research contributions and indicates the correspondence between the chapters and the RQs addressed. The arrows indicate the interconnection and knowledge flows between the different chapters.

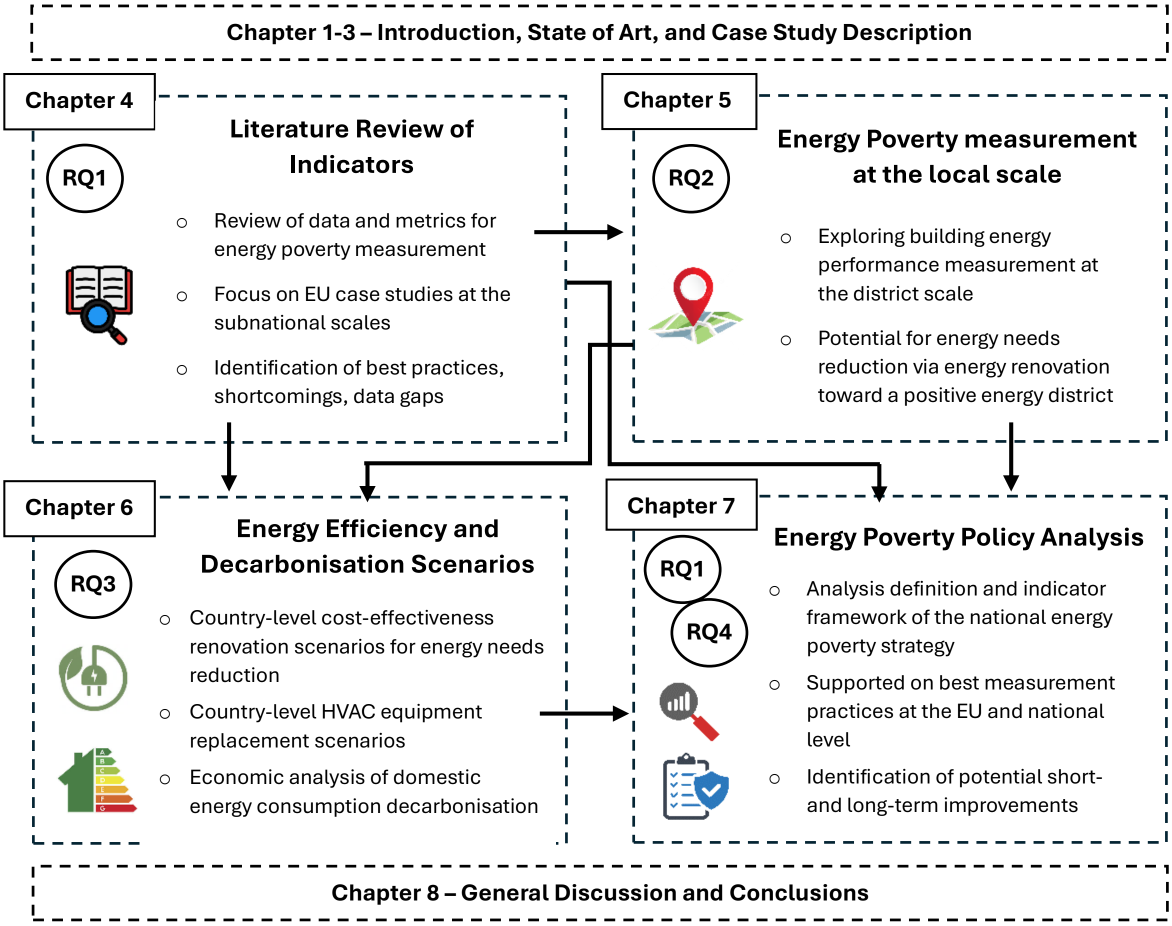

Figure 1.8 - Thesis structure schematic

The chapters are described individually as follows:

Chapter 1 introduces the thesis, drawing out the context that creates global inequalities and scarcities such as EP. It defines the problem, presents the objectives and the RQs, and outlines the research approach and foundational research that provides the basis for the research developed in this thesis. It also identifies the different scientific outputs of this research.

Chapter 2 presents the state-of-the-art EP knowledge, focusing on its different dimensions, the causes and effects, the types of measurement indicators, and the types of mitigation actions. It also sets the scene regarding EP in the EU, focusing on the current situation and the history of policy addressing this issue.

Chapter 3 defines the problem and presents an overview of EP in the case study of Portugal, focusing on the current situation regarding the different causes and effects of EP in the Portuguese population, and existing policy strategies and instruments to mitigate it.

Chapter 4 presents a structured literature review of EP metrics in the EU at subnational scales. It identifies the different indicators, measurement approaches, and datasets to identify the most common and innovative approaches for EP diagnosis, the different application cases, strengths and shortcomings, and data gaps. It aims to collect valuable learning to support policymakers at the regional and local levels in their EP mitigation policy and action. It directly addresses RQ#1.

Chapter 5 explores EP measurement at the local scale by adapting the method employed by Palma *et al.* (2019) to analyse a structural aspect of EP, the building energy performance, at the neighbourhood level in a historical district of Lisbon. It assesses the potential for energy needs reduction through building EE measures and rooftop solar photovoltaic production, estimating required investments and discussing forms of policy action to promote this transformation. It contributes to RQ#2.

Chapter 6 delves into country-level solutions to foster the energy transition in the domestic sector, namely through the increase of energy performance of buildings, EE of equipment and decarbonisation of energy consumption. Three different studies are presented. Firstly, an analogous method to Palma *et al.* (2019) is applied to a wide number of building typologies representing the entire building stock to calculate space heating and cooling energy needs before and after renovation measures, collected via a market inventory of measures. Different renovation scenarios are simulated to analyse the level of energy performance enhancement and the cost-effectiveness of the different alternatives. Secondly, the EPVI from Gouveia *et al.* (2019) is used to assess the regional impact of a full-scale space heating and cooling systems replacement, according to an EE rate increase of the existing equipment stock scenario and a national carbon neutrality 2050 scenario. Finally, an economic analysis of the cost of decarbonising the whole domestic energy consumption is presented. It focuses on the replacement of energy-consuming systems for the phase-out of fossil fuel consumption, curtailment of biomass, increase of renewable energy systems and promotion of EE. It addresses RQ#3.

Chapter 7 presents a comparative analysis of Portugal and Spain's national EP mitigation strategies. The analysis focuses on the diagnosis component, namely the definition and measurement frameworks proposed in each strategy. It leverages literature reviews on the EU and national levels, focusing on metrics and also reviewing definitions, to propose improvements in both strategies. It contributes to RQ#4.

Chapter 8 introduces the thesis's General Discussion and Conclusions, integrating and analysing the different outcomes of the previous chapters in the broader context of EP and energy transitions in Portugal and the EU. It highlights this thesis's contributions to policymakers and outlines the proposed answers to the RQs, limitations, and avenues for future research work.

1.7 Scientific Output

The research work conducted in the context and scope of this doctoral thesis resulted in several scientific outputs, such as peer-reviewed papers, international reports, book chapters, and conference presentations, listed below:

Publications:

- Gouveia, J. P., Seixas, J., **Palma, P.**, Duarte, H., Luz, H., Cavadini, G. B. (2021). Positive Energy District: a model for Historic Districts to address Energy Poverty. Frontiers in Sustainable Cities. Sec. Urban Energy End-Use, Volume 3. https://doi.org/10.3389/frsc.2021.648473
- **Palma, P.**, Gouveia, J, P. Mahoney, K., Bessa, S. (2022). "It starts at home: Space heating and cooling efficiency for energy poverty and carbon emissions reduction in Portugal." People, Place and Policy. 1-20. https://doi.org/10.3351/ppp.2022.5344968696
- **Palma, P.**, Gouveia, J. P., & Barbosa, R. (2022). How much will it cost? An energy renovation analysis for the Portuguese dwelling stock. Sustainable Cities and Society, 78. https://doi.org/10.1016/j.scs.2021.103607
- **Palma, P.**, Barrella, R., Gouveia, J. P., & Romero, J. C. (2024). Comparative analysis of energy poverty definition and measurement in Portugal and Spain. Utilities Policy, 90. https://doi.org/10.1016/j.jup.2024.101770

Manuscripts for future publication:

- **Palma, P.**, Gouveia, J.P., Climaco, N. (nd). Viability Analysis of decarbonising energy consumption in residential buildings. To be submitted.
- **Palma, P.**, Karpinska, L., Gouveia, J.P. (nd). Energy Poverty at High-Resolution Spatial Scale in Europe: Review of Metrics and Datasets. To be submitted.

Published reports:

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2

State of the Art on Energy Poverty Knowledge and Practice

2.1 Understanding Energy Poverty Diagnosis and Mitigation

2.1.1 Definition and conceptualisation

Several definitions of EP have been proposed. It is generally defined as 'the inability of households to access socially and materially necessitated levels of energy services in the home (Bouzarovski, 2014). It has been historically used to describe the lack of access to clean fuels in Global South countries due to low levels of networked energy provision, such as electrification. It is caused by economic underdevelopment and affects all energy services in the house, such as lighting, cooking, space heating and cooling, and electrical appliances (Bouzarovski and Petrova, 2015).

In the Global North, it emerged to describe energy affordability problems, having been initially referred to as "fuel poverty" (Chan and Delina, 2023), affecting mainly the provision of space heating and cooling in the household, but also cooking, lighting and appliance end energy-use (Bouzarovski and Petrova, 2015). Currently, researchers in this geography also describe it as EP, and both terms are used interchangeably. Nevertheless, the different expressions of this problem are not geographically exclusive, and they can be found in the same regions or countries, hence the need to overcome the existing accessibility-affordability divide (Chan and Delina, 2023). The EU currently defines EP in the recent recast EE directive (EU/2023/1791) as " 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 energy efficiency of homes".

Other concepts besides EP and fuel poverty have been used to describe identical conditions, such as inter alia, "energy deprivation", "energy precariousness", and "energy precarity". Some refer explicitly to symptoms such as 'energy non-payment', 'cold homes', or 'energy disconnection' (Bouzarovski, 2014; Petrova, 2017), arguably narrower in scope (Bouzarovski, 2018). It is important to single out some of these concepts and draw their relationship and distinction to EP. Energy vulnerability has been used to describe a similar condition to EP (Okushima and Simcock, 2024; Numminen *et al.*, 2024). However, energy vulnerability is often regarded as a framework for thinking and analysis. In the energy context, EP is described as a state within a temporal frame, and vulnerability is defined as the set of conditions that create that state (Bouzarovski, 2013; Hall, Hards, and Bulkeley, 2013). It is a probabilistic framework, representing the likelihood of households becoming energy-poor, given that the circumstances that create the problem may change within the temporal frame, potentially leading to a worsening of EP or even to the exit from this condition in the future (Middlemiss &

Gillard, 2015). This system thinking contributes to a theorisation of EP beyond affordability-access and even beyond the triad of energy prices, built environment, and income (Bouzarovski, 2018), which has been the most common approach. Bouzarovski and Petrova (2015) and later Thomson *et al.* (2017) present a vulnerability framework to analyse EP by defining six different factors (Access, Affordability, Flexibility, EE, Needs, and Practices). Broadening the scope of analysis with a vulnerability analysis or other types of system analysis unveils EP more clearly as a social-spatial condition at the nexus of physical characteristics of place and space, economic scarcities and inequalities, political decisions and commitment, organisational practices, as purported by Bouzarovski (2018).

Energy inequality can also be conflated with EP, as these terms are used interchangeably (Volodzkiene and Streimikiene, 2023), but an important distinction must be examined. EP is often conceptualised as a problem of absolute nature (Romero *et al.*, 2018), describing a situation where a household or citizen is not able to access adequate levels of energy resources or services, independently of the condition of the population. On the other hand, energy inequality is a concept of relative nature, as it is characterised by an unequal distribution or access to energy resources within a population (Chen *et al.*, 2022) with potential implications for EP and access to adequate energy levels. Inversely, EP may be caused by problems of resource inequality. Hence, the two concepts are interlinked despite their different nature. It is important to mention a particular form of inequality designated inequity, which has not been analysed in depth regarding this subject matter. It also refers to an unequal distribution of resources due to an unjust power balance, often resulting from injustices against disadvantaged or excluded population groups (Hasty *et al.*, 2024). In this context, where access to similar levels of energy services can be perceived as equality, if different needs are involved, it would constitute inequity, as the same level would not satisfy basic needs equally. Energy inequality is also linked to energy insecurity within the broader concept of energy justice. Energy security can be analysed at national and household levels. Whereas in the national level, it refers to energy supply and price stabilisation (Lee *et al.,* 2022) in the context of the households' struggle to afford energy bills and their exposure to dangerous energy services, confronting them with choices to balance all the essential needs (Chen *et al.*, 2022; Lee *et al.*, 2022). It is closely connected to EP, but it can be argued that it has a broader span since it can be used to describe not just the state or condition of being energy-poor but also the state of being at risk of EP and risk of physical harm, an aspect more closely linked to EP in the Global South.

The analysis of energy systems through the lens of justice theories has been the focus of an increasing body of work in research, materialised in the concept and frame of energy justice (Jenkins *et al.*, 2016). It is thus relevant to analyse EP in the framework of energy justice to investigate potential connections that can shed light and uncover other relevant aspects to the problematisation of this condition. The ethical aspects of energy systems are often imprinted in a tenet-based energy justice framework. Distributive, procedural, and recognition justice are the most common tenets (Heffron and McCauley, 2014). Distributional justice is often defined as the need for a just distribution of benefits and ills. Procedural justice states that all stakeholders should be able to participate in a non-discriminatory way in the decision-making process. Recognition justice recognises the need to respect individuals' social, cultural, ethnic, racial and gender differences. They must be free from any forms of degradation, threat, or insult and have equal political rights (McCauley *et al.*, 2013; Uffelen *et al.*, 2024). Other principles have arisen in literature, such as restorative justice, which describes the need to repair the harm done instead of focusing only on punishment (Heffron and McCauley, 2017). Cosmopolitan justice refers to citizens' responsibility and moral obligation for the well-being of others, regardless of borders (Phillips, 2023). Timmermann and Noboa (2022) also propose the principle of energy sovereignty. It describes the right of citizens and communities to have a degree of self-determination and non-domination that enables them to be in control of their energy sources and systems.

Sovacool *et al.* (2016) propose a different energy justice framework based on eight core principles: availability, affordability, due process, transparency and accountability, sustainability, intra-generational equity, inter-generational equity, and responsibility. Availability is the sufficient high-quality energy resources that people deserve; affordability refers to the fact that energy services should not be a financial burden for consumers; Due process is the upholding of legal rules and human rights in the provision and use of energy; Transparency and accountability emphasise that people should have access to reliable information about energy, environment and the decisions regarding the two spheres; Sustainability mentions that energy resources should not be depleted too quickly; Intra and intergenerational equity are the right to access the required energy services for a good standard of living, for all contemporary citizens and also future generations. Finally, responsibility refers to protecting the natural environment and reducing ecological harm. The two frameworks are presented in Figure 2.1.

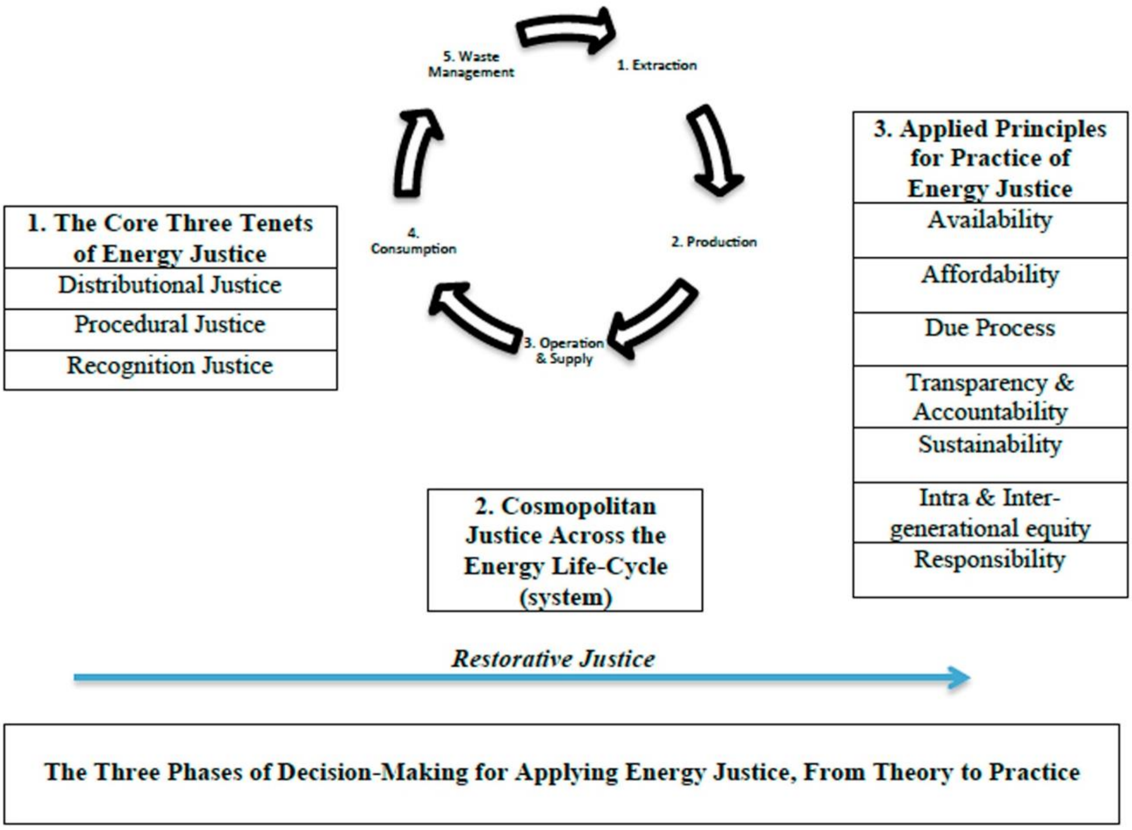


Figure 2.1 - Energy Justice frameworks (from Heffron and McCauley, 2017)

These analytical frameworks, which focus on ethical and justice concerns, provide valuable insights into the study of EP. Walker and Day (2012) affirm that EP can be understood as a situation of injustice, situating it as a conflict of distributional justice while recognising that other types of injustice can also play a key role in producing inequalities in energy access. The authors point out that tackling EP should address problems of cultural and political recognition of vulnerable and excluded groups and seek to provide them with the deserved procedural justice, enabling them to fully participate in energy decision-making. Within the framework of Sovacool *et al.* (2016), EP directly results from not respecting the availability and affordability principles. Still, the other principles also have implications for creating and perpetuating this condition. However, these frameworks have limitations, particularly regarding their account of power relations and responsibilities in the energy system, their prescriptive and top-down nature, which can lead to overlooking certain types and aspects of injustice, and the lack of description of ethical theories and description of the different injustices (Middlemiss *et al.*, 2019; Wood and Roelich, 2020; Velasco-Herrejon and Bauwens, 2020). Szulecki (2018) proposes to include the normative goal of "energy democracy" to address the problem of power distribution.

The Capabilities Approach (Sen & Hausman, 2007) is another framework that can be used to conceptualise EP, with a focus on well-being and human flourishing rather than just on material wealth, considering both the objective and subjective factors that determine it

(Shortall and Mengolini, 2024). It acknowledges people's different needs and its varying prioritisation of well-being aspects (Velasco-Herrejon and Bauwens, 2020). Day *et al.* (2016) use the Capability Approach to conceptualise energy use and EP, framing it as a state of reduced capabilities, as described by Middlemiss *et al.* (2019) and Bartiaux *et al.* (2021). Day *et al.* (2016) draw out the different elements and their relationship that link energy to its intended purposes for a good standard of living (Figure 2.2). Domestic energy carriers stem from energy sources and provide energy services, enabling secondary capabilities, which are concrete actions necessary to achieve basic capabilities, such as maintaining good wealth and social inclusion and relationships.

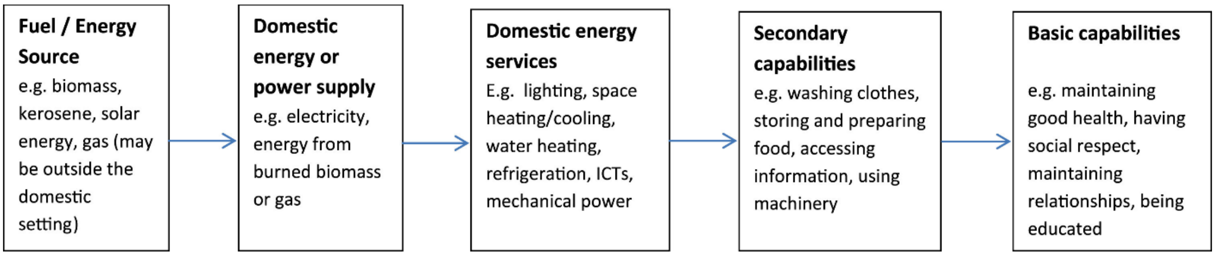


Figure 2.2 - Day *et al.* (2016) conceptualisation of the relationship between energy, services and outcomes

The Capabilities approach provides a wide variety of factors that should be considered to understand EP while unveiling the different association between justice concerns. It deconstructs conceptions of energy use and well-being underpinned by particular cultures and norms.

These different frameworks are, therefore, complementary and can help overcome existing shortcomings in each for a more pluralistic approach (Wood and Roelich, 2020). Confronting the concept of EP with all the tenets of the energy justice and well-being frameworks, as well as the other energy concepts aforementioned, broadens the reflection and understanding of the underlying causes, drivers and consequences across temporal and spatial scales, and the potential connection with other energy and climate-related goals and forms of hardship.

2.1.2 Causes, Drivers and Effects

In the global North, EP is generally considered to be the result of three leading causes: low incomes, high energy prices, and inefficient buildings, including the Heating, Ventilation, and Air-Conditioning (HVAC) systems (Garcia *et al.*, 2009; Pye *et al.*, 2015; Dobbins *et al.*, 2019). Low incomes and high energy prices are directly related to the problem of affordability and restraining access. Lack of EE determines higher energy demand for providing the required energy services and unnecessarily high energy consumption needs. Nevertheless, the complexity and multidimensionality of EP are not reduced to only these three causes. It is agreed that EP requires a wider and more comprehensive analytical framework (Thomson *et al.*, 2017a, b; Sareen *et al.,* 2020; Lowans *et al.*, 2021). Other factors or conditions can be relevant to the occurrence and rise of EP, shaping its configuration, such as household characteristics and vulnerabilities, education and literacy, sociocultural norms, climate, sociopolitical context and governance, territorial aspects (Bouzarovski, 2014; Bouzarovski and Petrova 2015; Hitchings *et al.* 2015, Middlemiss, 2022; Certomà *et al.*, 2023; Dokupilova *et al.*, 2024). Despite some level of overlap between EP and income poverty, it is recognised that housing EE is an important component of the problem, creating additional challenges and shifting its nature from one purely based on budget constraint and purchasing power (Bardazzi *et al.*, 2024). In fact, a household may have an average wage but still be energy-poor if this wage is not enough to pay the necessary energy services.

Conversely, not all income-poor households are necessarily energy-poor (Bouzarovski, 2014). In her review, Middlemiss (2022) identifies the specific social groups more likely to experience EP in the Global North. These are the following:

- Low-income households
- Unemployed adult in household
- People with limited education
- People from ethnic minorities and Indigenous people
- Immigrants
- Near-elderly or older people
- People with disability
- Women
- Young people and full-time students
- Single parent families
- Socially isolated people (infrequent family contact) or people living alone
- Large household size
- Multioccupancy/family

Martiskainen *et al.* (2021) also identified households living in older or insulated homes; Riva *et al.* (2021) describe renters and households living in rural areas as also more susceptible to EP. These special groups are often hard-to-reach energy users, meaning they are "hard-to-reach physically, underserved, or hard to engage or motivate in behaviour change, EE and demand response interventions" (UsersTCP, 2024). These are often consumers in a situation of disadvantage and with poor representation in policy (Mundaca *et al.*, 2023). Engagement with these consumers requires more than targeted strategies. It also requires greater involvement with co-creation efforts and the inclusion of trusted middle actors before and during the intervention (Ashby *et al.*, 2020).

One of the most direct consequences of EP is the financial stress due to the inability to pay the energy bills. Not only low-income households face this issue, but households with unstable incomes and those in debt (Middlemiss and Gillard, 2015). This situation can result in coping mechanisms such as incurring debt, carefully budgeting energy to avoid high energy bills (Brunner *et al.*, 2012), or trading off energy costs with costs of other basic needs such as food, transport, and medication (Brunner *et al.*, 2012; Bartiaux *et al.*, 2021).

Lack of adequate energy services can translate into a situation of thermal discomfort (Parsons *et al.*, 2014), which subsequently can progressively escalate to serious health issues such as mental health issues, psychosocial stress, heat/cold stress, arthritic and mobility issues, allergies and dermatological issues, suppressed immune function, pulmonary, respiratory, cardiovascular diseases and consequently increased excess mortality (Liddell *et al.*, 2015; Atsalis *et al.* 2016; Jessel *et al.* 2019). These effects can also be caused by poor air quality and exposure to hazardous chemicals and materials (Kez *et al.*, 2024).

The most vulnerable groups are more likely to be affected by the cold or heat (Middlemiss, 2022). EP can also have social consequences, such as stigmatisation and social isolation (Oliveras *et al.*, 2020). Limited or inexistent leisure activities or holidays, poor relationships with landlords and energy companies, and a feeling of powerlessness and reduced agency have also been identified as effects of EP (Middlemiss *et al.*, 2019; Bartiaux *et al.,* 2021). Living in EP affects people's cognitive resources, making decisions more susceptible to biases, such as the preference for smaller and faster rewards in contexts of scarcity (DellaValle, 2019). It also causes less serious issues, like loss of work productivity due to uncomfortable temperatures and deterioration of material possessions due to potentiating the presence of mould and humidity, which can cause a drop in economic value.

EP can be mapped and decomposed using the Problem Tree Analysis approach (ASHOKA, 2020), where each component represents a different part of a tree: the roots, representing the main causes; the trunk, representing the big problem; and the crown and leaves, representing the consequences (Figure 2.3). One more component can be added to this representation - the underlying systems (perhaps analogous to the soil in this metaphor), which are the standing paradigms behind the root causes that perpetuate and prevent the problem from being resolved. These systems are complex to change and can have different natures, such as technical, cultural, legal, educational, political, infrastructural, social, and economic, often converging several. Social inequality, climate change impacts, underpaid jobs, overbearing energy taxes, lack of adequate infrastructure, lack of political commitment, lack of environmental awareness, and lack of knowledge are just a few examples of underlying systems that can create the conditions for the problem.

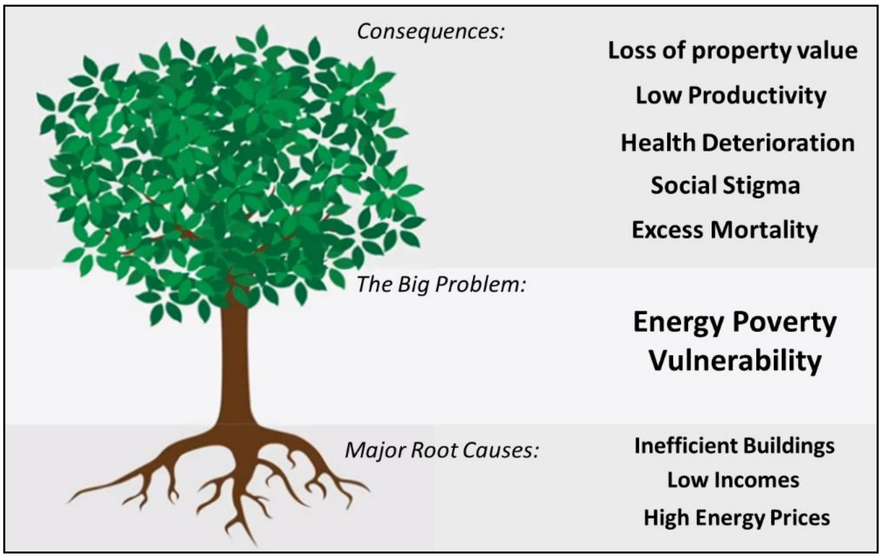


Figure 2.3 - EP Problem Tree (adapted from ASHOKA, 2020)

2.1.3 Energy Poverty Measurement and Indicators

Measuring and monitoring EP are crucial for studying and understanding the nature and scale of this condition. It should be the foundation for any efforts focused on tailoring evidenced-based policy strategies and schemes, setting and evaluating mitigation targets, and assessing the impact of policies, both prior to and after the implementation (Vondung and Thema, 2017; Tirado-Herrero, 2017). EP is difficult to measure due to its causal multidimensionality, the variability of its expression over space and time, and its private nature (Thomson *et al.*, 2017b). Therefore, the choice of indicators is crucial for adequately identifying the energy-poor, and should consider the context, scale, and data availability (Thomson *et al.,* 2017a). Indicators can be classified according to aspects such as objectiveness and subjectiveness, object of measurement (causes, drivers or outcomes), category, type, outcome, comparability, robustness and quality, and data availability (Rademaekers *et al.*, 2016). According to several experts (Rademaekers *et al.*, 2016; Thomson *et al.*, 2017a; Tirado-Herrero, 2017), when considering their type, indicators can be divided into three different approaches:

- Consensual-based approach, consisting of self-reported experiences and assessments by the occupants regarding thermal comfort or other housing conditions inside their homes, as well as the ability to afford and guarantee the basic energy services.

The most known examples of this kind of EP indicators are the nationally conducted European Union Survey on Income and Living Conditions (EU-SILC) indicators, presented in the Energy Poverty Advisory Hub dashboard (EPAH, 2024a), such as the "Share of population not able to keep their home adequately warm", "Share of population having arrears on utility bills"; and "Share of population with leak, damp or rot in their dwelling". These indicators provide personal accounts that can depict the causes but also the effects of EP in their daily lives, gauging the individual experience and burden in a bottom-up and arguably more democratic process. These indicators are easier to collect and can capture a wider set of elements, such as social exclusion and material deprivation (Healy and Clinch, 2002; Thomson *et al.*, 2017). On the other hand, their subjectivity results in errors of exclusion, as households may not report the reality of their situation (Thomson *et al.*, 2017; Tirado-Herrero, 2017). Also, underlying assumptions based on which these indicators are designed can result in errors, as they may not consider important particularities of certain households' reality, as well as cultural differences in the perception of affordable warmth and other energy services (Tirado-Herrero, 2017).

- Expenditure-based, where domestic energy expenditure or the share of income spent on energy on expenditure is compared to a defined threshold of EP. Depending on the threshold, a household is considered energy-poor if the expenditure is above (abnormally high expenditure) or below the threshold (abnormally low expenditure).

This method was first introduced by Boardman (1985), who defined as fuel poor the household whose fuel expenditure of all energy services surpassed 10% of the income, a threshold representing at the time twice the median expenditure. Variations of this method have been adopted subsequently in the devolved nations of the United Kingdom (UK) (Moore, 2012; Mahoney *et al.*, 2020). The threshold can be based on an absolute or relative measure. In an absolute measure, the threshold is a fixed percentage of the income spent on energy, whereas a relative threshold is based on a median or average energy burden (Thomson *et al.*, 2017a). Relative thresholds vary with the fluctuation of energy cost, therefore becoming a changing target. EPAH proposes two expenditure-based relative threshold indicators to evaluate EP: The "Low absolute energy expenditure" (M/2) indicator and the "High share of energy expenditure in income" (2M) indicator (EPAH, 2024a). The M/2 is an indicator that captures abnormally low energy expenditure, consisting of the share of households whose absolute energy expenditure is below half the national median. The results of this indicator can have two main interpretations: it can be due to the high EE of the building but also due to underconsumption. Inversely, the 2M indicator captures abnormally high energy expenditure. It represents the percentage of households whose share of energy expenditure in income is more than twice the national median share. Another example of a commonly used expenditure-based indicator is the "Low-Income High Costs (LIHC)". This is a dual indicator, under which a household is considered energy-poor if they have an energy expenditure above the national median and the remaining income after spending that amount is below the official poverty threshold (DECC, 2016). This method measures the extent of the problem, *i.e.* the amount of fuel energy-poor households, and the magnitude of the problem, *i.e.* how bad the fuel poverty of each household is.

The shaded area represents the energy-poor area, where households with higher than the median energy costs are below the poverty income threshold. The difference between the required energy costs and the closest threshold is the "fuel poverty gap", representing the magnitude (DECC, 2016). This was the official indicator for measuring EP in the UK but has been replaced with a modified alternative called Low-Income Low Energy Efficiency (LILEE). LILEE has a similar structure but identifies a household as energy-poor is energy-poor if it lives in a home with an EE rating of band D, E, F or G and its disposable income (after housing and energy costs) falls below the poverty line. Figure 2.4 displays the LIHC and the LILEE metric. There are several other expenditure-based indicators, each with its advantages and drawbacks. Others will be addressed and discussed later on in this document.

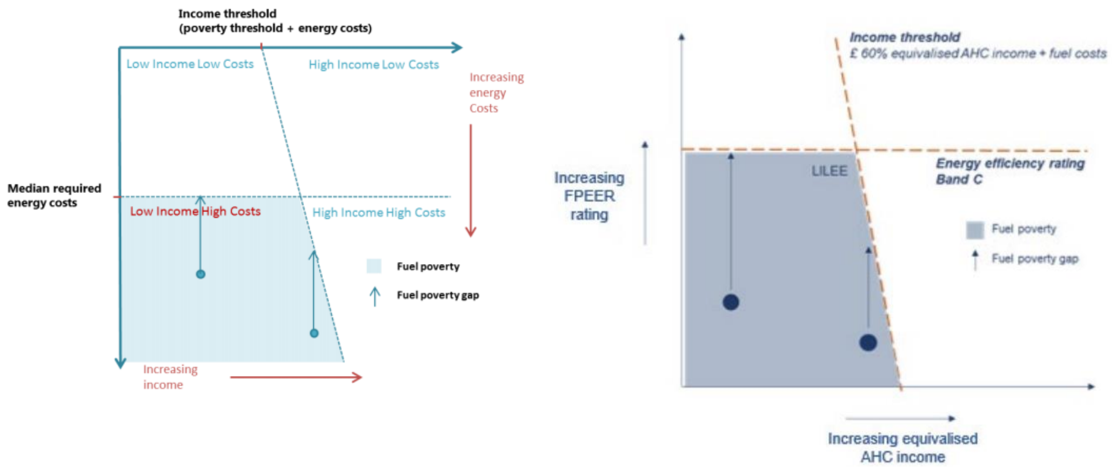


Figure 2.4 - The “Low Income High Costs” from (DECC, 2016) and “Low Energy Efficiency High Costs" indicators (from DESNZ, 2024)

Expenditure-based metrics offer an objective quantifiable estimative of this condition, which can be easily transferred and compared across households and contexts. However, there is an argument for the limited objectivity of these indicators due to the range of assumptions they are built on, namely the use of actual vs required energy expenditures, equivalisation of income and energy expenses, the inclusion of housing costs and the choice of threshold (Tirado-Herrero, 2017). In fact, the meaning of thresholds is debatable and can often lead to misleading identification of households and characterisation of households' energy needs (Thomson *et al.*, 2017a). In their technocratic nature, they reduce this condition to a number, oversimplifying it and applying the principle of "one size fits all", which is particularly problematic since there are people with higher degrees of vulnerability and requiring more energy (Snell *et al.*, 2015).

- Direct measurements are indicators based on comparing domestic energy services consumption versus a required set value. This method generally requires using temperature as a proxy to discern if households are maintaining comfortable temperatures. For that purpose, a reference comfort temperature is used, such as the World Health Organisation (WHO) standard of 18°C–21°C (WHO, 1987) or the ones set in the national regulations. Energy services consumption can also be used in this approach.

There are often practical constraints regarding the measurement and collection of temperature and energy services datasets, which hinder the employment of this approach for EP assessment. The selection of an appropriate standard can also constitute a difficulty, as thermal comfort has a subjective nature, varying according to geographical, climatic, cultural, and psychological conditions (Healy, 2004). As Thomson *et al.* (2017a) described, this method is rarely applied to EP assessments, being used more frequently for thermal conditions in dwellings. Cong *et al.* (2022) applied an approach that can be considered a direct measurement, using outdoor temperature data to identify when households turn on their cooling system, called the inflection temperature. The authors identified two groups of households according to their inflection temperature and considered the low-income households with higher inflection temperatures to be energy poor. Alternatively, together with income levels to avoid misidentification, Okushima (2019) and Kahouli and Okushima (2021) also used energy services use and a relative energy use threshold to identify energy-poor households.

Rademaekers *et al.* (2016) consider another approach, the outcome-based approach, using indicators that portray EP effects such as arrears and disconnections or health outcomes, such as winter excess mortality. The individual separation of this approach is not consensual in the literature, as consensual-based approaches can, for instance, include outcome assessment.

Supporting indicators can also be applied in an EP assessment study, particularly to depict the different aspects that influence the issue. These indicators individually do not describe EP, nor are they fit to measure it, but put together, they paint a picture of the context that might be creating the vulnerability, therefore being potentially valuable for helping target policy action. They can fall under several categories: Demographics, Energy demand, Income/expenditure, Outcomes, Physical infrastructure, and Policy-based (Rademaekers *et al.*, 2016). Examples of these indicators are energy prices; housing costs; final energy consumption and expenditure; excess mortality rates; at-risk of poverty and social exclusion rates; heating and cooling degree days; number of rooms per person; dwellings in densely populated areas; dwellings equipped with air conditioning, dwellings equipped with a heating system; household size; type of family; urban/rural; available income; number of children; number of elderly people; ownership of the dwelling (Rademaekers *et al.*, 2016; EPAH, 2024a).

- Multidimensional Metrics

The multidimensionality of EP is not easily captured by a single indicator, which has led to different authors following a more integrative perspective, highlighting the importance of considering a broader range of indicators or a combination through an index development. Several authors (such as Thomson *et al.*, 2017; Tirado-Herrero, 2017; Sokolowski *et al.*, 2020; Bardazzi *et al.*, 2021) defend using a range of indicators to measure EP. Framed as an energy vulnerability, each of the six vulnerability factors (access, affordability, flexibility, EE, needs and practices) can be expressed as a cause, driver, or outcome of EP, which on its turn may be portrayed using an indicator (Thomson *et al.*, 2017a). By combining these indicators, a composite or multidimensional index may be created. Depending on the context, some factors might be more relevant than others, or particular factors might not be the cause of vulnerability in that specific context, therefore not being included in the assessment. An adequate approach would entail a combination of drivers and outcomes, for a detailed assessment of EP (Thomson *et al.*, 2017a).

Nevertheless, it is difficult to reflect the diversity and complexity of EP using statistics without flattening the analysis and missing relevant details and aspects (Thomson, 2020). Several authors have proposed approaches that combine more than one indicator, focusing on different causes, drivers or outcomes. The previously mentioned approach developed by Gouveia *et al.* (2019) is one example of a compositive index for Portugal, but several other authors have dedicated their research to developing other approaches:

Walker *et al.* (2012) created an area-based EP risk index, combining an analysis of the heating burden, the built environment characteristics and socioeconomic variables in order to assess EP at a high-resolution spatial scale for Northern Ireland. To estimate the heating burden, the authors computed the heating energy demand through the heating degree-day method, using daily sea level outside temperature data for a period of 10 years. The approach has the merit of addressing several dimensions of EP, utilising a considerable range of different indicators, though the indicators used to describe each dimension are often simple and have limitations for transferability.

Fabbri (2015) developed a composite EP index that aggregates population, dwelling characteristics and income indicators, energy prices, and data on building EPCs for 9 provinces in the Emilia-Romagna region. The Building Fuel Poverty Index (BFP) enables the quantification of how many buildings need direct action and/or just economic incentives. The index threshold method is similar to the ones applied in the LIHC. Just like Walker *et al.* (2012), the author captures several dimensions of the EP issue for a small area, and the analysis of each dimension is limited.

Okushima (2017) developed a multidimensional energy poverty index (MEPI), composed of three dimensions of EP for developed countries: energy costs, income, and EE of housing. The author defines a threshold of poverty for every indicator. Each indicator is attributed 0 or 1, according to being or not considered in deprivation. A household is in EP if the score is higher than a defined value. The data from a sample of 50 thousand households was used in this study. The author addresses the three main root causes of EP, but the building stock is analysed only through one indicator, building age, which is insufficient to describe EE. Income and expenditure data sources are also outdated.

Papada and Kaliampakos (2018) modelled the required energy consumption for space heating and cooling, domestic hot water and cooking, lighting and electrical devices at household level, using heating and cooling degree-days, and subsequently a stochastic analysis, the Monte Carlo method, at the national level, to estimate the EP rate in Greece. The authors analyse the phenomenon by applying a comprehensive methodology that crosses the path from household to country level, accounting for its multidimensionality. Although the authors use annual values of consumption and income to estimate the EP ratio, they do not conduct a time and space-specific analysis of each dimension, thus not providing insights at a regional scale.

März (2018) applied a geographic information system (GIS) Multi-Criteria Decision Analysis to identify vulnerable neighbourhoods to fuel poverty in the German city of Oberhausen, identifying three criteria that determine EP vulnerability - heating burden vulnerability, socio-economic vulnerability and building vulnerability. To estimate heating burden vulnerability, the author selected heating degree-days (HDDs) as one of the indicators to be analysed. The authors propose an area-based approach encompassing three important drivers of EP, but do not consider energy costs in the assessment. Furthermore, the weights of the indicators are decided on very limited expert inquiry (only six experts).

Meyer *et al.* (2018) developed the EP barometer for Belgium, which draws on a set of complementary indicators, using EU SILC data, to describe the multifaceted nature of EP: excessive energy bills compared to available income (measured EP), restriction in energy consumption below basic needs (hidden EP) and self-reported difficulties to heat the housing correctly (perceived EP). The authors present an indicator with potential for transferability. However, it has low spatial resolution and only relies on self-reported indicators, failing to consider climate variability, building characteristics, and other socioeconomic factors.

Castaño-Rosa *et al.* (2018) propose an index to assess EP in vulnerable homes based on a monetary poverty indicator, using available net income; an energy indicator, comparing simulated energy consumption required using building characteristics and the median energy consumption required for the type of building in the area of study; and a comfort indicator, using indoor temperature data. The authors used the quality-adjusted life-years (QALYs) method to establish this relationship between quality of life and occupants' health and define the index. The methodology is comprehensive but difficult to replicate, as it might require considerable adaptation according to the chosen case-study area.

Pino-Mejías *et al.* (2018) built two statistical models, multiple linear regression and artificial neural networks, to predict the probability of low-income households falling into fuel poverty when being allocated a social dwelling. The authors used energy price, income and energy use patterns data. The case study used to validate the model is located in the Bio-Bio Region of Chile, and only the most vulnerable households were considered. Predictive models show adequate effectiveness in predicting EP but only focuses on low-income dwellings, in the very specific context of allocation to a social dwelling.

Charlier and Legendre (2019) created a multidimensional approach that depicts the relationship between monetary poverty, residential EE, and heating restriction, for a sample of around 2300 households. The three dimensions are captured in a sub-indicator each, using disposable income data, energy consumption and housing temperature. The EP indicator is expressed as the cube root of the product of the three sub-indicators. It is based on regional surveys, not considering quantitative, measurable indicators.

Sanchez-Guevara *et al.* (2019) analysed the connection between heat exposure related to dwellings' energy performance and the Urban heat island effect and heat vulnerability related to socioeconomic indicators with the purpose of identifying energy-poor areas in the summer season for the case-study cities of Madrid and London. The authors used air temperature data, to calculate cooling-degree days, in order to evaluate the urban heat island effect. This study introduces an important component to EP studies - extreme climate events such as heat waves - whilst testing the methodology in two different cities, which led to the use of different indicators to evaluate the same aspects of EP in the two cities due to the lack of data. Energy costs are not considered in the vulnerability analysis.

Besagni and Borgarello (2019) based their approach on modelling energy consumption of different building archetypes and comparing it to the thermal energy expenditure reported in the national household budget survey, to measure fuel poverty levels, considering the socioeconomic dimension and geographic distribution in Italy. The authors used meteorological data to estimate the yearly heating energy requirements for 140 residential buildings, representative of the Italian building stock. The authors developed a comparable approach at the regional scale, encompassing a significant diversity of indicators to capture the different facets of winter EP and analyse them in the light of different sociodemographic profiles. It has the limitations of the methods rooted in the comparison between real energy expenditure with a standard, as it does not consider qualitative self-reported indicators of lived experience.

Martín-Consuegra *et al.* (2020) overlapped deprived neighbourhoods and inefficient buildings using indicators such as low schooling, high unemployment rates, and a heating energy demand for archetypal buildings and then created an index for the resulting zones, aggregating the indicators of low housing income, high energy prices, unheated dwellings, and vulnerable population (+65 years old). The index results from the accumulation of the indicators in a particular zone, where the maximum risk is represented by the accumulation of all indicators. The authors make use of GIS techniques to increase EP targeting but the indicators used to calculate the multidimensional index are simple, not capturing different EP expressions and profiles in the assessment.

2.1.4 Mitigation policy and measures

EP is a rising concern in Global North societies, with an already significant body of literature on this subject and also taking a more prominent position in the political agenda, with increasing awareness and action at the policy level (Kyprianou *et al.,* 2019; Feenstra *et al.*, 2021). The goal of mitigating EP is interconnected with other agendas such as decarbonisation of energy use and carbon neutrality, energy transition, and climate change, with considerable potential for synergies but also with divergences which create trade-offs and competition points (Mahoney, 2024). Pesch *et al.* (2023) state that potential conflicting goals between environmental protection and human development are resolved by developing a deeper understanding of the connection between energy and well-being. Transformations in the energy sector have been known to cause increases in hardship and inequality (Bouzarovski, 2018). Energy transition has an implicit connotation with a change toward a more favourable socially desirable state, but the shape of the vision is not consensual among practitioners and scholars, particularly regarding the process of decarbonisation (Bouzarovski, 2018). Energy provision is a multifaceted and multilayered phenomenon, crossing social and technical realms, translating into a complex interplay of political interests and institutional practices (Bouzarovski, 2018). Therefore, the structural and long-term transformation of energy systems is a complicated, sensitive, and conflictual process (Meadowcroft, 2009), whereby development is often non-linear and the outcome uncertain. The outcome scenarios can take several forms determined by the interactions between politics, technology, and social formations (Bouzarosvki, 2018). Fundamental aspects are, for instance, the political economies of the socio-technical transition, resource production and distribution, the role of the state and the ability of community-based initiatives, and the role of intermediary institutions (Meadowcroft, 2009; Bouzarovski, 2018). The impacts of a transition to a low-carbon or net-zero economy on more vulnerable citizens, such as the energy poor, is seen as a concern due to the risk of excluding and potentially furthering the existing condition of disadvantage (Middlemiss, 2022).

The dogmatic view purporting that higher energy consumption always equates to a better life and a higher level of human development is to be challenged (Pesch *et al.*, 2023). It can actually have the opposite effect, as the impact of energy provision contributes to climate change, which in turn negatively impacts human development (Tran *et al.*, 2019). On the other hand, it is necessary to recognise that there are segments of the population who do not have the necessary levels of energy consumption, which calls for a better distribution of energy resources. It is generally agreed that a fair energy transition requires the decarbonisation of the energy system with renewable energy technologies, but EE and energy sufficiency must also be cornerstones of this transformation. The latter concept emphasises the need for sufficient consumption, fulfilling basic needs for a decent standard of life, and that is sustainable, below ecological thresholds and within planetary boundaries as described by Rockström *et al.* (2009). Middlemiss (2022) defends an approach that recognises historical injustice and its causes (Golub *et al.*, 2013) and combines restorative justice with climate-positive change (or just transition) (Heffron & McCauley, 2017; X. Wang & Lo, 2021), where the first step consists in understanding more accurately the people's experiences in the present moment.

Several types of mitigation actions generally fall under energy policy, social policy, or a combination of regulatory solutions (Kez *et al.*, 2024). Population's needs, policy targeting, political commitment, amount of investment, and the larger socioeconomic and political environment are factors that significantly impact the effectiveness of policies (Kez *et al.*, 2024). Demand-side interventions, aiming to reduce energy needs, are seen as adequate solutions for a more equitable distribution of energy resources (Millward-Hopkins *et al.*, 2020; Kikstra *et al.*, 2021). Supply-side intervention can also have an important role in EP mitigation, namely via energy market regulation and price control and incentives for renewable energy technology. Theorising EP mitigation policy through the lens of a system change analysis framework (ASHOKA, 2020) can yield useful insights.

When addressing a particular problem, three approaches can be employed (Figure 2.5). It is possible to tackle the consequences, or in other words, the symptoms of the problem, which implies a direct relationship between the resources and solution employed and the impacts, without resolving the causes, therefore not stopping but mitigating the issue. On the other hand, the goal can be to tackle the causes by changing the system responsible for them. This strategy implies a shift in the underlying dynamics that create the problem, enabling the production of different outcomes and, therefore, having a bigger scope. It can mean unlocking new resources, introducing or getting rid of new elements, changing roles and relationships, improving information flows, or changing the rules. Finally, there is another possible strategy: the frame change, which is a change in mindset, creating different new systems that slowly replace the ones that are in place, as these become obsolete. All these strategies can be useful, depending on the problem and circumstance. Direct approaches to tackle symptoms provide short-term solutions with easier-to-measure outcomes, whilst system and mindset changes are long-term higher-impact solutions whose outcomes are more difficult to evaluate (ASHOKA, 2020).

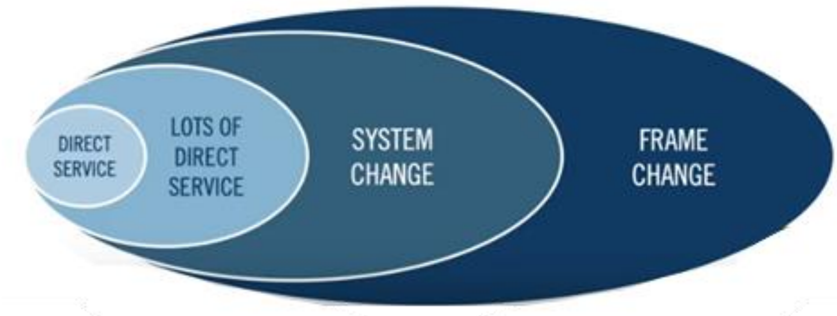


Figure 2.5 - Comprehensiveness of the system change approach (adapted from ASHOKA, 2020)

To conduct an overview of policies and measures directly or indirectly targeting EP mitigation, Kyprianou *et al.* (2019) categorise mitigation measures into four major types:

1) Financial Interventions;
2) Consumer Protection;
3) Energy savings measures, including EE and renewable energy sources (RES);
4) Information Provision.

Financial interventions are based on payments or subsidies to vulnerable consumers, typically identified through welfare services. Consumer protection focuses on access and affordability via special discounted tariffs or protection from disconnection to energy access. Energy savings measures are actions to promote EE and the use of renewable technologies, often through subsidies in the form of grants or loans. Information provision measures, such as campaigns, one-stop shops, energy cafés, and energy advice, are dedicated to increasing knowledge and awareness about EP and possible solutions to tackle it.

The authors state that the former two types of support constitute symptom-targeted short-term measures rather than more permanent solutions. This argument is corroborated by Schumacher *et al.* (2015), which affirms that social tariffs, debt time extensions, discounts and disconnection suspensions are short-term remedies and not sustainable policies in the long term, not addressing the underlying root causes of EP. Nevertheless, they can be vital to avoid cutting households off basic needs and in situations of deep hardship, where emergency action needs to be deployed in the very short term to avoid significant negative impacts on the household.

On the contrary, EE promotion is seen as a more structural approach that addresses underlying systems that create the problem. They reduce energy demand and potentially energy consumption and GHG emissions, ensuring long-term impact. EE measures are considered the most effective for EP reduction (Boardman, 2013). They enable people to have the same level of energy services with less energy consumed, resulting in reduced energy bills granted there is no rebound effect (Eisfeld, 2024). Several authors have assessed the effects of energy retrofit measures on buildings' energy demand and consumption, spanning different spatial scales and contexts, as well as in various types of buildings (Thomsen *et al.*, 2016; Lazzeroni *et al.*, 2017; Liang *et al.*, 2018; Gouveia and Palma, 2019). These studies support the case for the adoption of retrofit measures as an effective solution for energy needs and consumption reduction and, consequently, for climate change mitigation, increased thermal comfort and reduced indoor air quality problems. There are constraints related to the investment and uptake of building renovation measures, such as the split incentive issue (Bertoldi *et al.*, 2020) concerning the implementation of retrofit measures: either tenants are dependent on landlords who lack the financial capital or the incentive to improve the energy performance of a dwelling whose bills they are not paying; or tenants, whilst not being responsible for paying the energy bills, have little incentive to save energy. This dissonance of incentives can be a significant bottleneck for building renovation interventions. Therefore, vulnerable owners and tenants often need support, relying on public finance (BPIE, 2014). The attribution of non-repayable grants and premiums is generally the most common approach of support schemes, as energy-poor people are likely not to be creditworthy borrowers to qualify for loans and often are not willing to take on further debt. Zero interest-rate loans have proven effective in promoting improvements in the energy performance of buildings and improving occupants' health indicators in particular cases where the loan can be paid with the energy savings resulting from the retrofit, although not targeting specifically energy-poor households (BUILDUP, 2017).

Renewable energy subsidies also fit in this category of measures, as they allow consumers to partially or fully own and control the means of electricity production in their homes, not only reducing energy bills but also empowering them as consumers. In the case of collective production and association, they can help energy-poor citizens have a more central role in energy decision-making processes and promote community inclusion and participation, helping pave the way from passive consumerism to active energy citizenship (DellaVale and Czako, 2022). Information and awareness constitute another kind of measure that can be relevant to tackle EP in a different way by increasing awareness and the ability of consumers to make the right decisions regarding their behavioural actions, technological options and energy plans.

EP measures can be analysed in light of the energy justice frameworks to understand if they have embedded any type of injustice or effectively work towards mitigating or eradicating inequalities and deprivations. Day *et al.* (2016) provide useful insights regarding the different positioning and entry points of different measures in relation to their capabilities approach scheme, representing the whole pathway from energy source to basic capabilities (Figure 2.6). Consumer protection measures normally act on ensuring access to domestic energy supply, either guaranteeing the supply is not suspended or by reducing energy prices. Financial interventions typically aim to reduce the energy cost burden or guarantee a minimum level of domestic energy services, while EE programs reduce energy demand. Renewable energy programs focus on energy sources since they shift dependency from external sources to reliance on their own systems of production. Information and literacy directly act on secondary capabilities, providing people with information and the ability to change their behaviours.

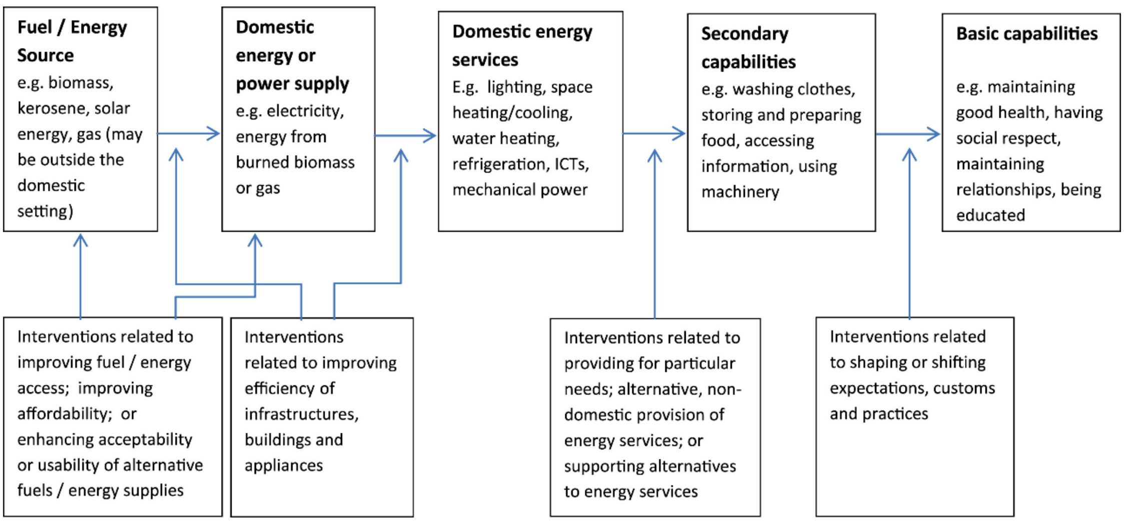


Figure 2.6 - Interventions entry points for EP alleviation (Day *et al.*, 2016)

2.2 Energy Poverty in the European Union

2.2.1 Overview of Energy and Climate Policy in Europe

Energy is a structural topic in the European Union, representing one of the pillars of the European project. It is historically significant in the formation of the EU, as the European Coal and Steel Community, established by the Treaty of Paris in 1951, is considered the first step towards European integration and a precursor to the organisational framework that characterises the current EU. Energy assumes today a central role in the European constitution basis and legislative instruments. However, energy access and affordability problems, in the form of EP or energy inequality, have not always been in the spotlight of European policymaking. The Treaty on the Functioning of the European Union, resulting from the Lisbon Treaty and stemming from the Treaty establishing the European Economic Community (known as the Treaty of Rome from 1957), states clearly in its Article 194 that Union policy shall ensure the functioning of the energy market, the security of energy supply, promote EE and energy saving and development of new and renewable forms of energy, and promote interconnection of energy networks. It established energy policy as a shared competence between the EU and the MS. Those are the base principles of the Energy Union, not opposing the MS's right to decide the conditions for exploiting their energy resources, the different energy sources, and the structure of energy supply (EU, 2016). These principles were built on the vision of a common singular market, which took several decades to come to fruition. Periods of hardship, such as the 1973 and 1979 oil crises, spurred coordinated European-level action to tackle energy shortages (Meyer, 2020), but only in 1987 were more effective steps given towards broader integration. The Single European Act marks the beginning of the energy sector liberalisation, by removing barriers to the free circulation of goods, capital, and people in the European Union. It prepared the ground for the competition law to be applied to the energy sector, leading to trans-European free market forces competing, cross-border trade, the separation of energy production, transportation, and distribution, and the introduction of market prices (Nguyen, 2022). It started the shift from the paradigm of domestic monopolies to a European single market.

In the 1990s, the European Union brought about the gradual opening up of markets to competition through several legislative packages, the first of which was called the First Energy Package, containing two Directives, the first Electricity Directive 96/92/EC and the first gas Directive 98/30/EC adopted respectively in 1996 and 1998. These directives laid out the common rules for the internal electricity and gas markets, focusing on developing market access and requiring the accounting unbundling of national transmission system operators from other activities (FSR, 2020). This unbundling has been a gradual process and it is yet not finished. The Second Energy Package, adopted in 2003, with the Electricity Directive 2003/54/EC and the Gas Directive 2003/55/EC, introduced the requirement of legally unbundling activities, *i.e.* one company could only operate in one of the activities in the value chain while requiring MS to create national regulatory agencies (FSR, 2020; Next, 2023; Ciucci, 2024). It also enabled consumers, either domestic or industrial, to choose their energy supplier from the existing range of possibilities (Ciucci, 2024). These directives mentioned and targeted vulnerable consumers in the energy sector for the first time, urging MS to implement measures to protect vulnerable consumers, namely to avoid disconnections, ensure contract transparency, dispute settlement mechanisms and the possibility for consumers to change suppliers.

In parallel, after a decade of limited progress, marked mainly by the commitment to 8% reductions of six GHGs during the period 2008-2012 (compared to 1990 levels) in the aftermath of the climate summit in Kyoto in 1997, the 2000s brought a more dynamic period in climate policy-making (Prahl *et al.*, 2014). Driven by the need to define a strategy to achieve the targets, the European Climate Change Programme was launched, leading to the introduction of the European Emissions Trading Scheme (ETS) in 2005. National caps for emissions from power and industry sectors were set for each MS. This period is marked by several European climate policies intersecting with the energy dimension, targeting GHG, renewable energy, and EE. Two are highlighted: the 2001 RES Directive and the 2002 Energy Performance of Buildings Directive (EPBD, 2002/91/EC). The former was the first directive promoting the increase in the contribution of renewable energy sources to electricity production in the internal market for electricity and setting national indicative targets. The latter is the first legal act on energy policy in buildings, defining minimum requirements on the energy performance of buildings and establishing energy certification. It aimed to improve EE, tap into the energy-saving potential of the sector, and improve energy supply security while addressing environmental protection and the need for the rational utilisation of fossil fuels, leading sources of CO_2 emissions for complying with the Kyoto Protocol. No mention of EP or vulnerable energy consumers is found in both instruments.

In 2009, the Third Energy Package (EC, 2024a) introduced further rules on the separation of energy supply and generation from transmission networks (unbundling), continuing the liberalisation process, a new agency of energy regulators to ensure the functioning of the internal market, new provisions for enhancing consumers' rights in retail markets. Directive 2009/72/EC on the common rules for the internal market in electricity mentions EP for the first time, urging MS to develop plans or frameworks to tackle this condition within the rules of fair competition in the internal market. It also requests Ms to define the concept of vulnerable consumers. Bouzarovski and Thomson (2019) state that this energy package was responsible for a wider recognition of EP within the EU, as it stipulated legal requirements to protect vulnerable consumers. For natural gas markets, the directive 2009/73/EC from this package is still applicable.

Brief EP mentions are also found in the buildings' energy performance (EPB) directive of 2010 (Directive 2010/31/EU), linking EE in buildings to reduced levels of EP, and the EE directive (Directive 2012/27/EU), regarding the need for implementing EE programs and measures in energy-poor households, without any legal provision.

The year 2015 marks the development of the Energy Union Strategy, reinforcing principles of security, solidarity and trust and the goals to achieve a fully integrated internal energy market, EE improvements to reduce imports and lower emissions, climate action, and decarbonisation to ratify the Paris agreement (EC, 2024b). The regulation on the governance of the Energy Union and Climate Action (EU)2018/1999 was implemented later in 2018 and it is a particularly important step because it mandated MS to develop National Energy and Climate Plans (NECPS), where they were required to report on EP levels, minding the "necessary domestic energy services needed to guarantee basic standards of living". MSs should also propose a mitigation target in case levels are significant and outline the policies and measures to address EP. As mentioned in the document, MS should take into account the EC Guidance on relevant EP indicators. Published in 2020, the Commission Recommendation (EU) 2020/1563 on EP provided concrete recommendations for MS regarding adequate indicators for measurement while underlining EU funding schemes that prioritise vulnerable households and promoting the exchange of best practices between EU countries (EC, 2020). It should be mentioned that previously in 2016, the EC's landmark project and platform Energy Poverty Observatory had been created, a user-friendly and open-access platform on EP providing MS and stakeholders with information and support to improve multilevel decision making in the EU (Kyprianou *et al.*, 2019), also supporting the development of the NECPs.

The Charter of Fundamental Rights of the European Union, legally binding since the Treaty of Lisbon, does not include any direct provision regarding the right to energy, mentioning only access to services of general economic interest. Still, the European Pillar of Social Rights, approved in 2017, finally acknowledges energy in the right to access essential services of good quality, stating that support shall be available to those in need (EC, 2017).

In 2019, the "Clean Energy for All Europeans" package (the 4th energy package) brought new electricity market rules, consumer incentives, active participation in sustainable energy generation, increased national energy regulators' competence for cross-border cooperation and mandated the preparation of risk-mitigation plans for electricity crises (Nguyen, 2022; EC, 2024c); It enacts the energy union strategy and deepens the link between energy and climate targets, contributing to pursue the EU's long-term strategy of achieving carbon neutrality by 2050, approved earlier in 2018. It promotes an overhaul of energy policy towards the shift from fossil fuels to cleaner fuels, aiming to realise the Paris Agreement targets of GHG emissions reduction. The new regulation (EU) 2019/943 on the internal market for electricity requires that the settlement of balancing energy is based on marginal pricing (pay-as-cleared) unless an alternative system is demonstrated to be more efficient by the MS. The EC states that this model provides efficiency and transparency and keeps the prices low, although limitations have been pointed out. Garcia-Casal and Bianco (2022) state that it can produce barriers for the energy transition and renewable-based power systems and lead to sociopolitical instabilities. This price coupling led to record levels in electricity prices due to the gas price crisis (Nguyen, 2022). The type of wholesale electricity market is relevant to EP's problem since it is a big determinant of retail energy prices. This legislative package also promoted recasts of the EE and EPB directives, which placed EP alleviation in a more prominent role as a goal to be integrated into long-term building renovation strategies (LTRS) and accounted for in EE measures. Later, in mid-2024, the EC published the Electricity Market Design reform, aiming to reduce electricity prices' dependency on fossil fuel prices. This reform opens up more possibilities for citizens in their electricity contracts, namely clearer information, more fixed price availability and flexibility to choose dynamic pricing. It protects vulnerable consumers by ensuring sufficient last-resort suppliers and more possibility to regulate retail prices. It also promotes power purchase agreements between businesses and power producers and investments and two-way contracts for difference with public entities for new power plant projects, to stabilise energy prices, secure minimum return on investment and preventing excessive costs (ECCEU, 2024a)

2019 also saw the approval of European Green Deal, a set of policies to set the EU on the path of green transition and reaching the goal of climate neutrality, highlighting the need for a cross-sectoral approach. Within this package, the European Climate Law was approved, turning political ambitions into legal obligations, namely the target of at least 55% of GHG emissions cut compared to 1990 levels. In 2020, the Renovation Wave strategy (EC, 2024d) was published to tackle EP and enhance buildings' energy performance, renovation of public buildings and decarbonisation of heating and cooling. It built on the existing directives to reinforce more accessible and targeted funding to double the energy renovation rate by 2030. This strategy confirms the growing prioritisation of EP in EU's energy and climate policy.

The European Green Deal prompted another legislative package, the Fit for 55 package (fifth energy package), approved in 2021. In the recast of the EE and renewable energy directive, two new binding targets were established: 11.7% improvement of EE and 42.5% of renewable energy sources by 2030 (49% for the building sector). The EE directive proposed an official definition of EP at the EU level. The revised EPB directive (Directive (EU) 2024/1275) set out new rules to increase performance of buildings, namely to ensure all new buildings are zero-emission by 2030 and existing ones are transformed into zero-emission by 2050 (ECCEU, 2024b). Among other provisions, this directive requires MS to draw plans for EP reduction in their LTRS and target the energy-poor in building renovation measures. It projects the gradual phase out of fossil fuel-powered boilers by ending subsidies from the beginning of 2025. The EE directive also ensures legally that the principle "Energy Efficiency First" is considered in planning, policy and investment. The Fit-for-55 also created a new EU ETS for building, road transport and fuels for other sectors, prompting an update of GHG emissions reduction targets (to 62%) in these sectors. The European Social Climate fund was created alongside the new EU ETS, to provide MS with funding to support vulnerable consumers in the energy transition, mobilising 86.7 billion over the 2026-2032 (EC, 2024e). This funding will be harnessed from auctioning allowances to the EU ETS 2 and EU ETS 1 and MS can use it for structural measures addressing EE and renovation of buildings, renewable energy integration, clean heating and cooling and low-emission mobility solutions. A part can also be spent on direct income support on a temporary basis. MS will need to compile these measures in their Social Climate Plan. The SCP will potentially constitute the largest funding source to support the energy-poor population. However, researchers have voiced their worry about the insufficient amount to meet the challenge of a just transition (Defard and Bergoënd, 2022).

Previous funding to support the energy poor was stemming also indirectly from the Just Transition Mechanism, the Recovery and Resilience Facility in response to the COVID-19 pandemic, and the Repower EU (€300 billion euros allocated) (EC, 2024f), which aims at phasing out Russian fossil fuel imports in response to Russia's invasion of Ukraine and accelerate the energy transition. The LIFE Clean Energy Transition Programme and the Horizon 2020 Energy Efficiency grant funding to projects to further explore EP mitigation (EC, 2024g)

In parallel, in 2021, the EPAH replaced the Energy Poverty Observatory as the EC platform of reference for EP knowledge, expertise, and practice, continuing to guide policymakers in their EP mitigation action, with a special focus on local-level project support and development. It promoted further collaborations with other relevant initiatives such as the Covenant of Mayors, also committed to tackling EP at the local scale. This initiative was followed by the creation of the Energy Poverty and Vulnerable Consumers Coordination Group as a platform for MSs to share information and best practices (Decision (EU) 2022/589). In 2023, the EC published a new recommendation on EP, focusing on measures and policies that can be implemented to address EP using the available funding, emphasising that vulnerable consumer protection should be a cornerstone of the European Green Deal (EC, 2023). The way funding is applied is the subject of debate, as the major share is not being used to support the energy-poor. Galgóczi (2023) shows that 58.6% of the total funding to shield EU households during the energy crisis has been spent in the EU27 on untargeted price measures such as excise duty cuts and value added tax (VAT), and 19.2% on untargeted income support measures. This funding reaches the entire population regardless of their economic condition. Cornago and Springford (2023) warn that EU governments have not focused as much on EE to reduce dependence on gas as they have on consumption subsidies. A timeline with the relevant events in EU energy policy regarding EP is displayed in Figure 2.7.

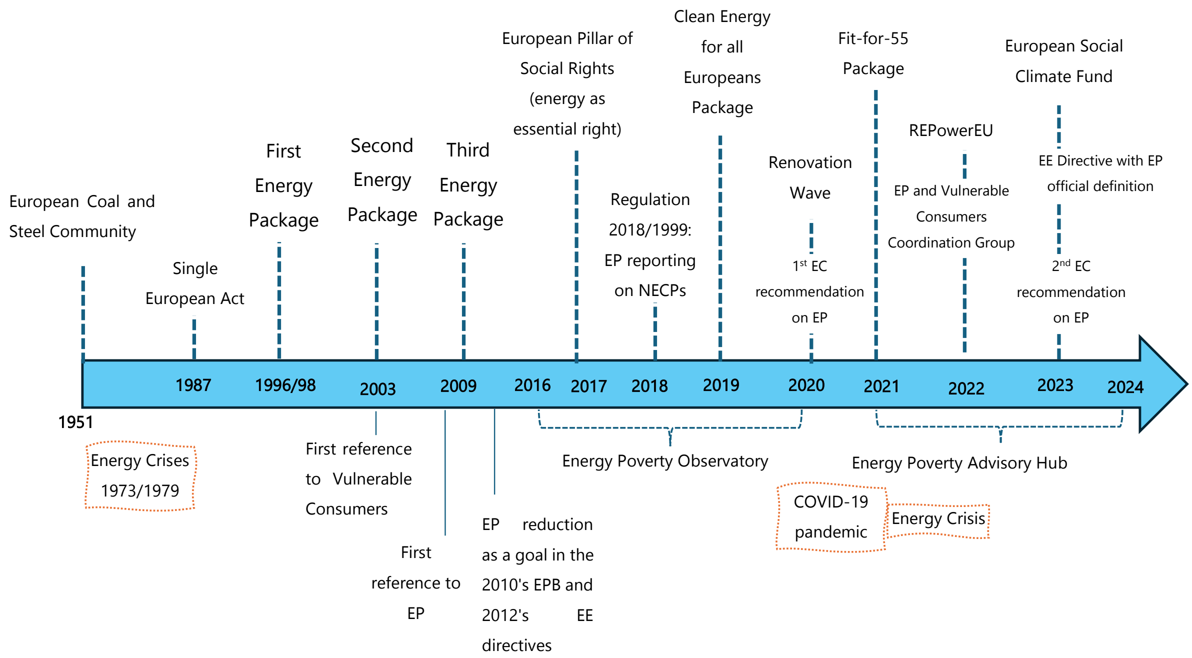


Figure 2.7 - Overview of energy and climate policy landmarks with a focus on EP

2.2.2 Current Situation

Despite increasing EP reduction integration as a main goal of energy and climate policy frameworks and the rising availability of EU funding to address this issue at the national level, EP remains a problem of considerable scale and magnitude in the European continent, harming the lives of millions of citizens every year. The EPAH has worked towards providing the best knowledge on EP measurement to aid MS in diagnosing this issue in their territories, compiling 28 indicators in their dashboard that can be used to assess different aspects related to the determination of this condition, from several European and national sources. Available at EPAH, the EU SILC indicators "share of population with arrears on utility bills", "share of population living in a dwelling with a leaking roof, damp walls, floors or foundation, or rot in window frames of floor"; and "share of population unable to keep home adequately warm in the winter", are still among the most commonly used to portray EP at the macro level (national and European). They are proxy indicators that represent potential effects of EP in households, regarding their ability to pay for energy, to maintain thermal comfort, and to keep their home in an adequate state of conservation. The EPAH presents these indicators in its dashboard, deeming them suitable for EP measurement at this level. The evolution of these indicators from 2010 to 2023 indicators is depicted in Figure 2.8.

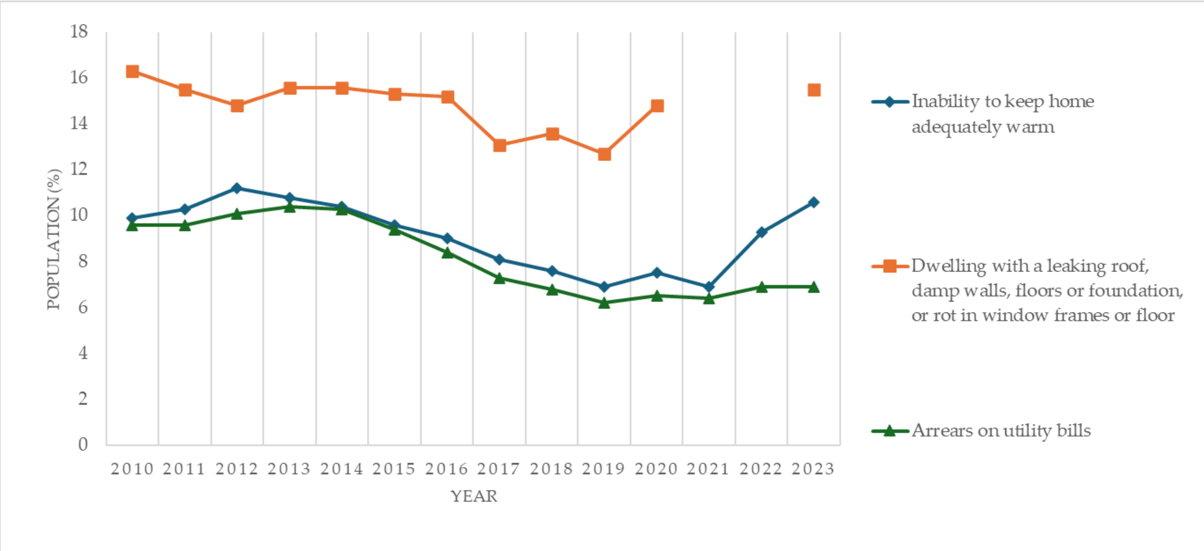


Figure 2.8 - European Survey on Income and Living Conditions proxy indicators for EP in the European Union (Eurostat, 2024a; Eurostat, 2024b; Eurostat, 2024c)

After an increase in the period from 2010-2013, potentially due to a period of economic recession following the 2008's crisis affecting families' budgets, percentages of the inability to keep home warm and arrears on utility bills were on a decreasing trend until 2019, until they started to rise again, with potential influence from the 2022's energy crisis. The indicator regarding deterioration in the dwelling followed a similar change from 2013 onwards, decreasing until 2019 and then seemingly having an upward shift until 2023. However, data is not available for 2021 and 2022, as the indicator was not collected in those years. As of 2023, in the aftermath of the energy crisis, 6.9% of the EU population have arrears on utility bills, 15.5% live in a dwelling with a leaking roof, damp walls, floors or foundation, or rot in window frames or floor, and 10.6% reporting an inability to keep home adequately warm, which translates in absolute figures to a total of 30.9, 69.5 and 47.5 million people respectively. These numbers are evidence that a serious EP problem may be afflicting a considerable part of the European population.

Some of these households may be suffering from compound vulnerability, as they may be reporting to be affected by more than one of these issues. Although only collected for the year of 2012, the indicator "share of population living in a dwelling not comfortably cool during summertime", also presented a worrying figure, 19.0% (Eurostat, 2024d). Examining how the previous indicators evolved and minding the impacts of climate change, it is probable that this indicator has not seen an improvement in later years. These indicators combined point out a persistent and still unresolved EP issue in the EU.

When analysing the same indicators per MS, as displayed in Figure 2.9, a significant variation in the results is observed, with notable asymmetries between central and peripheric countries. Southern European countries such as Bulgaria, Greece, Spain or Portugal, generally present higher percentages of inability to maintain thermal comfort in their homes, keeping their dwelling in a favourable state of conservation and affording their energy bills compared to central and northern European countries, hence potentially having greater EP problems among the population. The results of these indicators call for a deeper analysis to examine the known determinants of EP and verify if the results are substantiated by precarious situations regarding the factors that are pointed out as the root causes of the problem.

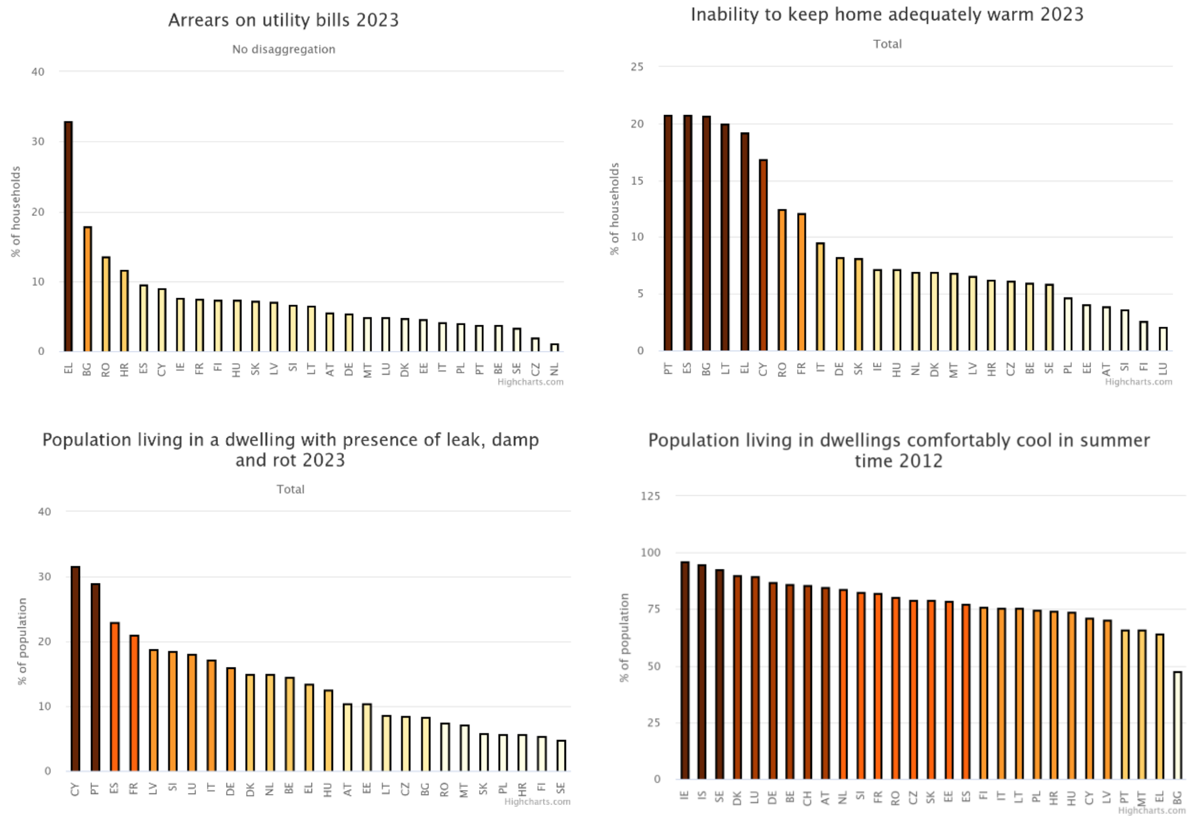


Figure 2.9 - European Survey on Income and Living Conditions proxy indicators of EP: “Share of population living in a dwelling with a leaking roof, damp walls, floors or foundation, or rot in window frames of floor” (top left); “Share of population unable to keep home adequately warm in the winter” (top right), and the “Share of population with arrears on utility bills” (bottom left); and the indicator “Share of population living in a dwelling comfortably cool during summertime” (bottom right) for 2012, per MS (EPAH, 2024a)

2.2.2.1 Income and Energy Prices

One of the main drivers of EP is affordability problems for households. Affordability is determined by income levels and energy prices. Displayed in Figure 2.10, the indicator of population at risk of poverty (EPAH, 2024a) is a measure of low incomes, representing the share of people with an equivalised disposable income below the at-risk-of-poverty threshold, set at 60 % of the national median equivalised disposable income after social transfers. In 2023, Romania, Bulgaria, and Spain occupy the top three in percentage of the population receiving lower salaries, and other southern countries such as Italy, Greece and Portugal also record high shares. It is a relative indicator of economic affluence but does not provide further information on other relevant metrics, such as quality of life. Levels of adjust gross disposable income in purchasing power parities (Eurostat, 2024e) are also lower in periphery countries from the south and northeast, particularly in Croatia, Greece and Latvia (Figure 2.11). Portugal and Spain are also among the countries with the lowest disposable income, reflecting a lower purchasing power and ability to invest in good and service in comparison to other EU nations. These results do not fully translate to higher income distribution inequality (Eurostat, 2024f), defined as the ratio of total income received by the highest 20 per cent of the population to that received by the lowest 20 per cent of the population. However, in countries such as Portugal, Hungary and Slovakia, low wages are accompanied by a situation of significant disparity between the rich and poor, a context characterised by both poverty and inequality (Figure 2.11).

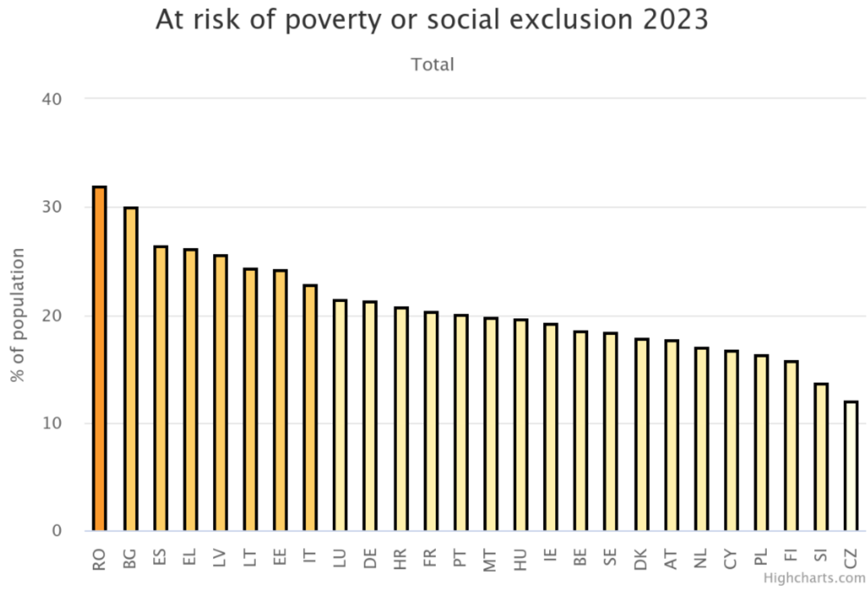


Figure 2.10 - Percentage of the population at the risk of poverty or social exclusion (EPAH, 2024a)

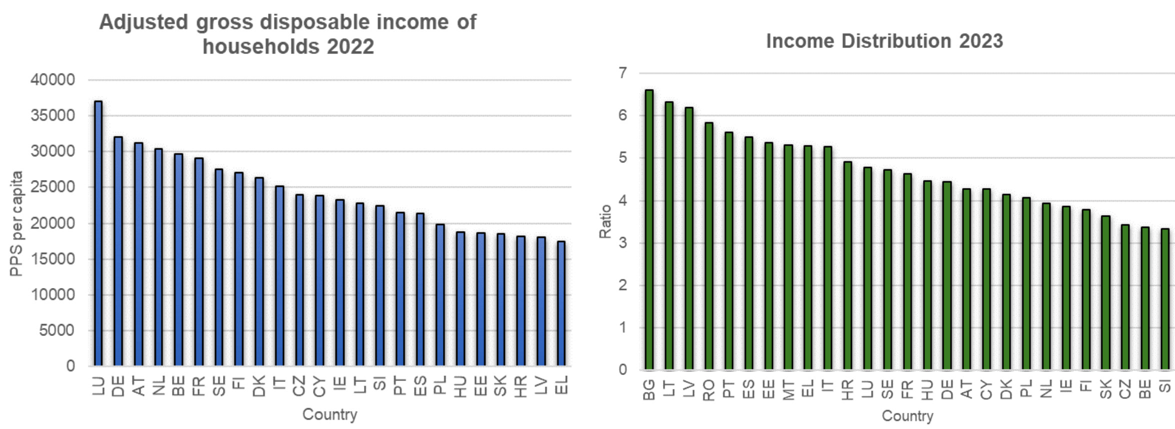
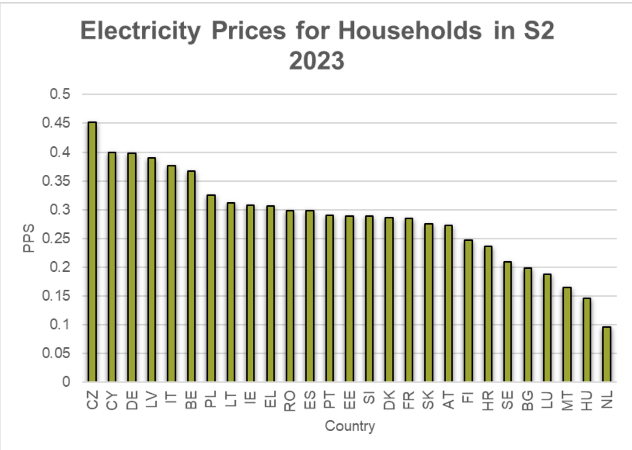


Figure 2.11 - Adjusted gross disposable income of households in 2022 (left) and ratio of income distribution in 2023 (right) (data from Eurostat, 2024e; Eurostat, 2024f)

Energy prices are the other key component to defining household ability to afford energy. Examining electricity and gas prices with all taxes and levies included adjusted to purchasing power standard (PPS) per kilowatt-hour (Eurostat, 2024g; Eurostat, 2024h), displayed in Figure 2.12, in the 2nd semester of 2023, the distribution of prices varies considerably across the EU, not following particular geographical patterns. The highest electricity prices in PPS were found in Czechia, Cyprus, and Denmark, whereas the highest gas prices in the domestic sector were recorded in Lithuania, Sweden, and Portugal. These prices are dependent on fiscal policy in each nation, energy exports, and internal energy resources availability and production. Analysed together in the income indicators, Latvia stands out for being in a situation of lower purchasing power, income distribution inequality and high electricity prices, whereas in countries such as Portugal and Lithuania, households are potentially most vulnerable regarding gas affordability.



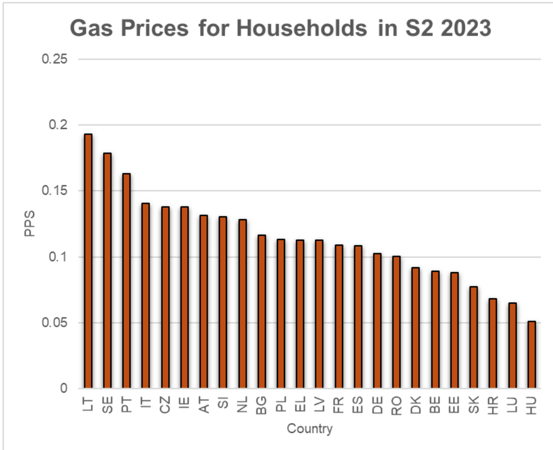


Figure 2.12 - Electricity (left) and gas (right) prices for households in the 2nd semester of 2023 (data from Eurostat, 2024g; Eurostat, 2024h)

2.2.2.2 Climate and Building Stock

Climate has a considerable impact on buildings' energy performance and energy demand, thus affecting households' ability to afford the necessary energy that guarantees their daily needs. in 2023, HDDs were higher in the northern nations, namely Norway, Finland, Lithuania and Latvia, contributing to the vulnerability of these two latter northeast countries (Figure 2.13). The southern countries have a naturally higher number of cooling degree days (CDD), as summer temperatures are more significant in this region of Europe, increasing energy demand in the cooling station and potentially affecting vulnerable households. Reference temperatures for HDDs and CDDs calculation are respectively 18°C and 21°C. Ciancio *et al.* (2020) estimate a future decrease in heating energy needs and an increase in demand for electricity and cooling in Europe, especially in the south, identifying it as the most exposed and vulnerable region to global warming.

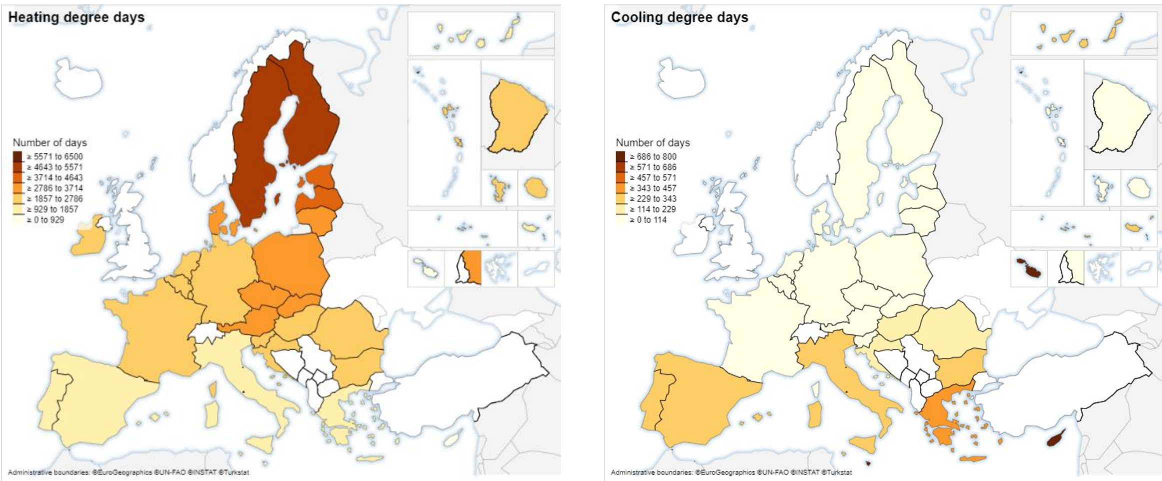


Figure 2.13 -Heating and cooling degree-days in 2023 (EPAH, 2024a)

The energy demand of buildings is determined by climatic conditions but also by the building envelope and energy performance and efficiency of buildings, considered a root cause of EP. Transversal EU data on buildings envelope or equipment is scarce. Besides the EU-SILC indicator portraying deterioration in dwellings, EPAH identifies three indicators to characterise building infrastructure and systems, which are the "dwellings with energy label A", "Population considering their dwelling as too dark", "Population living in a dwelling equipped with air conditioning" and Population living in a dwelling equipped with heating facilities". The first indicator is only available for a handful of countries, the second is arguably not a direct cause of EP, and the latter two have not been updated for several years.

National energy performance data is the only source of detailed data on the energy performance of the residential building stock, but it is not available in all EU countries. Gevorgian *et al.* (2021) report that the majority of the residential building stock, about 31%, was built before 1945. About 20% of the covered floor area corresponds to buildings erected from between 1945-1969. Buildings constructed after 2000 amount to a total of 28%. The countries with the largest covered floor area corresponding to old buildings (before 1969) are Austria, Cyprus, Germany, Hungary, Malta, Romania, and Slovakia. Buildings' older age can be a proxy of energy performance, in the sense that the older the building the highest the probability it has lower energy performance, and it requires renovation work, although this is not always the case, as some older buildings have good energy performance and newer ones do not. Using data from 16 countries/region and 66% of the European total floor area, BPIE (2024) states that 97% of the building stock must be upgraded to achieve 2050 decarbonisation goals, disqualifying the previous estimative of 75% of buildings needing renovation. It shows that most affluent countries from the centre and north Europe have a higher share of buildings with A or B EPC labels (Figure 2.14). Contrarily, Bulgaria, Spain, Italy and Estonia have a higher percentage of low EPC label building stock.

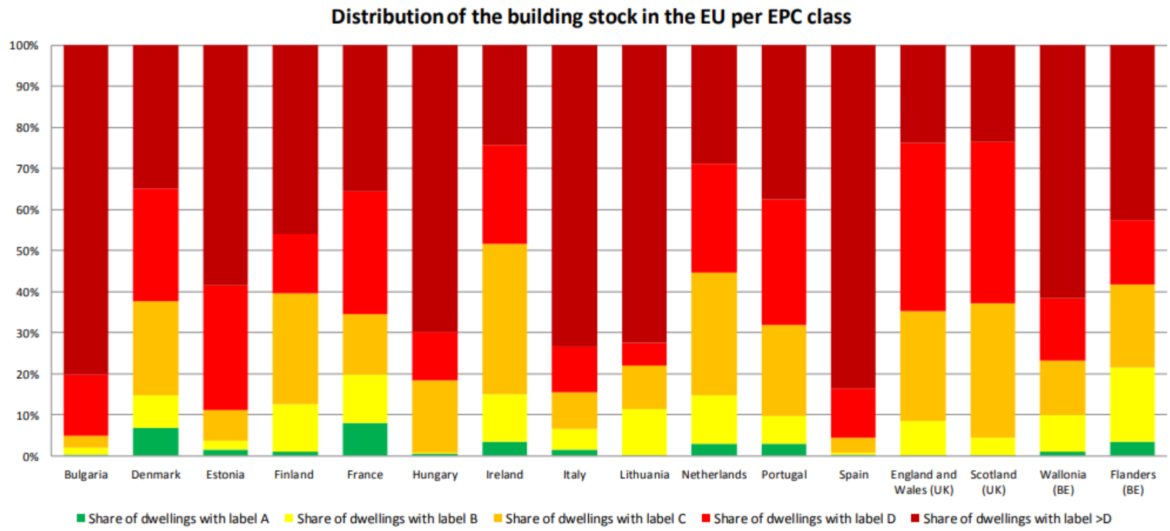


Figure 2.14 - Distribution of the building stock in the EU per EPC class (from BPIE, 2024)

These results are corroborated by Anagnostopoulos and De Groote (2016). The authors show that there has been a transversal improvement in building stock EE standards in the EU, reflected in the thermal coefficient values (U-value) of the different building elements (Figure 2.15), an improvement also proven by Building Performance Institute Europe (BPIE) (2024).

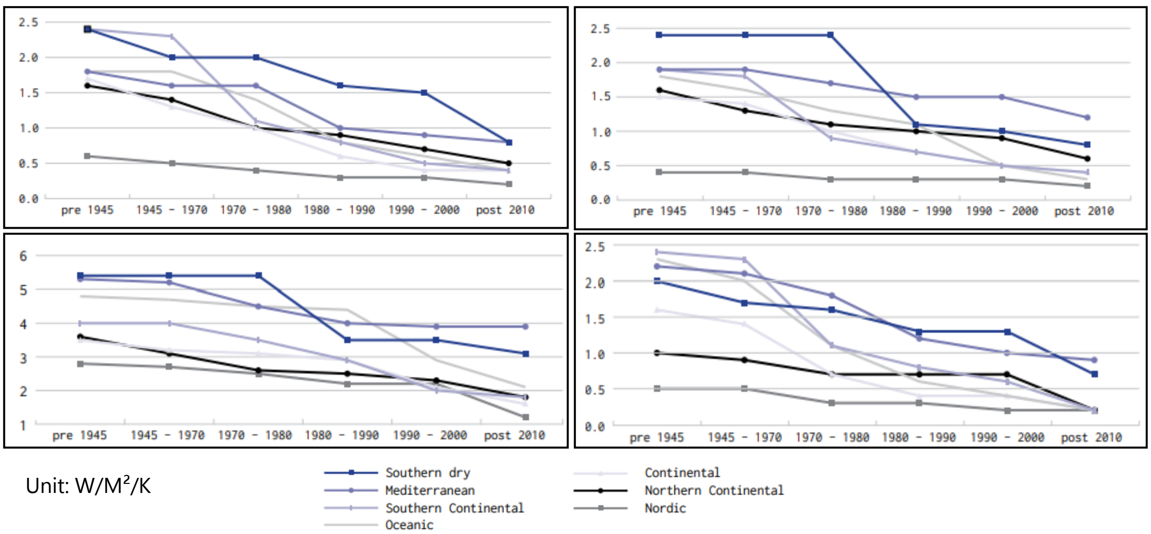


Figure 2.15 - U-values of wall (top left), floor (top right), window (bottom left) and roof (bottom right) of the building stock, in W/M²/K, per building age, for different country groups in the EU (iNSPiRe, 2014; Anagnostopoulos and De Groote, 2016)

Nevertheless, the building stock in the southern and Mediterranean countries in the EU is the less efficient one, presenting high heat transfer coefficient values for all building elements and in all building age typologies, which is an indicator of lower energy performance of the building stock. It should be noted also that colder climates require higher thermal transmittance of building elements, hence the lower values in warmer climate countries.

2.2.2.3 Energy Consumption

The combination of all the previous indicators - buildings energy performance, climate, income and energy prices – is reflected in the energy consumption of households. As illustrated in Figure 2.16, Malta, Portugal and Spain registered the lowest per capita final energy consumption in the households, in 2022 (Eurostat, 2024i). Simultaneously, these three countries, together with Cyprus, also presented the lowest share of final energy consumption for space heating (Eurostat, 2024j), as evidenced in Figure 2.17. The combination of low energy consumption and share of final energy consumption for heating is result of the warmer climate and lower energy needs but can be signs of a systemic EP issue in the population. Southern countries such as Malta, Cyprus and Greece have high shares of energy consumption for space cooling, contrary to other southern countries also with warmer climates, such as Portugal, Italy, and Spain, which can be interpreted as further signs of potential hardship (Figure 2.17). However, the validation of this assumption requires an in-depth analysis of further indicators.

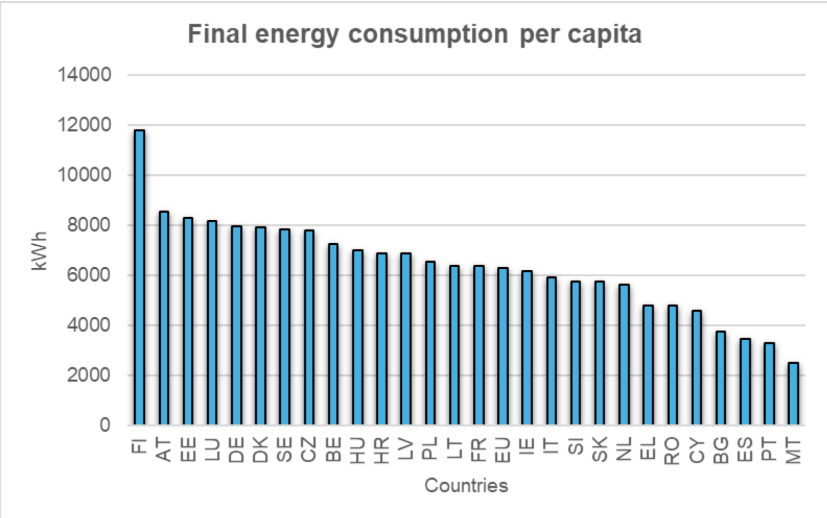


Figure 2.16 - Total final energy consumption (kWh) in 2022

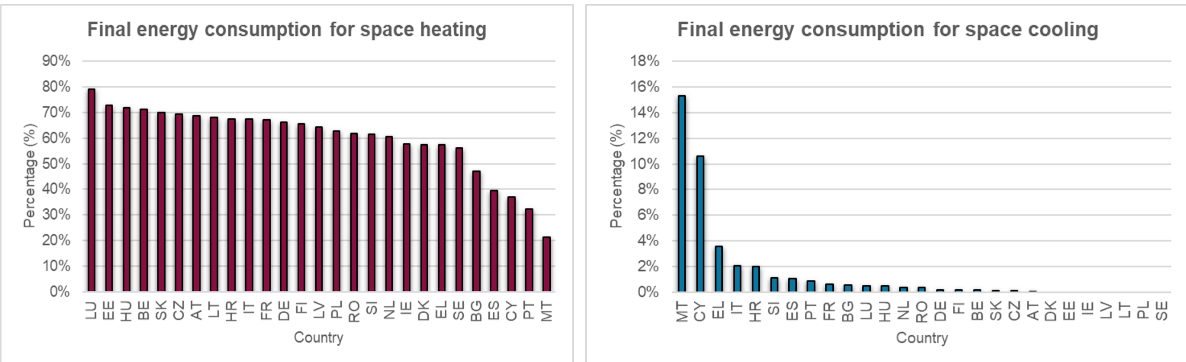


Figure 2.17 - Share of domestic final energy consumption (% of total) for heating (left) and cooling (right) in 2022

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3

ENERGY POVERTY: THE CASE OF PORTUGAL

3.1 Overview

Considering the asymmetrical geography of EP within the EU, reflected in an increased vulnerability of the population in southern countries, as previously shown, Portugal was chosen as the case study for this research. EP is a problem with historical roots in Portugal, which has significantly affected the population for as long as there has been data to characterise this phenomenon. Analysing the results for the EU-SILC indicators, significant percentages of the population report situations of difficulty. The percentage of the population unable to keep warm has generally fallen since 2004. Still, it has been on a rising trend since 2021, standing at 20.8 per cent in 2023, well above the EU average (10.6 per cent) and the highest among the MS, together with Spain (Eurostat, 2024a). Although it has also seen considerable reductions since 2004, Portugal also has a higher figure than the EU average for the percentage of the population showing signs of deterioration in their housing, 29 per cent, compared to the European average of 15.5 per cent in 2023 (Eurostat, 2024b). The Portuguese percentage is the second highest in the EU, below Cyprus. The case is different when it comes to late payment of bills. The percentage of the population has fluctuated slightly over the years, settling at 3.8 per cent in 2023, below the European average (6.9 per cent) (Eurostat, 2024c). One hypothesis for these contradictory results in the light of the former could be the active choice of households to avoid debt rather than avoid situations of thermal discomfort or deterioration problems in the home, which results in voluntarily restricted consumption and insufficient to provide the desired levels of energy services, as evidenced in the first indicator. This household strategy is generally considered a symptom of a form of EP defined in the literature as hidden EP (Meyer *et al.*, 2018). In 2012, the indicator " share of population living in a dwelling not comfortably cool during summertime" was lastly connected transversally in the EU, and Portugal recorded the second highest percentage in the EU, 35.7 per cent (Eurostat, 2024d). The new EU SILC carried out in 2023 in the country again collected data for this indicator and eleven years later the situation does not seem to have improved, as the figure recorded exceeds that of 2012, registering a total of 38.3 per cent, pointing to a generalised difficulty in maintaining thermal comfort in the cooling season (INE, 2023). The progress of the different EU-SILC indicators can be consulted in Figure 3.1.

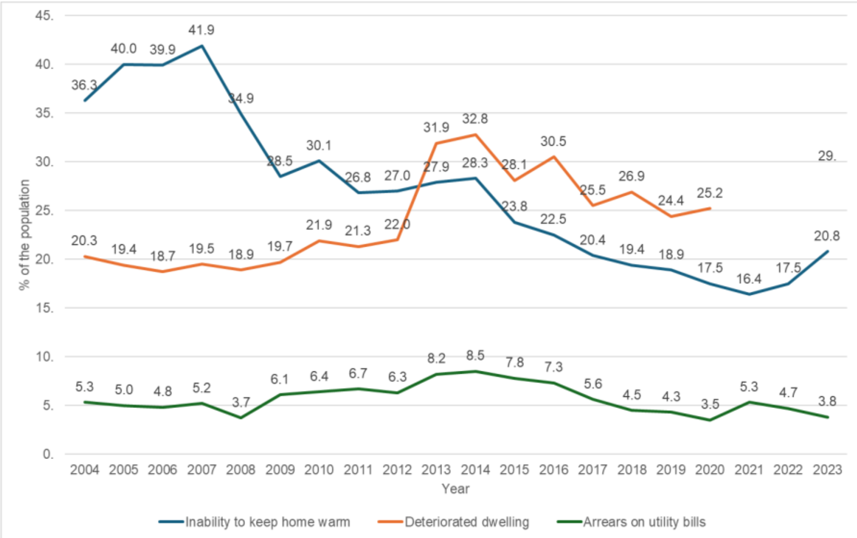

Figure 3.1 - Evolution of the EU-SILC indicators in Portugal

Collected every five years, the Household Budget Survey also provide relevant information for analysing EP in the country, namely the M/2 and the 2M indicators. In 2015, 6.8 per cent of the population spent less than half their income on energy than the population median, while 15.1 per cent spent more than twice the median (EPAH, 2024a). Both indicators point to potential situations of difficulty in accessing adequate levels of energy, either due to voluntary restriction or the burden of energy costs on the family budget.

3.2 Causes and determinants

Regarding the EE of buildings, the high percentage of the population living in homes with deteriorated construction elements suggests a precarious situation in terms of the energy performance of Portuguese residential buildings. This indicator simultaneously captures a condition that is both a cause and a consequence of EP. The deterioration of the building may be responsible for the reduction in EE and consequent increase in EP. Still, it may also be the result of inadequate temperature and humidity conditions, resulting from an EP situation. There are reasons to believe that the building stock is an important cause of this problem, as 65.5 per cent of residential buildings were built before 1990 (INE, 2021a), the year in which the first energy performance regulation for residential buildings was adopted. The age of construction is reflected in the energy performance indicators - 65 per cent of certified dwellings have an energy certificate of C or lower, as can be seen in Figure 3.2 (ADENE, 2024a), and the requirement for new and renovated buildings is class B-. Around 40.9% of the population reported having only single glazing in their windows, a less energy-efficient option (INE, 2023). For walls, windows and roofs, Portugal has one of Europe's highest thermal transmission coefficients, sharing the top spot with Spain (Zebra2020, 2016).

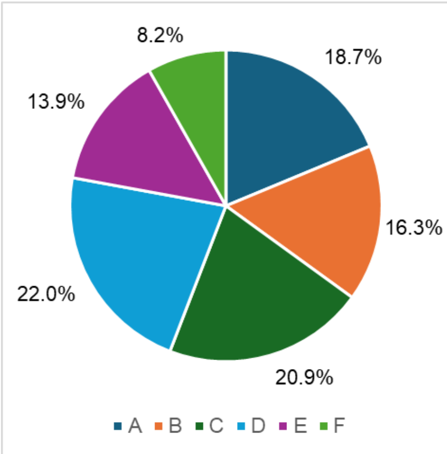

Figure 3.2 - Share of residential EPC per label (data from ADENE, 2024a)

Around 40 per cent of final energy consumption is in the form of electricity, which is the largest share of total consumption (Figure 3.3). Biomass is the second most important energy source, accounting for 26 per cent, followed by natural gas and LPG, which total 19.5 per cent (DGEG, 2024). The kitchen is where the most energy is spent in Portuguese homes (39.1%), while electrical equipment accounts for the second largest share of consumption (32.6%), followed by water heating (14.9%). Space heating accounts for just 9.1 per cent of energy consumption. Around 26.6 per cent of households reported not using any heating equipment in their home (INE, 2023).

On the other hand, the warmer climate in summer does not translate into consumption for cooling the environment - 0.9 per cent of total consumption, below countries with warm summers Greece, Cyprus, Spain and Malta. The low rate of ownership of cooling equipment in Portugal, around 32.7 per cent (INE/DGEG/ADENE, 2021), ultimately determines this low figure. Space heating is mainly obtained through biomass (81 per cent), generally associated with less efficient equipment such as fireplaces and air quality problems. On the other hand, part of the population in mainly rural areas has access to biomass at very low prices or even free of charge. There is also a high dependence on fossil gases for water heating (76 per cent), while cooling is 100 per cent provided using electricity.

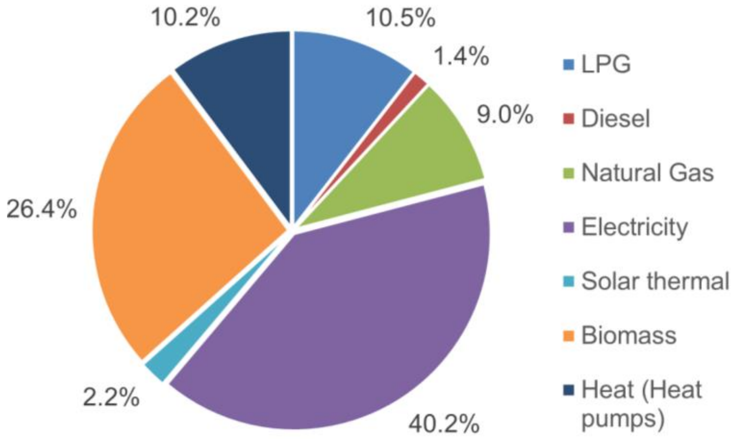

Figure 3.3 - Share of final energy consumption per energy carrier (data from DGEG, 2024)

The energy price situation differs according to the type of fuel (Figure 3.4). The price of gas in the domestic sector in PPS is on an upward trajectory, while the price of electricity is on the opposite trajectory, albeit with a less steep slope. In the second half of 2023, Portugal recorded the third and seventh highest price in the EU for natural gas in the consumption bands under 20 GJ and 20-199 GJ, and the 13th highest for electricity for the 1000-2500 kWh consumption band (Eurostat, 2024e; Eurostat, 2024f). Consumers in Portugal pay 6% VAT on a flat-rate basis for the volume of natural gas and the contracted power of electricity, respectively, less than 10 000 m3 and equal to or less than 3.45 kVA. VAT on electricity consumption is 13 per cent up to 100 kWh for consumers with contracted power equal to or less than 6.9 kVA, with additional consumption taxed at 23 per cent. Natural gas consumption is taxed at 23 per cent regardless of consumption levels, as is LPG. Thus, there is a fiscal incentive for consumers to shift from gas to electricity. Although electricity prices are still higher, the trends are reversing, with electricity prices falling in the future due to the increased production of renewable-source electricity in the country, with a low marginal cost of production. The increase in the price of gas in recent years is the result of the energy crisis and successive military conflicts with no end in sight, which are contributing to the inflation of fuel prices. This volatility is bound to continue for the foreseeable future.

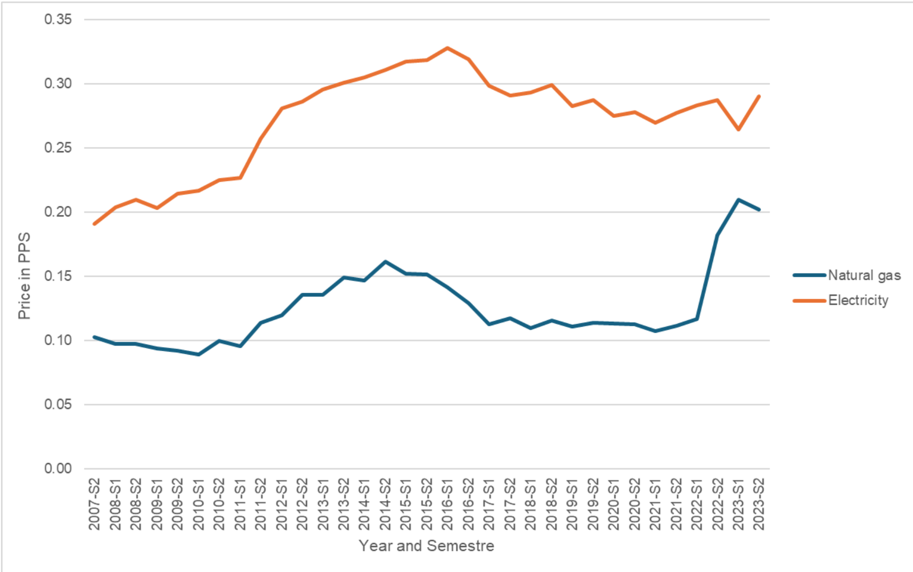

Figure 3.4 - Evolution of electricity and natural gas prices (PPS) in the domestic sector in Portugal 2007-2023

Examining the economic dimension, Figure 3.5 shows that inequality of disposable income (Eurostat 2024h) and the percentage of the population at risk of poverty (Eurostat 2024i) are on a downward trend. Figure 3.6 shows an upward trend in adjusted net salaries, after taxes and social security and taking into account social support received (Eurostat 2024g), thus there are some positive signs of reduced vulnerability regarding families' purchasing power and financial difficulties.

However, this sign of reduction is still insufficient to remove the Portuguese population from the top positions in the EU in terms of each of these indicators. Portugal is the fifth in income distribution inequality in the EU, the eleventh in the percentage of the population at risk of poverty, and the ten lowest adjusted gross disposable wages (in PPS), always presenting a more negative situation compared to the EU average. These results are symptomatic of the difficult situation faced by a large number of Portuguese families, with repercussions on access to levels of energy consumption that are adequate for a healthy life.

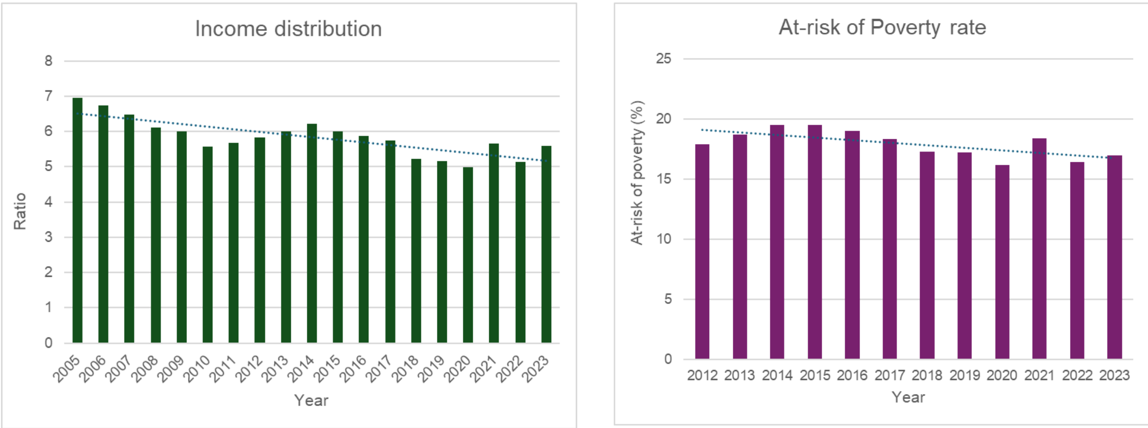

Figure 3.5 - Evolution of income distribution and risk of poverty in Portugal 2005-2023

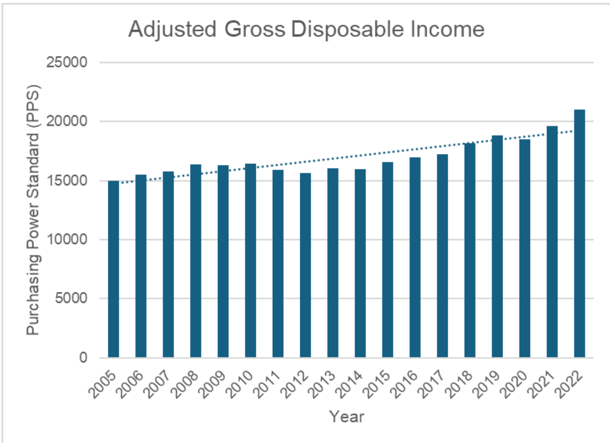

Figure 3.6 - Evolution of Adjusted Gross Disposable Income

Portugal has two predominant climate types according to the Köppen-Geiger climate classification and the 1971-2000 climatological normals. The southern and central interior regions, part of the northern interior, and Madeira Island have a temperate Mediterranean hot-summer climate (subtype Csa), characterised by hot, dry summers and mild, humid winters. The coastal regions of mainland Portugal, part of the northern interior and the eastern groups of the Azores islands have a hot-summer temperate Mediterranean climate (subtype Csb), with hot, dry summers and rainy, mild to cold winters (IPMA, 2022). At the aggregate national level, the configuration of climate types positions Portugal as one of the warmest countries in the European Union, with the seventh highest number of CDD in 2023 (235) and the third lowest number of HDD (1046) for the same year (Eurostat, 2024l). There are opposite trends in the recorded number of degree days in the heating and cooling season, as can be seen in Figure 3.7, with an increase in summer and a decrease in winter, partly justified by the impact of climate change in this region of Europe.

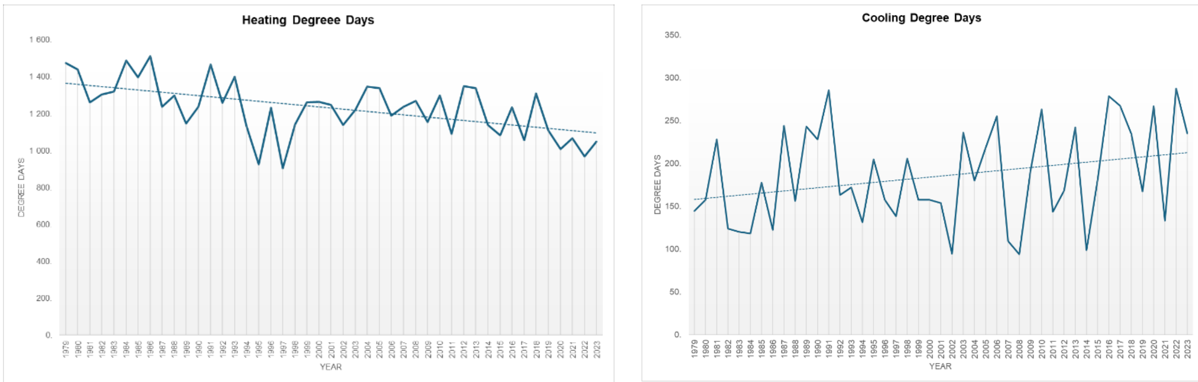

Figure 3.7 - Evolution of heating (left) and cooling (left) degree days in Portugal 1979-2023

Knowing that there is no data to investigate all the vulnerable groups mentioned in the previous section, the INE database and data from the 2021 Census (INE, 2021a; INE, 2021b) were used to select and characterise a diverse set of groups (Figure 3.8), aiming to understand their size, which is proportional to the need for investigating a potential intersection with situations of EP. Of particular note is the high rate of people with low levels of schooling, which could mean less knowledge and ability to alleviate their vulnerable situation.

The high rate of people with low levels of schooling, which could mean less knowledge and less ability to alleviate their vulnerable situation, is noteworthy. The high percentage of 12.7 per cent of households living in overcrowded dwellings is a possible indicator of precarious housing and inadequate levels of basic needs. The growing percentage of elderly people, who may have increased needs for energy services, namely thermal comfort, and poorer health, is also noteworthy, as it is necessarily linked to increased EP vulnerability, especially considering that part of this population group has below-average monthly incomes. The number of renters is also rising in the country, but still in considerably smaller numbers than homeowners. There is also a gender disparity regarding two circumstances of potential vulnerability - people living alone or looking after a child. The percentage of women facing this type of situation is higher, something that should also be taken into account in EP studies.

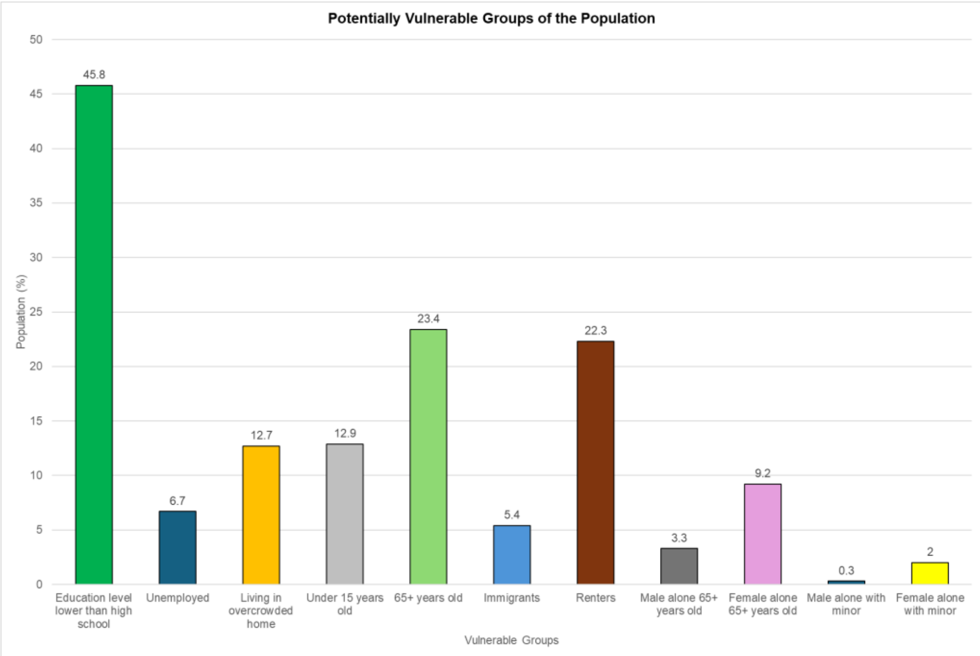

Figure 3.8 - Share of vulnerable groups in the Portuguese population (data from INE, 2021a; INE, 2021b)

EP effects occur in both winter and summer, and their magnitude is multiplied when extreme meteorological phenomena such as heat waves and cold snaps occur. In Portugal, there are still few studies that address this link, but there is some literature that supports the existence of an association that is both relevant and worrying in the country. In 2003, Healy (2003) reported that Portugal had the highest level of excess mortality in winter, naming precarious housing conditions as the fundamental cause. Twelve years later, analysing historical data from 1980-2013, Liddell *et al.* (2015) once again placed Portugal at the top of the table for excess winter mortality, reporting that the country had the second highest rate in the EU. In January 2021, 24% of excess mortality was attributed to low temperatures (JN, 2021). More recently, a study by Instituto Nacional de Saúde Doutor Ricardo Jorge (INSA) indicates that three heatwaves in 2022 were responsible for the premature death of 2 401 people in Portugal, corresponding to a 25 per cent excess over what was expected. The INSA points to EP as one of the main causes and also states that, if no measures are taken, every 1°C increase in the country's average temperature compared to pre-industrial times will result in a 2.17% increase in excess mortality by the end of the century (Executive Digest, 2023).

3.3 Energy poverty mitigation planning and policy measures

Although it remains a relatively unknown concept to the population, EP has afflicted the Portuguese population for centuries. Awareness and focus given to EP in the media and in national politics has increased significantly in the last decade, partly due to the growing research work carried out in the country and in Europe. In the political sphere, the decree-laws transposing Directive 2009/72/EC and Directive 2009/73/EC on the rules of the European internal market in electricity and natural gas are the first policy instruments with an impact on EP in Portugal, introducing the concept of vulnerable energy consumers into the country's legislation. At the strategic planning level, the 2012 National Long-Term Strategy for the Mobilisation of Investment in the renovation of buildings (DGEG, 2012) mentions EP for the first time, stressing the need to reduce it. Later, other mentions are found in important political strategies, such as the National Energy and Climate Plan (NECP) 2030 (Portuguese Government, 2020), the Roadmap for Carbon Neutrality for 2050 (Portuguese Government, 2019) and the Long-Term Strategy for Building Renovation (LTRS) (Portuguese Government, 2021). The NECP defines the reduction of EP as one of the lines of action to achieve a clean, democratic and just energy transition, proposing specific measures to improve the protection of vulnerable consumers, the development of policies, monitoring and the dissemination of information. The LTRS defines the mitigation of EP as a line of action, and it also proposes specific policies to achieve this goal in line with those of the NECP.

The National Long-Term Strategy to Combat Energy Poverty 2023-2050, approved in 2024, proposes an official definition of EP in Portugal. It defines a diverse set of indicators for measuring and monitoring the phenomenon, divided into primary and secondary indicators according to their level of relevance in representing the problem. It also estimates the number of people with PE, distinguishing between different levels of severity. The strategy outlines an action plan with specific measures to promote the energy and environmental sustainability of homes, promote universal access to essential energy services, promote integrated territorial action and promote knowledge and informed action. Several types of interventions have been implemented to tackle EP in the country:

Bill Support

The approval of these market decrees was followed by the adoption of social tariffs for electricity and natural gas in 2010 and 2011, respectively. The introduction of a social tariff for LPG cylinders has been debated, but no final decision has yet been made. These social tariffs work like discounts on regular energy tariffs, with the aim of reducing the energy bills of vulnerable consumers in the lower consumption bands. In March 2024, 737 174 consumers benefited from the electricity social tariff, while 49 289 benefited from the natural gas social tariff (ADENE, 2024b). The electricity social tariff is allocated automatically, with low incomes and social benefits as eligibility criteria, while the allocation of the gas tariff depends exclusively on social benefits.

Martins *et al.* (2019) conducted a study on the Application of the Energy Social Tariff, supervised by the Energy Observatory and funded by ADENE, the National Energy Agency. The authors state that there is no primary data to analyse the causality between the effect of the social tariff and the level of EP, although arguing that the financial resources that are freed by this discount can help mitigate the problems related to the building fabric, like leaks and mould. This is a financial instrument with a short-term horizon, aiming to help financially vulnerable consumers, though not specifically conceived to tackle EP. Although lack of finance is a relevant determinant of EP, the authors argue that an additional tariff directly targeting EP, focusing on EE in the longer term, would be more effective in reducing this condition. The authors also highlight the need for measures like information dissemination campaigns to promote increased awareness; to stop energy disconnections in critical seasonal periods; and other EE measures, including financial instruments to support investment. Moreira (2018) reached similar conclusions in her research work on the effectiveness of EP mitigation measures. Analysing the causality between the different measures and the indicators "inability to keep the dwelling adequately warm" and "arrears on utility bills", the author states that bill support helps reduce arrears but has no significant impact on thermal comfort, whereas EE measures help to improve both indicators.

Energy Efficiency Programs

Regarding measures and programmes with an impact on EP, the Recovery and Resilience Plan (PRR) has allocated 300 million euros until 2025 to support the renovation of buildings in Portugal. The More Sustainable Buildings Programme ("Programa de Apoio a Edíficios Mais Sustentáveis") was created to implement part of this funding with the aim of supporting any homeowner with 85% of the investment (excluding VAT) in heating and cooling equipment that is efficient in terms of renewable energy, water efficiency, building rehabilitation and bioclimatic building solutions. With an initial allocation of 122 million euros from the PRR, the programme will provide a further 100 million euros from RePower EU (Portuguese Republic, 2023). Also noteworthy is the Residential Condominium Support Programme, with an allocation of 12 million euros, closed at the end of 2023, designed to promote residential renovation (Fundo Ambiental, 2024a).

With a planned budget of 162 million euros, the "Vale Eficiência" programme distributes individual vouchers worth 1 300 euros, plus VAT, to households in situations of energy vulnerability (Fundo Ambiental, 2024b). Families who own their home and receive the social energy tariff, *i.e.* families on a low income or receiving some form of social support (*e.g.* the elderly, people with disabilities), are eligible for the voucher. The programme's second edition was recently implemented, after the programme was revised to increase people's participation. This is the renovation funding programme with the greatest potential impact on the EP population, as the allocation criteria guarantee allocation according to some degree of vulnerability, which could thus reach at least a significant part of the EP population.

There is also a national support programme aimed at poor consumers living in unhealthy housing called 1º Direito (Portal da Habitação, 2024a). In this programme, families report their situation to the municipality that promotes the application to the programme, although it can also be made by another entity. Support is given in the form of non-repayable payments and low-interest loans for the organisation and free of charge for families and can be used to renovate buildings. Other programmes offer financing through loans, such as the Rehabilitate to Rent Programme - Affordable Housing (Portal da Habitação, 2024b), which finances up to 90% of the cost for owners to renovate their buildings or homes that are more than 30 years old, if they are intended for affordable rent.

Consumer Protection

Under normal circumstances, there is no safeguard for disconnecting domestic consumers in Portugal. Energy suppliers can cut off consumers' access to energy for non-payment, as long as they send written notice at least 20 days before the scheduled cut-off date. The previous government promoted some tax benefits approved by state budget laws. Of particular note is Law no. 12/2022, which approved a reduced VAT rate on the supply and installation of solar thermal and photovoltaic panels; the 2023 state budget law, which instituted a reduced VAT rate on the supply and installation of solid biomass local space heaters and solid biomass boilers that do not exceed heat output thresholds, including those integrated into mixed systems with the two highest energy labelling classes. The same law determined that income earned from the sale of surplus electricity by self-consumption production units with an installed capacity of up to 1 MW is exempt from personal income tax if it does not exceed 1 000 euros.

Emergency measures

Emergency circumstances push governments to implement extraordinary measures to mitigate the negative impact on people's lives. Such measures were activated during the COVID-19 pandemic and the recent energy crisis. Several emergency measures were implemented at different moments such as, inter alia, extension of electricity cut-off notices, followed by suspension of disconnection; easier energy bill payment conditions; price caps and freezes; discounts on energy prices; tax reductions; price stabilisation through the regulated market; financial subsidies to families, and information and awareness campaigns. Moreover, as a common response to the energy crisis, the Iberian exception came into operation in an attempt to decouple the formation of electricity prices in the Iberian daily market (known as MIBEL) from the rising and increasing evolution of natural gas prices.

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4

Review of Energy Poverty Metrics at Subnational Spatial Scales

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Contribution: Writing – original draft, review & editing, Visualisation, Validation, Supervision, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualisation.

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Energy Poverty at High-Resolution Spatial Scale in Europe: Review of Metrics and Datasets

Abstract

Energy poverty is a complex multidimensional condition affecting millions of people in the European Union. Diagnosis is one of the key components of a successful policy strategy to mitigate the problem effectively. The European Commission emphasises the need for regional and local energy poverty mitigation action. Thus, disaggregated measurement is crucial in informing and directing policy design. This research aims to identify and analyse the literature on energy poverty measurement at the subnational level. It conducts a structured literature review based on a systematic protocol of 125 peer-reviewed articles published from 2010 to 2023, identified in scientific databases, focusing on relevant appraisal criteria from energy poverty metrology literature. This study identifies the current practices in indicators and data use and collection. It discusses merits, shortcomings, underexplored aspects, and potential developments regarding measurement approaches' nature, dimensions, outcomes and targets, contributing to further practice and theory. The results can guide researchers and practitioners in tailoring more comprehensive and inclusive energy poverty assessments at subnational scales. These assessments can be the foundation of more inclusive and effective local and regional policies and programs targeting the energy poor in European regions.

4.1 Introduction

Energy Poverty is a social issue that continues to afflict millions of people in the European Union (EPAH, 2024a). It remains a complex phenomenon to measure due to the considerable variability of its causes over time and space, as well as its private nature (Thomson *et al.*, 2017). Awareness of its ill effects has been considerably growing in the policy arena, reflected by numerous references to the need for its mitigation in major policy strategies and legislation. Reducing EP is frequently highlighted as a concurrent goal of decarbonisation, boosting energy efficiency, and a clean energy transition, namely in the Green Deal strategy and, more recently, in the subsequent "Fit for 55" legislative package. The previous "Clean Energy for All Europeans" instructed the EU MSs to address EP in their NECPs, by assessing the extent of the problem and proposing a strategy to mitigate it if posing as a significant risk to the population (European Commission, 2019). Effective measuring is one of the keys to a comprehensive understanding of this problem, enabling the design of more effective evidence-based policies and the monitorisation of its real impacts. However, the multidimensional complex nature of EP represents a major challenge to this task. The selection of adequate indicators is crucial for correctly identifying the energy poor and should consider context, scale, and data availability (Thomson *et al.*, 2017). Experts have different perspectives regarding the most appropriate metrics to analyse this issue, resulting in a significant pool of diverse approaches and an ongoing debate. Various experts (Rademaekers *et al*, 2016; Tirado-Herrero, 2017; Thomson *et al.*, 2017) categorise EP indicators into three main types: (1) consensual-based, depicting the self-experience of occupants in their homes regarding thermal comfort, housing conditions and ability to afford energy services; (2) expenditure-based, based on the analysis of energy expenditure as a share of income; (3) direct measurement, comparing domestic energy consumption against a required set value. Other indicators such as demographics, socioeconomics, and building fabric and equipment are used to assess EP. However, they do not provide a direct and dichotomous outcome of being in EP. Hence, these are considered supporting indicators (Rademaekers *et al.*, 2016). Several authors combine indicators of different categories in a multidimensional approach, either considering the selected indicators individually or in a composite metric or index (Walker *et al.*, 2012; Fabbri, 2015; Gouveia *et al.*, 2019; Martin-Consuegra *et al.*, 2020).

At the national level, particularly in the EP strategies, the approaches to evaluate and monitor levels in the country most often use self-reported proxy indicators depicting housing and living conditions, such as the EU SILC. Generally favoured at the EU level, these indicators are simple to analyse and use and have advantages regarding data availability and commensurability (Bauler, 2013; Sareen *et al.*, 2020). However, they fail to capture the full range of relevant determinants that shape this issue and are not designed for EP evaluation. On the other hand, multidimensional approaches are more equipped to represent EP in the diversity of its causes. Still, they can be complex, context-specific and challenging to transfer to other realities and scales without compromising their transparency and meaning.

Regarding the scale of analysis, notwithstanding the relevance of national scale approaches to evaluate and monitor the extension of the problem in a country, analysing EP at subnational scales can help uncover and unpack vulnerability situations that go unnoticed in larger scale indicators. The EC highlights the importance of bottom-up approaches to complement national-level indicator analysis while exalting the important role of regional and local authorities in driving a sustainable and fair energy transition (EC, 2020). Regional and local assessments can provide more insightful and nuanced perspectives, enabling the identification of specific drivers, contexts and groups that require attention. These metrics at disaggregated scales are especially relevant when considering that EP, like any social scourge, calls for significant efforts at every level of governance. From a policy perspective, it can be argued that regional and local authorities are better prepared to identify and engage with vulnerable households, understand their needs, and provide different forms of support. Whether at the city, town or district level, these authorities have a closer and more immediate connection with the population, along with straighter links to social and civil organisations. This provides them with more information about the population in their jurisdiction area, potentially enabling a swifter and more accurate identification of the energy-poor.

Consequently, monitoring vulnerability levels and policy impact are also bound to be more effective at this scale. Regional and local action is key for connecting and aligning national commitments with the specific EP configurations, and population needs across the territories, which are essential for achieving real progress in reducing EP levels. Tackling regional vulnerabilities is a priority in the EU, as evidenced by the Just Transition Mechanism, in which the MSs committed to preparing plans to identify the needs and propose alleviation measures for vulnerable regions. The EPAH is designed to support European local governments in eradicating EP (EPAH, 2022b). The Covenant of Mayors is also focusing on this subject, and it has proposed a set of indicators for assessing and monitoring EP at the local level as part of its commitment to providing access to secure, sustainable and affordable energy (CoM, 2022). The set of indicators should address several macro-areas, namely climate, facilities and housing, mobility, socioeconomic factors, policy and the regulatory framework, and participation and awareness-raising. The Covenant of Mayors signatories have committed to "providing access to secure, sustainable and affordable energy for all", and alleviating EP is part of the solution (CoM, 2022).

In summary, as EP lingers, it should be a policy priority for the low-tier authorities. Literature shows that energy poverty configurations can be widely diverse across the regional scale (Robinson *et al.*, 2018a; Gouveia *et al.*, 2019). Different contexts may require different approaches regarding measurement and solution implementation. Accounting for this diversity is a necessary step to tackle this issue effectively. On the other hand, the geography of EP is highly sensitive to the type of measure or metric used to assess it (Fahmy *et al.*, 2011).

Nevertheless, there are complex challenges when addressing energy poverty at disaggregated scales. One of the most significant ones is the lack of bottom-up data at these scales, significantly hindering the production of nuanced and evidence-based assessments. Local authorities or agencies often rely on informally collected data from social services, information points, policy programs, and other forms of contact with the population (Palma and Gouveia, 2022). Moreover, selecting appropriate indicators in a context of low data availability can also be arduous. Extensive research on energy poverty measurement at a subnational scale across the EU spans different scales and contexts. These approaches are often very particular in their methods and the contexts and populations they focus on, and the learnings and insights obtained are difficult to directly extrapolate to other geographies. However, they can still provide important knowledge on data and metrics for improving and advancing their energy poverty strategies and policies in the respective areas and generate valuable insights for other regions that face similar challenges. The need for this knowledge transfer is particularly evident, considering there is a historical disconnection between research and policy, especially at disaggregated scales, preventing the local authorities' practical use of this scientific knowledge.

Several literature reviews on EP metrics have been published, developing critical analysis on the strengths and lacunae of existing approaches and methods, analysing different uses and data, and examining patterns and trends (*e.g.* Tirado-Herrero, 2017; Thomson *et al.*, 2017; Castaño-Rosa *et al.*, 2019, Siksnelyte-Butkiene *et al.*, 2021; Brabo-Catala *et al.*, 2024). However, none of these studies focused on the issue of scale, conducting an exclusive and extensive analysis of measurement studies developed at subnational scales to unveil existing good practices, challenges and shortcomings, and innovation regarding data and indicator use at disaggregated scales, which is valuable information for local policymakers. Aiming to bridge this pressing gap, this paper conducts a structured review of studies based on a systematic protocol focusing on energy poverty assessment at higher resolution spatial scales, particularly those crafted for identifying, targeting, and characterising the energy-poor population in subnational analysis. It delves into a pool of different data sources, datasets, indicators and methods, aiming to investigate their use, utility, and suitability, analyse benefits and shortcomings, and ultimately collect learnings and produce insights for more effective policy design and action at smaller scales. This study can potentially unveil new datasets and metrics for authorities to use, complementing their resources and toolkits and supporting decision-making for assessing energy poverty in their territorial contexts. It also takes stock of the current situation regarding energy poverty measurement at disaggregated scales for the research audience, highlighting gaps to overcome towards improving metrology at this level.

The paper is organised as follows: Section 4.2 presents the method employed to conduct the literature review. Section 4.3 presents and analyses the results. Section 4.4 synthesises the study's main conclusions and limitations.

4.2 Methodology

As described by Sorrell (2007), systematic reviews should conduct comprehensive syntheses of the available research, aiming to reach conclusions regarding a set of defined RQs, explain differences between studies, and identify areas of improvement. With these considerations in mind, this study draws on McAndrew *et al.* (2021) systematic approach, who builds on the work of Sorrell (2007), as well as the PRISMA framework (Page *et al.*, 2021), to develop a structured (quasi-systematic) literature review that captures all the relevant studies and findings in energy poverty measurement research at subnational scale. The goal is to synthesise the main findings and provide adequate and reliable scientific evidence for policymakers in a field where the volume of work has considerably increased in the last decade, with the great diversity of approaches in very context-specific case studies. The structure comprises six different steps:

1. Defining the research questions meant to be answered in this study.
2. Searching for the literature systematically and exhaustively using research databases.
3. Setting the inclusion and exclusion criteria, according to the goal of this review and the validity of the analysed studies.
4. Assessing the studies, using a transparent method to collect and analyse data and methods used in the analysed research.
5. Reporting the results, and subsequent discussion in the context of the research questions.
6. Synthesizing findings after interpreting the collected results.

4.2.1 Research Questions

Measuring EP is crucial for the effectiveness of policy schemes in identifying and monitoring EP. Still, it is also a subject of ongoing debate both in policy and research. A diverse and extensive range of metrics and datasets are being used to study EP in different contexts. This study aims to investigate the indicators, datasets, and methods currently being applied to EP studies, focusing on identifying or characterising the energy-poor population and measuring this problem in a territorial context at subnational scales. It aims to identify and analyse the different approaches in downscaling metrics to assess vulnerability at high-resolution scales and collect evidence regarding the best practices on data and indicators to inform local governments and organisations in their efforts to alleviate this social blight. Therefore, to attain this goal, this literature review aims to answer the following RQs:

- What indicators are used at higher resolution scales (subnational) to assess energy poverty?
- What datasets and sources are being explored?
- What are the main takeaways, and what is lacking in regional measurement?

4.2.2 Literature Search

This review used Web of Science Core Collection and Scopus to search for peer-reviewed research papers connected to the aimed subject. As highlighted by Denyer and Tranfield (2009), the rigour of the search and selection process increases if two parallel sources are used. These databases have a considerably diverse collection of published scientific literature, crossing over different areas of study. One important note is that energy poverty is frequently described as fuel poverty, as the terms can be used interchangeably for the same meaning. Nevertheless, occasionally, they have slightly different meanings, as historically, EP has often been referred to as households' lack of access to energy in the context of developing countries. In contrast, the term fuel poverty originated in the UK and has been frequently used to define the inability to afford adequate warmth (Li *et al.*, 2014), especially in developed countries. This study only considers the latter definition, as it focused on the European Union. Still, both terms were included in the search since they are often used interchangeably. Aiming to maximise the collection of peer-reviewed studies developing assessments at smaller scales than the country level that consider this specific definition of the problem, the keywords "energy poverty" and "fuel poverty" were used in three separate searches, together with a group of keywords, depicting disaggregated assessments. The following string of keywords were used in the search: ("energy poverty" OR "fuel poverty") AND ("area" OR "areas" OR "area-based" OR "borough" OR "boroughs" OR "case study" OR "case-study" OR "cities" OR "Central" OR "city" OR "district" OR "districts" OR "East" OR "Eastern" OR "geographic" OR "geographical" OR "georeferenced" OR "GIS" OR "island" OR "islands" OR "local" OR "local-scale" OR "map" OR "mapping" OR "municipality" OR "municipalities" OR "neighbourhood" OR "neighbourhoods" OR "North" OR "Northern" OR "province" OR "provinces" OR "region" OR "regional" OR "regions" OR "rural" OR "small-scale" OR "small scale" OR "South" OR "Southern" OR "spatial" OR "territorial" OR "territory" OR "town" OR "towns" OR "urban" OR "ward" OR "wards" OR "West" OR "Western" OR "zone" OR "zones"). The Boolean operators "OR" and "AND" were applied to find any study that included "energy poverty" or "fuel poverty" plus at least one of these terms. A total of 2041 and 2355 studies were found in this initial search, respectively, on Web of Science Core Collection and Scopus.

4.2.3 Screening Process

The first criterion in the preliminary screening process was only to include English-written studies. Also, only studies from European countries were included, as the goal is to provide insights for local policy tailoring in this particular geographical context. Only studies from January 2010 to February 2023 were included. Only peer-reviewed articles were included in the pool. A manual check was then conducted to remove duplicates and join the records of both sources. Subsequently, a secondary screening process was conducted, focusing firstly on the title of each record. All the titles that described studies that did not connect in any way with the aim of this review were discarded. Those who met this criterion and the ones for which it was not possible to discern their eligibility were subject to the following screening phases: the abstract analysis and then the first context analysis. In this step, all the studies that used data, indicators, or metrics to identify and/or study the energy-poor population at disaggregated scales were included. Only studies focusing on the domestic sector were considered. Studies that do not conduct measurement at a subnational scale, only consider the regional factor as a dummy variable, or that do not present how EP identification was conducted were not included in the review. Some studies do not specifically mention energy poverty, but they address forms of energy vulnerability that are akin to the concept that this study aims to investigate. There is space for subjectivity in this step, as there is a component of bias deriving from the author's judgment when evaluating these research works. The screening process is displayed in Figure 4.1.

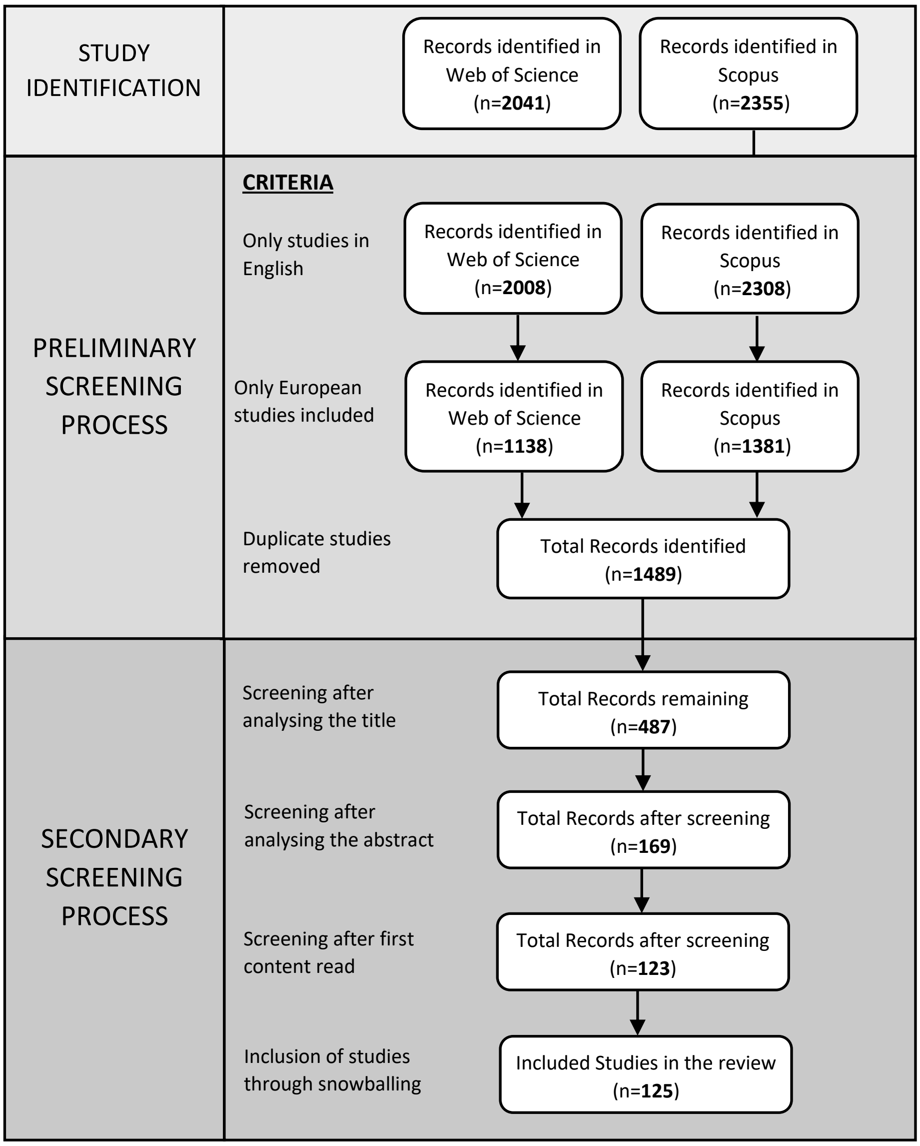

Figure 4.1 - Screening process schematic

4.2.4 Approach Analysis

The selected pool of indicators was analysed according to a set of criteria that enables a deeper understanding of their applications, advantages and shortcomings, as well as the identification of innovative and underexplored aspects of EP, datasets and approaches.

Composite indicators are analysed according to their integral parts to discern the primary indicators used in their composition. The goal is to obtain an insight into energy poverty measured at smaller scales, regarding its uses and effectiveness, to devise a set of valuable learnings for local governments and organisations to support their actions and policies for energy poverty assessment and monitoring, as for researchers to continue exploring to push forward the state of affairs and address potential gaps towards more robust measures. Several assessment criteria shaped the review, such as region, spatial and temporal scales, objectiveness and subjectiveness, object of measurement (causes, drivers or outcomes), territorial unit, category, outcome, type of indicator, topic, nature and origin of data, and target groups, inspired by authors like Rademaekers *et al.* (2016).

4.3 Results and Discussion

4.3.1 Overview

A wide range of indicators and assessment approaches have been developed for measuring EP at a higher spatial resolution – at the regional or local scale – across Europe. A total of 125 different studies were identified and analysed. The list is displayed in Annex A1. Examining the geographical distribution of the studies can provide insight into the level of focus on this issue across Europe, materialised in the resources and time employed to study EP.

Different regions also have important distinctions regarding climate, socioeconomics, energy consumption patterns, infrastructure, and EP levels, which can translate not only to the level of attention to this issue but also to the different approaches and indicators used to examine it. The countries per region are displayed in Annex A2. The majority of case studies focus on Southern European countries – Spain (41), Greece (18), Portugal (8), and Italy (5). This group of countries is particularly vulnerable to EP, as evidenced by the EU-SILC EP proxy indicators, displayed in the EPAH dashboard (EPAH, 2024b). These countries have generally low building energy efficiency (Anagnostopoulos and De Groote, 2016; BPIE, 2024) and household economic affluence (Eurostat, 2024a), and despite having warmer climates, they record alarming levels of inability to maintain an adequate indoor temperature in both seasons (Eurostat, 2024b; Eurostat, 2024c).

The Western European region is also well-represented, mainly due to the UK, as 26 studies focus on this country. France (4), Netherlands (4), Austria (3), Belgium (3), Ireland (1), Germany (1) also contribute to this pool. The high number of studies stemming from the United Kingdom is coherent with the historical recognition - the term was introduced in England (more precisely as "fuel poverty" by Isherwood and Hancock, 1979), and the longstanding tradition of EP study in this country (Mahoney *et al.*, 2020), which has produced a diverse range of studies focusing on the measurement of this phenomenon in the last decades at different spatial scales.

From the Central and Eastern European region, there is a more reduced pool of studies addressing measurement at smaller scales - 11 focusing on Poland, 4 in Hungary, 3 in North Macedonia, 2 in Ukraine, 1 in Croatia, 1 in Romania, 1 in Serbia, 1 in Latvia, and another from Romania. Poland is the outlier of this group, as EP has been on the radar of scientific inquiry for the past decade, with several relevant analyses produced. The study of EP measurement in other countries is still scarce, potentially due to other priorities capturing the attention of researchers despite signs of relevant EP issues in these countries. The northern European region is only represented by two studies, one in Norway and another in Sweden. The lack of case studies in this region may be related to the countries' lower EP rates and economic affluence despite growing inequalities on the horizon (Bredvold and Inderberg, 2022).

These numbers consider studies focusing on locations in different countries in the same study, thus amounting to a higher number than 125. Figure 4.2 presents the distribution of the number of studies per European region. Most authors of the reviewed studies agree on the importance of looking at EP through a magnifying glass, understanding the geography of patterns, what relates to the influence and impact of the different drivers, the characteristics of the energy-poor population, and the nuances of the complex landscape regarding climate, location, infrastructure, and politics and governance (Lis *et al.*, 2016; Mashhoodi *et al.*, 2019). An analytical background supported by the study of geographic context and vulnerability at smaller scales is paramount when tailoring local support initiatives and policies (Mashhoodi *et al.*, 2019).

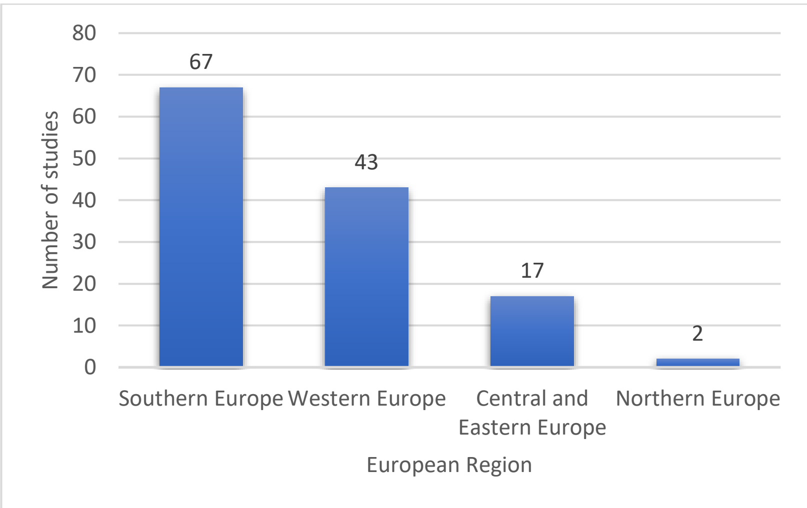

Figure 4.2 - Distribution of the number of studies per European region

Publications focusing on subnational EP diagnosis approaches have been on an upward trend since 2015 and reaching a peak in 2021, denoting a potential increase in interest and awareness of EP following the rise of policy attention regarding this topic in the EU. The cut-off date of the publication pool was February 2023, justifying the low number of studies in 2023. Figure 4.3 presents the distribution of studies per year of publication.

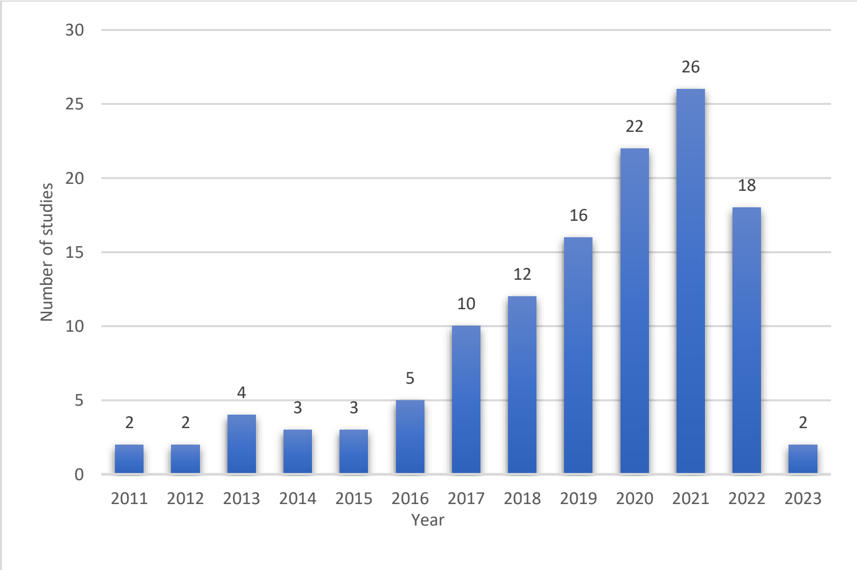

Figure 4.3 - Distribution of studies per year of publication

Most studies focus on specific areas within the country rather than developing a cross-country analysis for the whole territory (Figure 4.4). This may be a consequence of the lack of data for transferring the assessment to every territorial unit or just the specific aim of understanding the particular causes and expressions of EP in a location. While specific case studies are useful to deepen the understanding of EP in a particular place, potentially to a greater level of detail, cross-country approaches enable comparison between regions and the identification of the disparities regarding causal factors and effects of EP across the spatial scale, which can be valuable for orienting policy action. Studies are crafted at different territorial units: parish, municipality, neighbourhood, region, city, and others. The spatial scale of analysis is directly linked to the availability and representativeness of data resources. Data also influences the temporal scale. Most studies (102) undertake a snapshot analysis, using data for a normal past year (Figure 4.4). A smaller number of authors (19 studies) analyse how EP has evolved across a determined period, aiming to investigate the incidence and the temporal character of this problem over the years. There is a lack of studies addressing future vulnerabilities (only four), using data from forecasts and future scenarios to inform studies projecting future EP vulnerabilities at the local level.

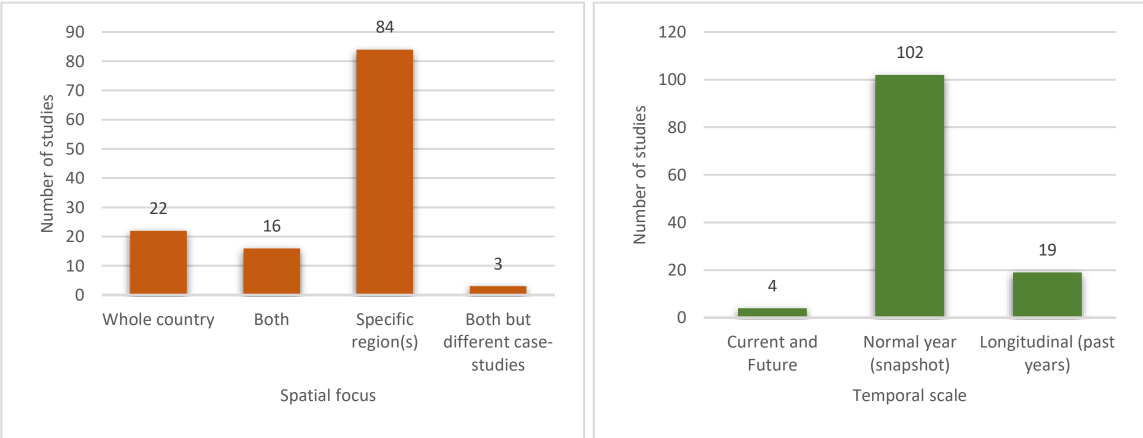

Figure 4.4 - Distribution of study per spatial and temporal scales

Although several analyses compare countries at the national level, only a few studies (7) conduct analyses of EP incidence or determinants across different contexts in several countries, such as Antepara *et al.* (2020), Stojilovska *et al.* (2021) and Desvallées *et al.* (2022). If these studies can provide in-depth, nuanced analysis, the findings are valuable for comparing the EP configurations in different geographies. Such analyses can be similar for different contexts, opening the possibility for knowledge transfer and enabling effective solutions to be more rapidly tested or adopted.

4.3.2 Approach

Data and indicators harnessed to construct a measurement approach have a philosophical paradigm as their foundation. However, the reduced EP resources at deeper spatial scales and the impossibility of collecting or producing new ones might limit the range of possibilities and ultimately determine the type of approach and philosophical stance that is adopted.

Several authors rely on secondary quantitative data from official statistics for a more objectivist approach to the endeavour of EP assessment, which focuses on measuring, for instance, the number of people in EP or the magnitude of their vulnerability. The same approach can be done with qualitative indicators. Still, some authors decide to employ a more constructivist approach, focusing on meanings rather than facts, from the belief that knowledge of a phenomenon is always a human and social construction (Bredvold and Inderberg, 2022). They aim to characterise what it is like to be in EP rather than quantifying or measuring it. Own data collection through interviews is one of the methods employed in this type of approach.

Following the predominant theoretical tradition in this field, the majority of studies develop quantitative analyses. Secondary data is still the most used resource (74% of the time), although 44% of the studies collected some form of primary data. Most studies (89) focus on measuring extent or incidence, *i.e.* the number of people affected by EP. As previously addressed by Hills (2012), Meyer *et al.* (2018) reiterate that monitoring energy poverty requires the analysis of its extent (number of affected households) and depth (magnitude or severity) and that these two factors are essential for policymakers to formulate instruments and decide on their actions. Depth is still an underexplored aspect of EP measurement at subnational levels, as only 16 undertook magnitude evaluations.

The dynamic and persistence of EP across the temporal scale is also relevant to address, as it magnifies the effects on the population and the difficulty of tackling it. Drescher and Janzen (2021), Karpinska and Śmiech (2021), and Halkos and Kostakis (2023) highlight the importance of assessing this aspect in EP measurements. At the regional level it is vastly underexplored, as only one study was found to address it.

A total of 65 studies delve into EP characterisation rather than more direct measurements of incidence or depth. Studies often characterise EP by collecting both quantitative and qualitative data. Only 11 studies employ a more subjective constructivist approach, such as Stojilovska *et al.* (2021), collecting qualitative data through surveys and questionnaires and analyses it qualitatively (*i.e.*, non-numeric information), exploring the link between household characteristics, decisions, and behaviours and EP.

A significant percentage of studies employ a mixed approach (48), using quantitative and qualitative data to assess EP. As previously mentioned, experts argue in favour of methods that consider the array of dimensions that characterise EP, bringing in and combining several indicators to more thoroughly capture the complexity of this social issue at different scales (Tirado-Herrero, 2017; Baker *et al.*, 2018; Thomson and Bouzarovski, 2018). This applies to the inclusion of objective and subjective aspects of EP, which enable a thorough understanding of this condition. The number of studies per nature and origin of the data can be observed in Figure 4.5. The number of studies per type of outcome is displayed in Figure 4.6.

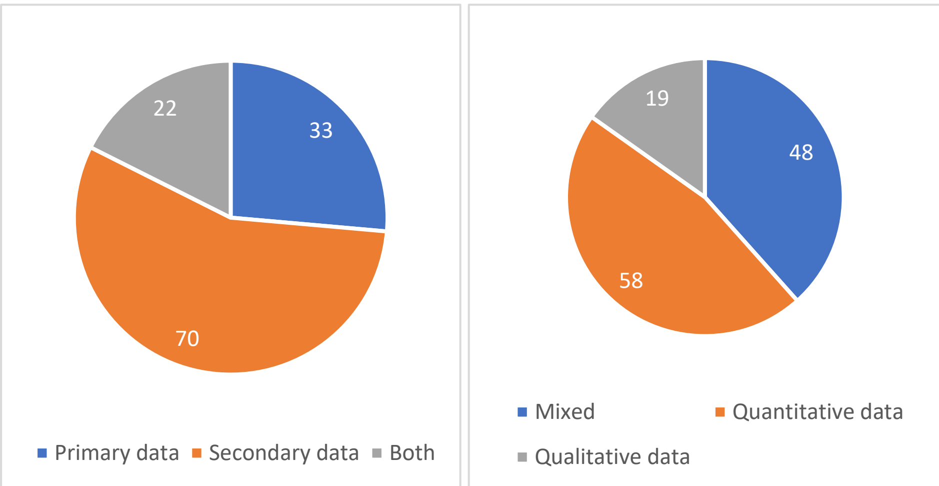

Figure 4.5 - Number of studies per nature and origin of the data

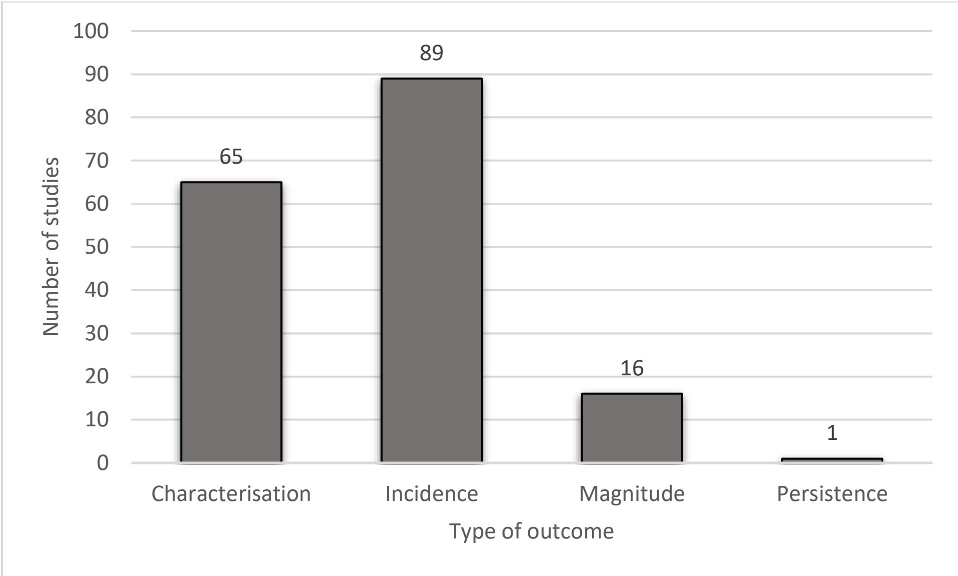

Figure 4.6 - Number of studies by type of outcome

Most studies address EP without a specific focus on the season, described as "Joint" in Figure 4.7, as they deal with aggregate energy consumption or expenditure. However, when EP in a specific season is assessed, winter and space heating (48) are more often the focus, as summer EP continues to be underexplored (only 16 studies), despite signs of increasing struggle with indoor cooling in the summertime in Europe (Thomson *et al.*, 2019). Twelve studies analyse EP in the heating and cooling season separately in the same study.

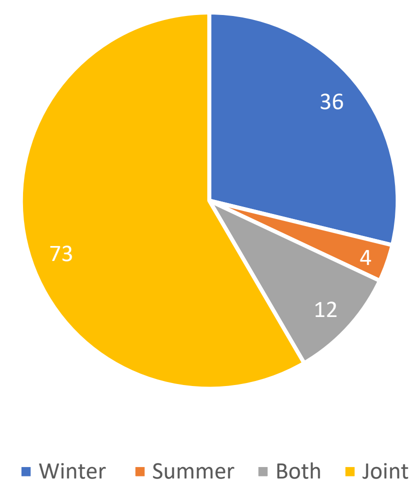

Figure 4.7 - Number of studies according to the season of analysis

4.3.3 Indicators

The methods applied in the reviewed studies are considerably diverse. Various authors adopted the traditional expenditure-based metrics, which are well established in the literature, such as the 10% threshold of income spent on energy and the Low-Income High-Cost indicator, developed in the UK. In fact, in UK case studies, such as those by Paravantis and Santamouris (2014), Fahmy *et al.* (2011), Robinson *et al.* (2018a), Marchand *et al.* (2019), this kind of indicator is still used for disaggregated assessments. These indicators have been historically used to capture the economic vulnerability of households. Outside of the UK, some authors in Southern Europe transferred these indicators to their specific contexts, such as Panão (2021), Lis *et al.* (2016), Sokolowski *et al.* (2020a), and Sokolowski *et al.* (2020b) in Poland; Aguilar *et al.* (2019) in Spain; Ntaintasis *et al.* (2019) and Spiliotis *et al.* (2020) in Greece. Panão (2021) in Portugal and Aguilar *et al.* (2019) in Spain compared the number of people identified as energy-poor with several expenditure indicators. Even when considering only one dimension of the problem, in this case, the economic dimension, the use of different indicators might result in the identification of different people. The 10% indicator, using a fixed threshold, provides a more binary and homogeneous assessment of EP vulnerability, although it is susceptible to the energy price driver (Panão, 2021; Robinson *et al.*, 2018a). Ntaintasi *et al.* (2019) and Spiliotis *et al.* (2020) used this threshold to mark the frontier between energy-poor and non-energy-poor in Greece. It should be noted that this indicator was tailored according to the British context and society, potentially not being as suitable for other contexts (Thomson *et al.*, 2017). Its use reveals a situation of path dependency, as a past indicator with arguably suboptimal outcomes persists due to historical preference (Banton, 2021).

Indicators such as "2M", "M2," and "LIHC" use relative thresholds, thereby avoiding this problem as they represent the reality of each context. Nevertheless, due to the relative thresholds, these indicators might falsely identify energy poor in high-income groups or non-energy poor in very low-income groups (Panão, 2021; Robinson *et al.*, 2018a). Romero *et al.* (2018) point out that these indicators portray inequality rather than poverty due to their relative nature. Authors such as Romero *et al.* (2018) and Barrella *et al.* (2022b) propose another type of household-level expenditure-base indicator, the Minimum Income Standard, for subnational scales, arguing that this indicator is more suitable to capture the objective nature of EP, overcoming misrepresentation issues of the 10%, LIHC and 2M indicators, and also considering a more detailed representation of the household expenses other than energy, for a more integrated analysis regarding household cost burdens.

Most expenditure-based approaches focus on analysing a specific type of EP - the measured EP (as denominated by Meyer *et al.*, 2018), which identifies EP as a problem of excessive expenditure in energy. Out of 125 studies, 64 measure this type of energy poverty. However, EP takes on different forms that need to be acknowledged in a comprehensive approach that identifies and considers the different manifestations of this problem and does not leave anyone out of the picture when it comes to energy poverty assessment and, ultimately, in providing aid. EP can also manifest as abnormally low energy expenses - 'hidden energy poverty' (KBF, 2015), as households restrict their consumption to reduce their energy cost burden in the household budget. Only more recently has this type of EP gained some visibility, and studies that set out to assess it are still scarce (12 out of 125) and mainly from a more quantitative perspective (Barrella *et al.*, 2022a; Desvallées *et al.*, 2022). However, it is a relevant expression of EP, especially in Southern European countries, where the combination of milder winters and high energy prices prompts households to adopt forms of coping with the cold.

EP can also be analysed through the households' self-experience regarding thermal comfort, health, coping mechanisms, and behaviours. It can be described as perceived EP, as it relies on households' reports of their situation. This form of EP is usually captured through qualitative indicators, although the use of this type of indicator can also integrate analysis of other nature. A total of 43 studies have been tailored to assess perceived EP. As previously mentioned, qualitative data can be employed more objectively to measure incidence or magnitude. Still, they can also serve a more constructivist approach focusing on characterising a household's EP, with qualifications of meanings and experiences. These indicators have different levels of subjectivity, providing various types of input to the analysis. The use of qualitative indicators in more objective assessments is more common, as several authors, such as Thomson *et al.* (2019), Papada *et al.* (2021), Lya *et al.* (2022) and Carrere *et al.* (2022), who use indicators of ability to keep home at adequate temperatures, difficulty in paying bills and signs of dwelling deterioration to assess EP in their case-studies.

Authors have found a limited overlap of objective (based on energy expenditure) and subjective indicators (Wadams-Price *et al.*, 2007; Fahmy *et al.*, 2011; Meyer *et al.*, 2018) of the incidence of energy poverty. Dubois *et al.* (2012) propose that this is due to the rationing of energy consumption by people who claim to be in energy poverty. Still, Meyer *et al.* (2018) affirm that this hidden EP can only partially justify the limited overlap, thus stating that people who claim to be energy poor are not detected by the objective expenditure measures analysing measured and hidden EP. This emphasises the importance of considering both types of measures in EP assessments.

Various authors develop mixed approaches using quantitative and qualitative indicators (Fahmy *et al.*, 2011; Boemi *et al.*, 2017; Boemi and Papadopoulos, 2019; Sokolowski, 2020a; Bardazzi *et al.*, 2021; Eisfeld and Seebauer, 2022). Sokolowski *et al.* (2020a) created a five-indicator framework composed of two objective and three subjective indicators, with cut-off points resulting in a weighted level of energy poverty. Bardazzi (2021) also calculated five indicators of energy poverty, two consensual-based and three expenditure-based, and performed a multivariate analysis using other indicators as determinants or independent variables representing income inequality and socioeconomic conditions, as the goal was to explore the connection between energy poverty, income inequality, and socioeconomic factors. Boemi *et al.* (2017)

collected quantitative (income, building characteristics, socioeconomic) and qualitative indicators (self-perceived thermal comfort, arrears on utility bills, energy measures implementation) to relate energy poverty, education level, and energy behaviour in the economic crisis in northern Greece. Boemi and Papadopoulos (2019) used the two types of indicators informed by collected questionnaire data to study the relationship between energy poverty and health impacts and the adoption of energy efficiency measures. Einsfeld and Seebauer (2022) used income, expenses, and subjective indicators regarding heating behaviours and environmental concerns to investigate whether energy-poor households are overlooked due to self-restrictive heating. For England, Fahmy *et al.* (2011) also used quantitative (income, energy prices, energy costs, building data) and qualitative, subjective indicators to investigate the better predictors of energy poverty in regression analysis and predict the odds of a household being energy poor.

These authors combine the analysed indicators in distinct ways and with varying levels of complexity: some conduct a direct comparison of indicators, some build linear mathematical models, deterministic by nature, while others advance statistical analyses trying to estimate the probability of specific outcomes. Each method is selected according to the study's goal and the type of outcome the authors aim to obtain. Most statistical approaches provide correlation analysis between EP predictors and local prevalence estimates, estimated via direct EP metrics. They enable data-driven multivariate analysis that captures the complex origins of EP, discerning the most impactful determinants and how they relate. They allow a systematic assessment of the problem. Longa *et al.* (2021) point out that this kind of approach provides an established and transferable methodology to estimate the weight of each EP determinant, a research gap identified by Walker *et al.* (2012), who state that drivers are often assessed using the intuition or common sense of the authors or consulted experts or predefined models. Machine learning models have advantages in the statistical field compared to traditional regression models, as they are more equipped to handle big data sets. They do not necessitate prior assumptions on the correlation of factors and can deal with non-linear dependencies, which is important when studying complex issues such as EP (Longa *et al.*, 2021). Replication of these models to other contexts is also possible. Nevertheless, they are complex to build and analyse, requiring expertise that may not be at hand for local governments or organisations. On the other hand, looking at the other side of the spectrum, deterministic approaches supported via assumptions can be more straightforward to apply and allow for a broader range of parameter testing. However, these are potentially less replicable and scientifically sound.

Generally, the predictors are variables regarded as supporting EP indicators, not directly used to measure EP, but that can impact vulnerability. These indicators address different EP-related dimensions such as climate, household economics, health, education, household composition and demographics, environment, air quality, and building quality. Several studies (32) developed quantitative, multidimensional approaches capturing more than one dimension of vulnerability using supporting indicators, such as Gouveia *et al.* (2019), Martìn Consuegra *et al.*

(2020), Sanchez *et al.* (2020), Castãno-Rosa *et al.* (2020), Alba-Rodriguez *et al.* (2021); Karpinska *et al.* (2021), among others. They use groups of indicators representing climate, building characteristics or energy performance, energy consumption and HVAC equipment, energy prices and expenditures, and socioeconomic features of households, such as income, age, or employment status, encompassing the three leading causes of EP. Gouveia *et al.* (2019) calculated a vulnerability level for all of Portugal's civil parishes, identifying vulnerability hotspots. Martìn Consuegra *et al.* (2020) combine indicators to study the severity of energy poverty in deprived neighbourhoods in Madrid, aiming to establish priority areas for refurbishment. Castãno-Rosa *et al.* (2020) and Alba-Rodriguez *et al.* (2021) use a composite assessment considering monetary, energy consumption, and thermal comfort indicators and a Health-Related Quality of Life Cost analysis to assess energy poverty vulnerability for case studies in Spain. For Madrid, Sanchez *et al.* (2020) used several indicators to calculate energy poverty incidence, identified the most important indicators at the city level, and then drew conclusions using proxy indicators at the district level. Karpinska *et al.* (2021) first calculated energy prevalence with expenditure and energy consumption indicators. Then, they used a varied set of indicators to explain and identify different profiles of energy poverty at the local scale. The distribution of studies per type of EP is displayed in Figure 4.8.

These types of measures enable the use of supporting proxy indicators that are frequently available in national statistics, making up comprehensive assessment frameworks and offering important insights. Proxy indicators for which available data exists help overcome the lack of important datasets, which, as pointed out by Sanchez *et al.* (2020), is a common issue in finer spatial scale assessments.

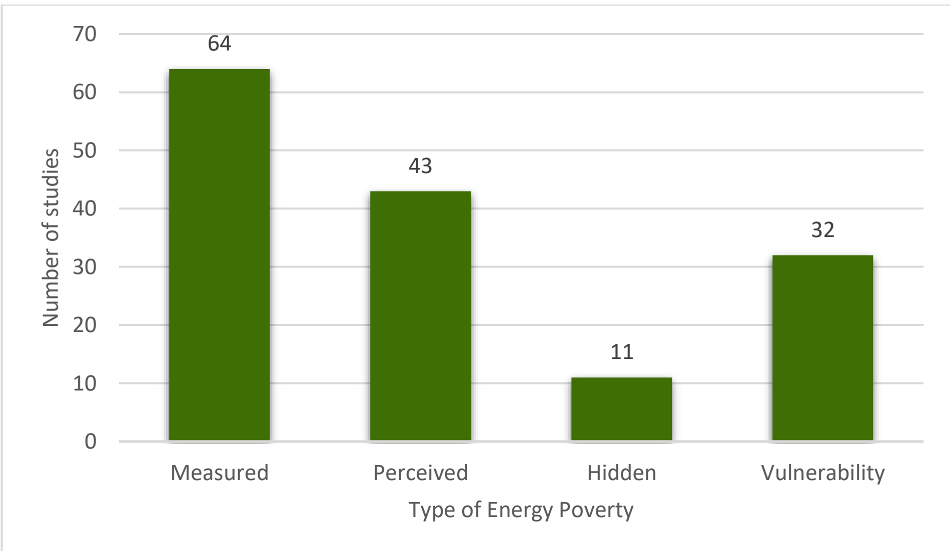

Figure 4.8 - Distribution of studies per type of energy poverty

Aggregate models can still fall short of encompassing all the facets and dynamics of EP in every geographical area. Approaches adapted to local characteristics and specificities of culture, habits, sociodemographics, and economy are necessary, but adequate indicators must be included for a comprehensive technical analysis (Sokolowski *et al.*, 2020a). This becomes evident when observing the varying results of the analysed case studies across Europe.

Of all the indicators used in the review, income is the most popular, appearing in 93 studies, denoting the significant weight still given to the economic dimension in the study of EP. It is followed by building indicators, 91 in total. It should be noted that income is often used in direct indicators as expenditure-based, whereas building indicators are more often used as supporting indicators. Energy expenditures and prices are present in 73 articles, whereas consensual-based indicators analogous to the EU-SILC stats are used in 51 studies and more direct assessments. The number of studies per main indicator type can be consulted in Figure 4.9.

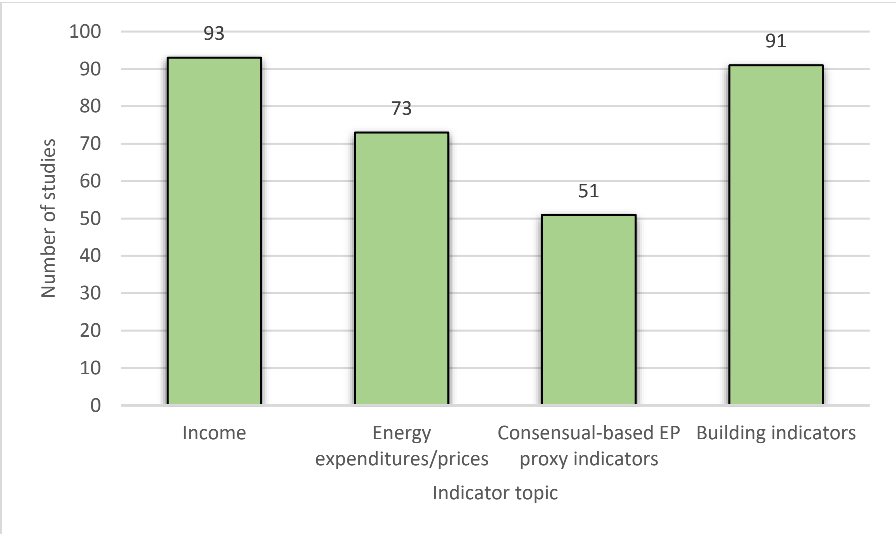

Figure 4.9 - Number of studies per main indicator type

The outcome of objective approaches can assume different forms, from a binary representation, more common in incidence analysis, to a range of values, often seen in vulnerability-based approaches. It is also connected with the scale, as averaged area-based approaches are usually based on vulnerability approaches, whereas binary assessment often relies on household data. In binary outcome approaches, thresholds are frequently used to characterise the dependent variable and divide the energy poor from the non-energy poor. Different thresholds can significantly impact the exercise of identifying the energy poor and assessing its magnitude (Longa *et al.*, 2021). Therefore, they have considerable influence on policy instruments if these methods are to be used for policy formulation. On the other hand, a range of values avoids this constraint, but meaning that translates to a real application has to be attributed to the values.

Robinson *et al.* (2018) and Morrison and Shortt (2008) warn of the ecological fallacy in area-based approaches, as aggregated area-based data can hide variations of energy poverty vulnerability at even smaller scales, namely at the neighbourhood level. Kelly *et al.* [68] corroborate this assertion, stating that aggregate and average data mask issues and that finer spatial scales are preferable from social and policy perspectives. It is possible to identify a trade-off situation where small-scale analysis should be prioritised, but the finer the scale, the lower the amount of data available, as there are issues in data sourcing in European countries at finer spatial scales. Ultimately, data availability is the key to improved disaggregated energy poverty assessments.

Some authors resorted to indicators not common in EP assessments, standing as alternatives to common proxy indicators. An example of this instance is the use of the property value of buildings as a proxy of the economic status of their occupants or housing quality (Fahmy *et al.*, 2011; Robinson *et al.*, 2018a; Longa *et al.*, 2021) or property age as a proxy of their energy efficiency (Walker *et al.*, 2014; Mulder *et al.*, 2023). Other authors propose indicators not usually featured in EP analysis but can provide insight into overlooked links with EP, expanding the scope of analysis in the study of EP. Boemi and Papadopoulos (2019) identify outdoor space, namely the presence of green spaces, as a relevant factor to consider in their case study. Pignatta *et al.* (2017) also integrate the quality of the neighbourhood and the existence of green spaces and a good outside view. Von Platten (2022) considers the self-perceived flexibility capital to respond to a hardship situation. Robinson *et al.* (2018b) also assessed a similar indicator, the lack of capital to invest. Bouzarovski and Thomson (2018) and Ortiz *et al.* (2021) investigate the occurrence of energy disconnections, an indicator more used in Global South populations but also represents a reality in the EU. On the same topic, Desvallées *et al.* (2022) identify energy cuts as a sign of EP and Llera-Sastresa *et al.* (2017) examine the characteristics of energy installations, such as voltage. Ramsden (2020) looks at energy payments and highlights that changing payment methods can be synonymous with hardship. Avanzini *et al.* (2022) and Castaño-Rosa *et al.* (2019) assess quality of life in relation to EP. Robinson *et al.* (2018b) assess a range of different indicators - physiological need for energy services, underrepresentation in fuel poverty policy, lack of awareness of support, social relations in/outside the home and unhealthy warm-related practices. Within the building dimension, Taltavull de La Paz *et al.* (2022) integrate dirt and pollution as worthy of further investigation in relation to EP. On the subject side, Heredia *et al.* (2022) draw a link between EP and emotions. This link can also be framed in the capabilities approach. Pellicer-Sifres *et al.* (2021) investigated the impact of EP in six central capabilities - health, emotions, affiliation, play, practical reason and senses. The authors find that EP can directly harm these six capabilities, which calls for addressing EP as a energy justice problem.

It is crucial that indicators can increasingly capture the variability of the human condition, namely the different vulnerabilities of population groups. Most approaches are not crafted to accurately identify the most vulnerable groups, which are at the nexus of various forms of hardship. However, several studies aim to study these groups or account in some way for the added vulnerability (76), either by assessing the EP situation of households belonging to these groups or by attempting to establish a link between typical EP indicators and other vulnerability indicators. Sociodemographics characteristics that are linked to potential added vulnerability such as gender, age (elderly and children), education level, household composition (*e.g.* lone parent), tenure status, employment status, occupancy, social support recipiency, are by far the most integrated aspects in subnational EP studies, as 92 studies examine at least one of these factors. Health issues, general health mortality and disability are becoming relatively more common, being found in 42 articles. Other vulnerable groups such as immigrants, ethnic minorities, people living in informal housing, and people in a homeless situation are primarily absent from these studies. They can have a relevant expression in particular regions. Increasing focus on these groups is an important step forward, bridging the gap between EP study and recognition justice (McCauley *et al.*, 2013).

Other relevant aspects to the study of EP, though not necessarily related to a situation of heightened vulnerability, can be found in this pool of studies. Climate indicators, representing a determinant of energy needs, are integrated in 41 studies, whereas energy behaviour, a means of coping with EP and saving energy, has been assessed in 26 studies. Indoor conditions inside the home, namely indoor temperatures, are underrepresented, being a relevant component in only 24 studies. The distribution of studies per use of supporting indicator topic is displayed in Figure 4.10. The underrepresentation is even more evident when considering air quality, which is thoroughly absent. Sustainability and environmental impacts of energy provision are also not considered in this group of studies, just as Siksnelyte-Butkiene *et al.* (2021) described in another review. It links with the principles of Sustainability and Responsibility for protecting the natural environment, proposed by Sovacool *et al.* (2016), which provide extra insight for studying energy deprivation within the broader and more comprehensive energy justice framework. Nowalska-Kapuścik (2021) briefly addresses the latter by households' examining recycling habits.

Energy literacy and cultural behaviours are also not integrated into these subnational EP assessments. They should be further investigated as they can actively contribute to shaping EP vulnerability, as shown in behavioural studies such as Horta *et al.* (2019) and Bredvold and Inderberg (2022). Literacy is also connected with transparency and access to information and decisions, as described by Sovacool *et al.* (2016), which are paramount for a broader understanding of vulnerability. Territorial configurations (*e.g.* rural and urban) are addressed in 32 studies, which is pertinent since relevant differences in EP vulnerability across typologis have been found (Roberts *et al.*, 2015; Simcock *et al.*, 2021). Weather dynamics, namely the impact of extreme weather events (cold spells, heat waves), is significantly unaddressed, as only four studies focus on their connection with EP.

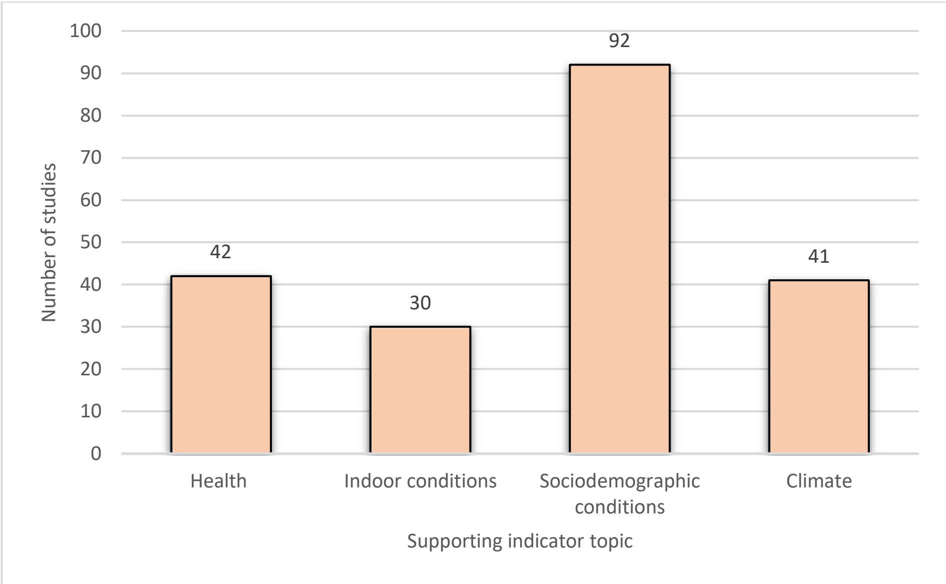

Figure 4.10 - Distribution of studies per use of supporting indicator topic

Siksnelyte-Butkiene *et al.* (2021) also highlight the importance of stakeholder consultation in building a more democratic and legitimate approach with the local actors and population. Stakeholder participation can occur in different fashions and at different phases, such as type of approach selection, data collection, and indicator selection, combination, or weighting. Only in 7 of the 125 studies were stakeholders an active part of the process.

The ability to respond to crises and unpredictable circumstances that require higher energy costs, highlighted by von Platten (2022) and Robinson *et al.* (2018b), is also a relevant aspect to analyse and show has a more prominent position in measurement approaches, as only seven studies address it in some form. The joint analysis of EP with the deprivation of other essentials is key, as a household may not be identified as EP due to self-imposed deprivation of another basic need such as water, food or housing. This circumstance is described by Castaño-Rosa *et al.* (2019), and it is examined in a few of the reviewed studies such as Castaño-Rosa *et al.* (2020), Bouzarovski and Thomson (2018), Balaskas *et al.* (2021) and Taltavull de La Paz *et al.* (2022), through different indicators. Robinson and Mattioli (2020) linked domestic EP with transport EP, as the transport cost can be a significant burden and constitute an energy expense in fuel. The intersection of different types of deprivation should gain further traction in local assessments and constitute an integral part of EP measurement for a more inclusive approach that captures the diverse underpinnings of EP.

The connection between EP prevalence and the implementation of different mitigation measures can give local governments valuable knowledge to draft their mitigation strategies according to the most effective measures and households/regions in need. From the pool of review studies, Walker *et al.* (2013) associated the number and type of retrofits with energy poverty risk, and Carrere *et al.* (2022) established the connection between EP and council interventions. Still, there is plenty of room for exploration regarding this aspect, which is particularly relevant for policymaking. Several identified underexplored aspects of EP analysis are presented in Table 4.1.

Table 4.1 - Underexplored aspects in subnational EP analysis

Underexplored aspects in local EP measurements	**Authors that have addressed these aspects (not exhaustive)**
Exploring EP resilience and variation in extreme weather events	Mashhoodi *et al* (2019); Thomson *et al.* (2019); Sánchez *et al.* (2020b)
Sustainability and environmental impact of energy provision	None
Promoting stakeholder participation	März (2018); Gouveia *et al.* (2019); Sánchez-Torija and Nieto (2022)
Including vulnerable groups such as immigrants, ethnic minorities	Sanchez *et al* (2020a); Brunner *et al.* (2012)
Explore the connection between EP and the restriction of other essentials	Castaño-Rosa *et al.* (2020); Bouzarovski and Thomson (2018), Balaskas *et al.* (2021); Taltavull de La Paz *et al.* (2022)
Examine resilience of households in case of emergency	None
Analyse indoor air quality and ventilation	Ortiz *et al.* (2021); Stevens *et al.* (2022);
Assess the link with the lack of energy literacy and the lack of access to information	None
Identify connections with cultural aspects	Horta *et al.* (2019) and Bredvold and Inderberg (2022).
Estimate EP reduction due to specific interventions	Walker *et al.* (2013); Carrere *et al* (2022)

Several authors (40 in total), such as Gouveia *et al.* (2019), Robinson *et al.* (2018a), and Murage *et al.* (2018), use GIS data to map results supporting visualisation and better spatial understanding. Georeferenced data enables the mapping of energy poverty estimates and, thus, the identification of "cold" and "hot" spots of energy poverty, which is the basis for zonal policy approaches, where certain areas are targeted to receive greater support than others based on differences in vulnerability März, S. (2018). It also enables clustering analyses to identify the geographical context – if it is an outlier zone ("hot" in a "cold" area or "cold" in a "hot" area) or part of a homogeneous landscape of vulnerability, as described by Robinson *et al.* (2018a) and Walker *et al.* (2012).

4.3.4 Data

The availability of adequate data is vital for obtaining information on energy poverty vulnerability in small areas, namely on the varying nature and magnitude of its determinants. This knowledge can inform local policies and programmes for addressing areas in greater need – the highest incidence and extent of energy poverty – and improve the effectiveness of the use of resources (Fahmy *et al.*, 2011). The efficacy and effectiveness of instruments depend not only on the adequate identification of vulnerable people but also on matching the type of support to the characteristics of the people in need (Roberts *et al.*, 2015; Lis *et al.*, 2016). Nevertheless, the lack of data remains one of the most complex challenges in energy poverty measurement, both at a macro or local scale (März, 2018; Sareen *et al.*, 2020) . As this review observes, data availability considerably shapes the studies at minor scales. As März (2018) affirms, using alternative supporting indicators- prevalent in most subnational scale studies- is a way to bypass the lack of data for pinpointing the energy poor. However, not every proxy indicator is comprehensive enough to help study the complexity of energy poverty. A considerable diversity of datasets was identified in the reviewed studies. Several authors of the analysed studies shaped their assessments according to the available data, whilst others collected their own data through surveys and questionnaires. The data used determines the scale of analysis - different spatial scale resolutions are explored in the reviewed works, from Nomenclature of Territorial Units for Statistics (NUTS) 2 to very small scale like the Lower Layer Super Output Areas in the UK. The smaller the scale, the more specific and potentially hard-to-get the data is.

Most of the analysed studies (83) rely on some kind of official statistics from state or governmental entities at different scales, although most data resources stem from central government entities. Data available varies according to the country where the case study is conducted. Census data are relevant datasets in these assessments and are used in case studies across the European Regions. The National Statistics Office often provides census data disaggregated by administrative units for some countries at a very small scale. England, the recommended size is 125 households for each output area. The census statistics feed diverse indicators, from socioeconomic to building stock envelope and equipment characteristics, often used as energy poverty proxies in the analyses. An important limitation of census data is its frequency – these statistics are only collected every ten years. Some indicators, such as unemployment and sociodemographic conditions, become outdated quickly. For building data, as changes in that particular sector are bound to be slower, they still hold value after a few years. In the scope of a census, there is no data collection to directly inform a specific indicator to measure EP. Only in the UK do national authorities provide direct EP statistics at the local scale.

National surveys are one of the most used sources of official data for subnational EP assessments. There are several examples of national surveys which vary across countries. Some examples are household (or family) budget surveys, House condition/Housing survey, Income and Living Conditions, Energy Consumption in the Domestic Sector Survey, and National Survey on Family Income and Expenditure. HBSs are also a prevalent source of data used in these studies, releasing data every five years on energy consumption (*e.g.*, consumption levels, equipment ownership) and expenditure, often used in EP measurements. This was used in Western, Southern and Central and Eastern European countries, namely the UK, Italy, Portugal, Poland, Czechia, Hungary, Spain, and Scotland. These are conducted with a representative sample of people from across each country. Results are given at the national or NUTS2 level; hence, it only enables regional analysis and not local. Nevertheless, they often combine useful socio-economic indicators with dwelling information at the household level (Panão, 2021; Karpinska *et al.*, 2021), which can be used to understand correlations between variables. The HBS is also used to collect qualitative data on the households' perceived thermal comfort and dwelling conditions, which are the cornerstone of consensual-based energy poverty indicators (Lis *et al.*, 2016; Karpinska *et al.*, 2021).

Conducted in a similar way to the HBS, the Energy Consumption Survey (ECS) also provides valuable information on household energy consumption broken down by energy use – generally collected every five years. This is utilised in studies that apply direct measurements of energy or performance gaps to identify the energy-poor, as demonstrated by Gouveia *et al.* (2019) and Karpinska *et al.* (2021). National statistics from several state entities are also a key data source for the reviewed studies. Departments dedicated to energy issues (such as the DECC and BEIS) and statistical authorities (such as INE for Portugal and Spain, Hellenic Statistical Authorities for Greece, KWB for the Netherlands, or ISTAT for Italy) provide socioeconomic, energy tariff, building, energy consumption and even climate data.

Eurostat is also a reliable data source, namely the European Union Statistics on Income and Living Conditions, providing longitudinal and cross-sectional proxy indicators of energy poverty at the NUT2 level for the EU MSs, which can be valuable for regional assessments, as in Meyer *et al.* (2018). This database also provides socioeconomic data at the same scale. Although the authors rely primarily on national official data sources, EU SILC and other Eurostat data have been mainly used in Spain (*e.g.*, Martín-Consuegra *et al.*, 2020; Alba-Rodríguez *et al.*, 2021; Castaño-Rosa *et al.*, 2020); Greek (*e.g.* Papada and Kaliampakos, 2019; Karpinska and Smiech, 2020; Lyra *et al.* (2022). These provide relevant proxy EP indicators, which have been historical anchors for EP studies and are still reference indicators in the Energy Poverty Advisory Hub (EPAH, 2024b). A critical advantage of the Eurostat database is that it provides comparable data between the MSs. Although HBS are conducted in virtually all EU MSs, questionnaire methodologies might vary across countries, and the harmonisation of categories is not ensured; hence, the results are not so easy to compare.

At the national level, energy prices and consumption levels are occasionally collected from energy providers (Ntaintasis *et al.*, 2019). Climate data such as heating and cooling degree days or seasons and average outside temperatures can be accessed from European databases like Eurostat and the Commission Joint Research Centre, which provides data for Bardazzi *et al.* (2021). However, more disaggregated data can be withdrawn from national entities like meteorological institutes. These provide local data from available climate stations in every country (as in Walker *et al.*, 2012; Lis *et al.* (2016); März *et al.* (2018); Mashhoodi *et al.*, 2019; Spiliotis *et al.*, 2019;). Regulations on the energy performance of buildings (Simões *et al.*, 2016; Gouveia *et al.*, 2019; Besagni and Borgarello, 2019) and energy modelling software (Castaño-Rosa, 2020; Alba-Rodríguez *et al.*, 2021) are also used as a source of climate data.

Apart from the census and national surveys or other statistical authorities, building data is occasionally collected from studies in literature and academia (Simoes *et al.*, 2016; Gouveia *et al.*, 2019; Alba-Rodríguez *et al.*, 2021), including the regulations on energy in buildings (Spiliotis *et al.*, 2020), and energy modelling software (*e.g.*, Fahmy *et al.*, 2011). Energy performance certificates (EPC) are an essential source of building and equipment and energy needs data used in a few studies (Fabbri and Gaspari, 2021; Camboni *et al.*, 2021); EPC data are more often used to study building energy use and consumer profiles, rarely integrating EP assessments. EPC provides information on the building stock characteristics and thermal performance at higher spatial resolution, which is rare, especially in the topic of buildings, which is one of the root causes of EP. As EPC schemes are continuously enforced in the European Union, with the subsequent ongoing data collection (at least 24 MSs have established EPC registries) (BPIE, 2014), the potential of this data source is increasing. However, there are often some constraints regarding its use due to confidentiality issues, preventing its wider use. The entities responsible for managing them are conscientious when sharing data, even for research purposes. Some municipalities are responsible for managing the EPCs for buildings, which makes it possible for their data to be disclosed for research purposes (Fabbri and Gaspari, 2021) or used in their EP assessments. Land registries can also provide building data (Sanchez Guevara *et al.*, 2019). The digitalisation of the energy sector is producing large amounts of relevant, trusted data, which can help shape EP measurement studies. Big data is collected through smart meters, building automation systems, sensors, thermostats, and mobile devices. In households, these can be used to collect data on temperature, humidity, occupation, and energy consumption indicators. Among the research works reviewed herein, only one (Gouveia *et al.*, 2018) used smart meter data directly to study energy poverty, particularly for cross-referencing electricity consumption profiles with socioeconomic data and building energy simulation in a small case study. While data confidentiality issues are a considerable barrier to the use of this highly granular data, there is significant potential for leveraging these data resources in EP research in the future.

Several studies use regional or municipal data stemming from city surveys or agencies/entities, mainly in Spain. Examples are the Urban Audit database for Madrid and the Greater London Authority, providing income for Sanchez Guevara *et al.* (2019); or municipal agency for Zaragoza, providing socioeconomic and building data to Llera-Sastresa *et al.* (2017); or Barcelona's municipal register also providing socioeconomic and building data to Marí-Dell'Olmo *et al.* (2022); Barcelona Health Survey providing socioeconomic data to the latter authors, as well as to Oliveras *et al.* (2020) and Carrere *et al.* (2021); and the NINIS (Northern Ireland Neighbourhood Information Service), providing the same type of data to Walker *et al.* (2012).

Non-governmental organisations (NGOs) can also be a source of data. Desvallées *et al.* (2022) used data from two NGOs on income, energy expenditure, consensual-based indicators and energy cut-offs to assess EP in Porto and Barcelona. Nevertheless, this was the only case identified where this type of entity provided data for a subnational study.

Addressing the available official data in Spain, Sanchez *et al.* (2020) argue that there is limited official statistical data regarding energy-poverty-related indicators, pointing out issues in data disaggregation, update, and the discontinuity of indicators, which mainly apply to surveys such as those mentioned above. These issues pose a challenge for tracking the evolution of the problem. This review makes it apparent that most of these assertions are valid for other European countries. Furthermore, the authors defend the need for a dedicated EP section in existing surveys to improve statistical resources.

It is important to highlight another significantly relevant data source for several of the analysed studies – questionnaires, surveys and interviews conducted by authors to collect primary data for their research. These methods have been conducted in 46 of the 125 reviewed studies across all European regions, such as Boemi *et al.* (2017), Gouveia *et al.* (2018), Boemi and Papadopoulos (2019), Sokolowski *et al.* (2020a), Stojilovska *et al.* (2021), and Eisfeld and Seebauer (2022).

These surveys or interviews conducted explicitly to assess EP can be less ambiguous and more apt to capture the different facets of this issue. They enable the collection of various types of indicators, from energy expenditure and self-perception of the cold or warmth to building characteristics and socioeconomic features. These methods allow intersecting indicators and data from different dimensions, unveiling relevant connections that shed light and help deepen the understanding of EP. In this kind of survey, health indicators such as doctor visits, disease rate, and types of health problems are collected to analyse energy poverty impacts on the population (Boemi *et al.*, 2017; Papada and Kaliampakos, 2019; Besagni and Borgarello, 2019; Sokolowski *et al.*, 2020a; Carrere *et al.*, 2021). These surveys enable the collection of detailed data on energy behaviour, coping strategies, and heating periods (Boemi and Papadopoulos, 2019) and thermal comfort assessments (Castaño-Rosa *et al.*, 2020; Alba-Rodrìguez *et al.*, 2021).

Such surveys are an effective tool to overcome difficulties in accessing adequate data or the lack of data, but they require expertise and resources. The quality of these results is highly dependent on interviewee answers, which introduces the factor of unpredictability and error. If conducted periodically, at least yearly, they can track EP levels more frequently instead of relying on outdated national statistics.

4.3.5 Potential Future Developments

There are various official data sources, but since datasets are collected using different methods, timescales and different forms, it is always a challenge to combine them and not introduce an unreasonable percentage of uncertainty to the assessment that could jeopardise its scientific soundness or replicability potential. This is a difficult gap to overcome because it is an issue at the source, depending on decisions from the policymaking side. Camboni *et al.* (2019) propose a method to match different sources of information at the micro-scale (EPCs and socioeconomic from administrative sources) to identify areas at risk of EP. This is an example of a method confronting the considerable barrier of official data harmonisation. Further investigation on this topic, namely on transversal approaches, could prove helpful for the multi-source comprehensive analysis of energy poverty, as changing the political modus operandi is often an arduous endeavour.

Citizen science is a relevant but untapped source of data emerging in natural science, which has significant potential. ENGAGER (2019) points to its essential role in new research approaches and more participatory and democratic forms of knowledge production. As it assumes more relevance, these data sources can fill gaps in official datasets, particularly regarding qualitative indicators. In their study, Frankowski *et al.* (2020) show how citizen science data, namely smog alerts, can be leveraged to explore the connection between air pollution and energy poverty.

Local governments and agencies often design their policies and programmes based on data collected informally through multiple methods, from social services, advice points, helpdesks, surveys, online platforms for support programme applications, home visits, and other forms of contact with the population. These datasets are not to be neglected, as they facilitate identifying energy-poor households and support policy measures when other datasets are absent. The EPAH Atlas provides several examples of local governments using and collecting their own data to support their initiatives (EPAH, 2024c). Three examples are provided: In the Italian project “Energia su Misura”, conducted by the local authority Comune di Milano, energy bills of families living in social housing were consulted, and smart meters were installed to engage the identified families and provide them with personalised reports and advice. The city of Sztum in Poland conducted a survey with single-family households of a specific quarter for collecting data on buildings (type, age, thermal insulation, past renovations) and socioeconomic data (income, age, number of people), which will be used for upcoming measures to reduce emissions and subsequently improve health and comfort conditions for citizens in the city. In Barcelona, the project "Indicadors municipals de pobresa energètica a la ciutat de Barcelona" compiled and assessed various local datasets from state surveys, local projects, social services, and energy advisory points to estimate energy poverty at the local scale in Barcelona. Finally, in Portugal, through a network of different partners, the project “Ponto de Transição” is assembled one-stop-shop on an renovated maritime container to collect data and provide energy advice for the residents of municipalities from the greater Lisbon area, as well as providing training to young agents who conduct home visits for even more personalised support to households in need (Gouveia *et al.*, 2024).

Several underexplored indicators are highlighted in this study, and their integration in EP subnational analysis can provide additional insight for understanding the varying shapes and colours of energy deprivation across population groups. Examining the interconnection with energy justice aspects is particularly relevant, as it provides a more comprehensive and deeper analysis of EP causal factors and lasting effects while broadening the analysis in the temporal and spatial scales. Other energy justice principles can be integrated besides the already mentioned aspects of transparency, sustainability, and environmental responsibility (Sovacool *et al.*, 2016) and recognition justice (McCauley *et al.*, 2013). For instance, the ownership of the means of energy generation is relevant to lower energy bills but also to increase households' and regions' energy sovereignty (Timmermann and Noboa, 2022), which is essential for higher degrees of self-determination that guarantee more long-lasting mitigation action. Further study of Due Process (Sovacool *et al.*, 2016) and Cosmopolitan justice (Phillips, 2023) could frame EP in the broader context of rights and justice outside the geographical case-study context. It is essential for a more internationalist perspective of EP as a problem that is produced and reproduced within a complex weave of relations and exchanges across the globe linked to distributional injustices. Furthermore, examining intergenerational equity (Sovacool *et al.*, 2016) and restorative justice (Heffron and McCauley, 2017) can unveil persistent and deep-rooted determining factors affecting past generations and projected unaccounted effects on future generations. Both should be considered when planning for action that tackles EP in contemporary generations without potentially increasing risk for future ones.

4.4 Conclusions

Energy poverty remains a severe problem in the European Union, affecting the lives of millions of people across the continent. As funding is increasingly unlocked to address this issue at the policy level, adequate diagnosis is a key component for effective programs and measures that tackle its structural causes and produce long-term impacts. Building on the Energy Poverty Advisory Hub and the European Commission's emphasis on the need for regional and local level action to address the varying configurations of this problem on the spatial scale, this research delves into the existing scientific literature of energy poverty indicators and metrics at subnational scales. It conducts a structured literature review of 125 peer-reviewed articles identified in scientific databases, focusing on their application, type, nature of data, topic, object of measurement, targeted groups, and other relevant factors to appraise indicators. This study identifies common practices, discusses strengths and shortcomings, and points out deficiencies in energy poverty measurement at disaggregated scales regarding indicator use and data availability. It examines the different possible approaches to measurement and analysis, highlighting relevant underexplored aspects regarding their dimensions, outcomes, and targets for a more comprehensive and nuanced assessment.

Most studies focus on particular case-study regions or locations in Southern European countries, conducting snapshot analysis of one normal past year. Most studies use secondary data from official sources to conduct quantitative objective approaches that measure winter energy poverty incidence (number of people in energy poverty). A relevant number of studies also use qualitative indicators or a mix of quantitative and qualitative (separately or in composite metrics) for objective approaches. In contrast, constructivist subjective approaches are rarer while providing relevant accounts for the deeper study of this issue. Several authors conduct their own surveys as a valuable way to collect specific data and craft more tailored and nuanced studies. In some cases, statistics are not enough to discern specific and extreme situations of energy poverty and need to be complemented by other data from surveys and direct temperature measurements for instance, to capture specific types of vulnerability, particularly affecting underprivileged and disenfranchised groups (Ruiz-Rivas *et al.*, 2023).

Relevant practices to be pursued include the integration and intersection of the wide variety of causes and effects; assessment of several types of assessment outcomes (incidence, persistence, depth, vulnerability); integration of objective and subjective factors and analyses; examination of different manifestation such as abnormally low energy consumption (hidden energy poverty), restriction of other essentials, and self-reported vulnerability; focus on summer energy poverty and temporal dynamics; and increase in stakeholder participation for more democratic approaches. There is potential for more nuanced and comprehensive assessments from several underexplored indicators on aspects such as energy supply, environment, sustainability, quality of life, feelings, disadvantaged groups, indoor conditions, literacy, access to information, participation, culture, territorial typologies, household resilience and ability to adapt. The link between energy poverty levels and the specific solutions (such as energy efficiency measures) is underdeveloped, as well as meaningful connections to energy justice issues that would enable deeper insight into the causes and effects across territories and generations.

This study also discusses the advantages and disadvantages of area-based and household-level approaches. It identifies different data sources that can be explored to build energy poverty measurements and untapped data sources that can be more prominent in future assessments. It exposes the dire need for more data at disaggregated levels, namely dedicated surveys for data collection on varied energy poverty indicators, selected democratically in multistakeholder groups, that enable cross-territory analysis rather than isolated and rare case studies.

This review takes stock of the state-of-the-art scientific practice of energy poverty measurement at this level, identifying avenues for future development and improvement in EP metrology, aiming to advance current practice and even theory. It can support the work of researchers aiming to build a more comprehensive and inclusive energy poverty assessment at a subnational scale while providing transferable insights for energy poverty measurement at all scales. The uncovered data resources and metrics can also expand and strengthen the database available to local governments, joining them to the local datasets that these entities have at their disposal. The combination of research data and methods, national and regional statistics, and local datasets from local governments, organisations, and civil society can form a comprehensive kit of resources to support the tailoring of effective interventions towards reducing energy poverty at the local level.

It is important to remember that indicators are tools that simplify complex phenomena, relying on more straightforward concepts that guarantee their communicability and policy traction. These concepts (implicitly) elicit prescriptions for political action, hiding certain aspects while privileging others and representing heterogeneous populations as homogeneous groups of society, hiding significant variability. With this notion in mind, this analysis is conducted aiming to reduce these limitations and broaden understanding of this problem while being conscious of the trade-off between complexity and operationalisation. Indicators are connected to the definition of the problem. Different definitions result in different perceptions and measurements and, ultimately, in identifying households with distinct characteristics. This uncovers the political nature of definitions and metrics, which often provide an ambiguous basis for policy design and targeting. While false positives and false negatives is a risk in energy poverty measurement, theories of justice prioritise the avoidance of false negatives over the identification of false positives (Schuessler, 2014).

This research uncovers a significant sample of data and indicators used in the research at subnational scales in Europe. Although it is a quasi-systematic exercise, it arguably does not consider all the studies that focus on energy poverty measurement at this scale, as the selected pool is inevitably curtailed due to the selection of search words, time period, manual selection of articles through the abstract and content read. The process of choosing what an assessment of energy poverty is or not, despite the defined objective criteria, always has an inherent component of bias and subjectivity, which is challenging to overcome. Challenges also arise in representing and analysing such a numerous pool of studies without simplifying the approaches and overlooking certain aspects that may be deemed relevant. Nevertheless, it provides a compilation and a critical analysis that can apport direct inputs into improved energy poverty diagnosis at disaggregated levels for tailoring more accurate, fair, inclusive and effective local and regional level policies and programs targeting the energy-poor across the European territory.

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5

EXPLORING ENERGY POVERTY ASSESSMENT AT THE NEIGHBOURHOOD SCALE IN PORTUGAL

Paper published in Frontiers in Sustainable Cities:

Gouveia, J. P., Seixas, J., **Palma, P.**, Duarte, H., Luz, H., Cavadini, G. B. (2021). Positive Energy District: a model for Historic Districts to address Energy Poverty. Frontiers in Sustainable Cities. https://doi.org/10.3389/frsc.2021.648473

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Positive Energy District: A Model for Historic District to Address Energy Poverty

Abstract

The Positive Energy District (PED) concept has been pointed out as key for cities' energy system transformation toward carbon neutrality. The PED may be defined as an energy-efficient and flexible urban area with net-zero energy import and greenhouse gas emissions, aiming toward annual local surplus of renewable energy. Most of the studies and practical experiences about PEDs are based on newly built districts, where the planning and integration of innovative solutions are less complex and more cost-effective. However, to achieve Europe Union's 2050 carbon-neutral ambition, we argue that the transformation of the settled districts is essential, including historic districts, which present common challenges across European cities, such as degraded dwellings, low-income families, and gentrification processes due to massive tourism flows. This paper aims to discuss how the PED model can be an opportunity for historic districts to reduce their emissions and mitigate energy poverty. The historic district of Alfama, in the city of Lisbon (Portugal), is used as a case study to show the potential of energy renovation measures and solar photovoltaic (PV) production in households, cornerstones of a PED. The annual energy needs potential reduction due to building retrofit is 84 and 19% for space heating and cooling, respectively, while the integration of building-integrated PV technologies in rooftops and windows potentially generates up to 60 GWh/year. At the district scale, these two components of the PED concept could require an investment of 60Me to 81Me depending on the PV technologies in the rooftops, a sensitive aspect in historical districts. Unlike other mechanisms to tackle energy poverty, like the social tariffs, the adoption of structural measures like building energy efficiency retrofit and renewable energy integration will contribute to solve the energy poverty problem, which is significant in Alfama, in both the winter and summer. The highlighted investments require an innovative financial scheme to support not only buildings' owners but also tenants, as these are among the most vulnerable to energy poverty. However, the social benefits of that investment, on the health system, air quality, climate resilience, labour productivity, and social integration, would be invaluable.

5.1 Introduction

It is estimated that 55.3% of the world population lives in urban settlements, and projections state that by 2030 one third of the global population will live in cities with at least half a million inhabitants (UNDESA, 2019). Cities have a relevant environmental impact and are estimated to be responsible for 2/3 of the global energy consumption and 70% of the global CO_2 emissions (Satterthwaite, 2008). On the other hand, they have a large potential to drive global action against climate change and develop innovative solutions to reach the Paris Agreement Goals (UNFCCC, 2016) of limiting global warming. Moreover, cities are a fundamental player to reach the SDGs. SDG 11 explicitly states that cities should become inclusive, safe, resilient, and sustainable by 2030 (UN SDGs, 2015), and its sustainable development is critical for other SDGs and target achievement (Frischmann *et al.*, 2020).

In the last decade, efforts to develop solutions to reduce the environmental impacts of cities have multiplied, with the smart city concept being a promising one to cut greenhouse gas (GHG) emissions. Smart city solutions are a set of integrated and holistic cutting-edge urban development strategies, often based on ICT (information and communication technologies) applications, which contribute to urban sustainability and citizen welfare (Mosannenzadeh *et al.*, 2017). Embedded in this concept, the smart energy city strategy focuses on site specific transition toward sustainability, self-sufficiency, and resilience of energy systems, which should ensure accessibility, affordability, and adequacy, through optimised integration of energy conservation and energy efficiency (EE) measures, local RES, and promotion of energy flexibility (Mosannenzadeh *et al.*, 2017).

To accelerate the decarbonisation of urban areas and foster the scalability potential across cities, the PED concept was developed as part of the smart energy city strategy. JPI Urban Europe (2021), the hub for urban transitions in Europe, defines the PED as an energy-efficient and flexible urban area that has net-zero GHG emissions and actively manages to generate an annual local surplus of renewable energy. It also specifies that the PED requires the integration of different systems (*e.g.*, buildings, energy, mobility, ICT) and interactions between different stakeholders while optimizing the liveability of the urban environment (Bossi *et al.*, 2020). Besides technical aspects, it is widely recognised that social aspects play an essential role in successfully implementing the PED. These districts are innovative frameworks for the development of cities toward clean energy consumption and increased energy security while contributing to improve the quality of life of the population within the city. They are a fundamental part of creating a comprehensive approach toward sustainable urbanisation; dealing with the technological, spatial, regulatory, financial, legal, social, and economic perspectives (Alpagut *et al.*, 2019); and paving the way toward the goal of 100 climate neutral cities in Europe (European Commission, 2020a). The PED concept plays a relevant role in the vision of climate-neutral cities, which are an essential step on the way to the Green Deal goal of a climate-neutral Europe by 2050 (European Commission, 2019).

In the last years, many feasibility studies and pilot projects about PED implementation have been conducted in many cities across Europe. The action 3.2 of the EU's Strategic Energy Technology Plan (European Union, 2018) supports the planning, deployment, and replication of 100 positive energy districts by 2025 (Bossi *et al.*, 2020). Most studies and practical experiences about PED are based on projects in newly built districts, where the planning and integration of innovative solutions are less complex and the ambition is usually higher (Bossi *et al.*, 2020). However, to achieve Europe's 2050 decarbonisation challenge, a transformation of the urban systems is required, including the already settled districts. Therefore, as part of the urban transformation, a renovation wave of the existing building stock is pursued in the next years (European Commission, 2020b), aiming to improve the energy efficiency of the current European building stock, estimated to be around 75% energy inefficient (European Commission, 2020b). According to Mckinsey (2020), the European Union (EU) buildings' emissions must be reduced by 29% by 2030 and the sector should achieve climate neutrality (*i.e.*, net-zero (GHG) emissions) by 2050 (C40 cities, 2020). The bulk of this reduction could be achieved by retrofitting and replacing the heating systems in existing buildings, which will still account for 75–90% of EU building stock in 2050 (Mckinsey, 2020).

Within the existing building stock, buildings in historic districts present particularly challenging characteristics to ambitious energy refurbishment and therefore are usually not considered in PED projects (Bossi *et al.*, 2020). The combination of characteristics of many historic districts, like those located in southern Europe (*e.g.*, narrow streets with few green public spaces, ancient and degraded heritage buildings, elderly population, high tourism dependency), negatively impacts the quality of life of its inhabitants and exacerbates problems such as reduced climate resilience; low energy performance and poor thermal comfort of buildings (Gouveia and Palma, 2019), energy poverty vulnerability (Gouveia *et al.*, 2018, 2019), and congested streets with negative effects on air quality and noise. These environmental and well-being problems, coupled with severe regulatory limitations to implement EE measures and to integrate RES in historical buildings, represent serious restrictions to unlock the potential interventions (Gregório and Seixas, 2017) aimed at implementing the PED concept, which has the potential to improve the inhabitants' quality of life. Nevertheless, historic districts could profoundly benefit from the integration of PED solutions being a promoter of dynamics of change (Eurocities, 2020).

One of the critical socioeconomic issues in historic districts, especially in Southern and Eastern Europe, is energy poverty. Energy poverty generally refers to a situation in which households are not able to adequately heat their homes or meet other necessary energy services at an affordable cost (Pye *et al.*, 2015). This phenomenon is mainly due to high energy prices, low incomes, and poor energy efficiency in buildings (Dobbins *et al.*, 2019). The negative impacts on the affected households are health problems, enhanced poverty risk, increased inequalities, inadequate participation in society due to stigma, reduced climate action ambitions, and lower quality of life (*e.g.*, Bouzarovski and Petrova, 2015). Some of the key measures previously identified to achieve a PED could potentially address energy poverty, such as an increase of decentralised RES generation and a larger integration of EE measures (European Commission, 2020c).

The connection between energy poverty and PED is still scarce in most studies and EU projects, with only a few (*e.g.*, MAKING-CITY, 2018, launched in 2018, and POCITYF, 2019, started in 2019) including in the project KPIs the reduction of energy poverty during the project. However, it is considered as a consequence of the PED implementation and no direct relationship is described. Therefore, in the integration assessment of PED solutions, it is important to include energy poverty reduction targets and extensive citizen engagement for better identification and support of the most vulnerable households, while certifying that PED solutions do not amplify inequalities and increase vulnerabilities. Thus, there are no studies the authors are aware of in the current published literature linking the PED potential to a solution model to reduce energy poverty in historic districts.

This study aims to cover two key questions of the PED concept implementation, applied in historic districts in southern Europe Mediterranean cities: (i) what is the potential of building energy efficiency retrofit measures and solar energy generation and (ii) how these solutions could potentially drive the reduction at scale of energy poverty. The analysis is performed within the framework of the Sustainable Historic Districts project (2018–2020), co-funded by EIT Climate-KIC, which addressed the challenges of historic districts in five Mediterranean European cities for a holistic and sustainable transformation pathway (Lisbon, Savona, Sassari, Ptuj, Nicosia) (SUSHI, 2020). In this paper, the historical district of Alfama will be used as a case study. This assessment advances the state of the art by presenting valuable knowledge on critical components of PED development within a historic district, through a high spatial scale analysis of building retrofit and solar energy integration potential (*i.e.*, for over 120 statistical subsections of the district). It also brings together an integrative discussion between PED implementation and energy poverty mitigation. The case study application improves the understanding of the energy retrofit and solar photovoltaic (PV) specificities for a European Mediterranean city with a deep need for both building stock renovation and solar integration at a large scale, aiming to identify where efforts to mitigate energy poverty should focus.

The paper is structured into four sections. The next section presents the case study of the historical district of Alfama (Lisbon) and describes the methodologies used to estimate the techno-economic potential of both EE and RES generation at district scale. The results are described in section Results, whereas section General Discussion unfolds a critical discussion and conclusions on the role of PEDs in historic districts and its potential for energy poverty mitigation.

5.2 Methods

In an effort to deliver key defining aspects of the PED framework as an embedment of an urban energy system, driven by a high level of EE and RES, the methodological approach of this study was divided into three major steps: (i) a case study analysis and identification of the energy poverty vulnerability, setting the scene for further detailed assessment; (ii) a spatially explicit analysis for 121 statistical subsection levels for buildings' renovations (windows, walls, roofs), and (iii) building-integrated photovoltaic (BIPV) electricity generation, considering the best measures and technologies to be integrated within a historical district context.

5.2.1 Case Study Location and Characteristics

Portugal receives some of the highest levels of solar irradiation in Europe and also boasts a high number of solar hours, with values between 2 200 and 3 000 hours of sunlight per annum, and as such makes it an excellent candidate for solar energy projects (Cavaco *et al.*, 2016).

The case study location is the Alfama historic district, in the city center of Lisbon. It is a traditional district with an important role in the cultural heritage and identification of the city of Lisbon. It is one of the oldest districts, with unique history and characteristics; it spreads between São Jorge Castle and the Tagus riverfront (in the civil parishes of Santa Maria Maior and São Vicente). Resembling a typical Arab medieval city, Alfama is known for its morphology due to its maze-like narrow streets, being one of the few areas of the city that has survived the 1755 earthquake. For these reasons, it is one of the main touristic locations of the city.

Historically, its population came from an important rural exodus during the middle of the last century. This rural origin is embodied in a way of life, characterised by strong neighbour relations and a sense of solidarity, reproducing the practices of the population origins. Still today, Alfama has an aging population that remains in the neighbourhood, maintaining active commercial establishments. The Alfama population has been shrinking over the years. Despite its decrease in population, however, its population density is still very high (13 854 persons/km^2) when compared to Lisbon's average population density (5 477 persons/km^2). The high-density areas occur since the streets are very narrow and thus the buildings are very tight with each other (INE, 2011).

Due to their social culture and habits, the traditional inhabitants of Alfama are an important asset of Lisbon intangible heritage. However, gentrification and mass tourism are putting Alfama and its inhabitants under pressure, due to real estate needs, which tends to replace traditional low-income inhabitants with local accommodation schemes (*e.g.*, Airbnb) and hotels. Currently, tourist accommodations represent 26% of the total available households (Gago and Cocola-Gant, 2019). If all the tourist accommodation houses are at full capacity, they can accommodate almost the same number of tourists/visitors as local inhabitants.

The cultural profile of the district and the tourism play a major role in the selection of building renovation measures and renewable energy technologies in the district, with public opinion having a considerable weight in what technologies should be integrated, *e.g.*, reluctance to change the building façade or to install solar panels and/or small wind turbines on roofing. These aspects are regulated in specific guidelines that limit the rollout of building retrofit interventions and renewable technologies in the district.

5.2.2 Energy Poverty in Alfama

In connection with the building stock thermal performance and energy use in homes, energy poverty stands out as a serious issue affecting the Portuguese population. According to the EU SILC indicators, the estimated energy-poor population ranges approximately between 2.0 and 3.7 million inhabitants, which is between 18.8 and 35.7% of the total Portuguese population (Eurostat, 2021a,b). This issue is particularly serious in historic districts such as Alfama, due to the socioeconomic profile of the inhabitants and the underperforming building stock. Figure 5.1 depicts the EPVI developed by Gouveia *et al.* (2019), zoomed in on the Lisbon municipality region and highlighting the Alfama district, for the purpose of this paper. The EPVI is an aggregated assessment of the dwelling stock's energy performance, households' energy consumption (DGEG, 2021), and the ability of the population to implement alleviation measures, defined by a set of socioeconomic indicators from INE (2011).

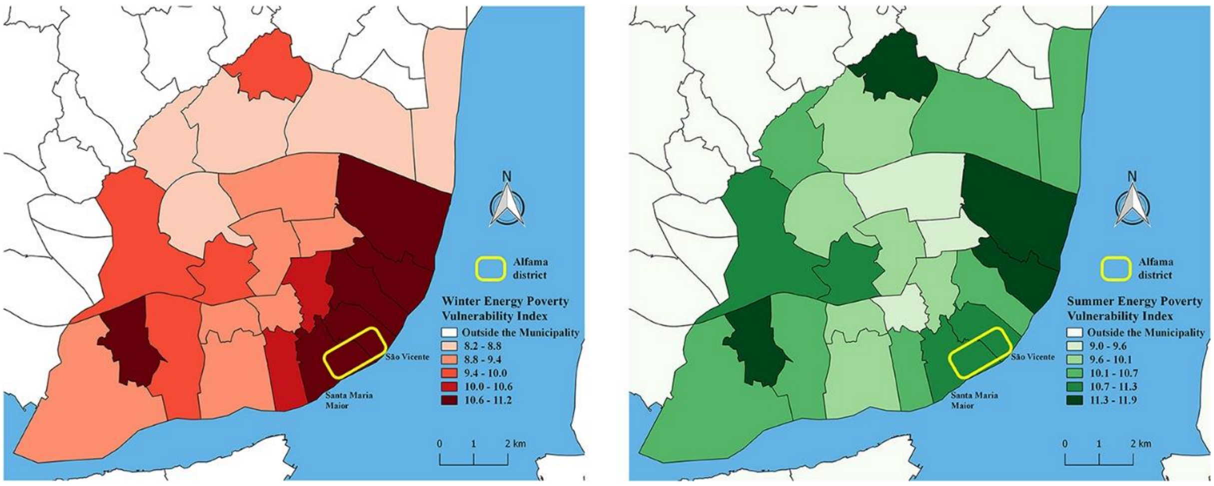

Figure 5.1 - Winter (left) and Summer (right) Energy Poverty Vulnerability index in Lisbon's civil parishes [adapted from Gouveia *et al.* (2019) and CML (2020)].

The Lisbon Municipality is one of the least vulnerable municipalities of the country, due to high levels of alleviation measure implementations, determined by a favourable combination of socioeconomic indicators, such as average monthly income and share of the population with a university degree, as well as its location in milder climatic zones, particular for winter. Nevertheless, the energy poverty vulnerability index levels of the municipality still point to a significant energy poverty issue among the population. Within the municipality, the most vulnerable civil parishes in winter are located in the southeastern region, including Santa Maria Maior and São Vicente, where the Alfama district is located. These are the civil parishes with the oldest building stock, as well as a higher concentration of elderly people, with lower incomes and education level. In the summer, although not being in the highest interval of vulnerability, Alfama's civil parishes still present significantly high indexes of vulnerability.

An important cause of the high index levels is the existent energy performance gap, described by Palma *et al.* (2019), which consists in the difference between the real energy consumption for space heating and cooling, and the energy that should be consumed to guarantee the thermal comfort inside the dwellings. These gaps (expressed in percentages) are high across the whole country, and Lisbon's civil parishes are not the exception, presenting space heating and cooling energy performance gaps above 80%. These gaps stem from the combination of the low energy performance of buildings, which leads to high building energy needs (common in older buildings) and the low real energy consumptions for climatisation, related to the energy affordability issue. For instance, in the first semester of 2020, Portugal had the highest price of natural gas for households in the EU, considering the purchasing power standard (PPS) (Eurostat, 2021c), while the electricity price was ranked fourth highest (Eurostat, 2021d). Furthermore, while ownership rates of cooling systems are historically low (18.7% in the metropolitan area of Lisbon), the ownership of decentralised low-efficiency heating systems is generalised (INE, 2017), including a significant share of electric oil heaters (ADENE, 2017). Coupled with low incomes, these indicators point to potential difficulty in affording adequate energy services. In a survey conducted by the national energy agency (ADENE, 2017), the participants claimed to spend on average 87€/month, which can represent a considerable burden for certain groups, such as elderly people who receive low pensions. The majority of the interviewed claimed to be worried about energy efficiency, in the perspective of reducing burdening energy bills. Additionally, cultural conditioning is also partially responsible for low consumption as people resist to heat or cool their homes, not only due to energy prices but also because thermal comfort is not a priority compared to other basic needs; it can be considered as a waste of money, particularly among elderly people, as evidenced by Horta *et al.* (2019).

From the policy perspective, the social tariff for electricity and natural gas use is the only measure that directly addresses the energy vulnerability of the population. Moreover, there are several policy instruments and schemes providing support for building renovation, in the form of soft loans and non-refundable grants. However, these options are not viable for low-income families. Nevertheless, the annual energy renovation rate of buildings in Portugal is about 0.01% (INE, 2019), well below the EU average, which is around 1% (European Commission, 2020b). This difference raises questions about the effectiveness of these schemes, strengthened by the persistently high results of the energy poverty proxy indicators each year.

5.2.3 Representative Building Typologies

The first step of the methodology was the identification of representative building typologies of the residential building stock in the Alfama district, based on the predominant building characteristics obtained with the CENSUS 2011 (INE, 2011). The analysis focuses on the characteristics that are potentially relevant for the purpose of this study, such as construction period, building form, number of floors, and roof type (as developed in Gouveia *et al.*, 2018). The census data (INE, 2011) portrays details for 1 863 buildings in the district. The majority of the buildings are multi-apartment buildings (62%) followed by terraced houses (24%), semidetached (5%), detached (5%), and other types (4%). For this category, all types of houses were combined since their differences and impact on energy needs would not considerably differ in such an urban-dense area. The year of construction is used as a proxy for material types and construction techniques. About 48% of the buildings were built before 1919 and 30% between 1919 and 1945. Overall, around 89% of buildings were built before 1960, before the application of energy efficiency and thermal performance regulations (*i.e.*, 1990), evidenced by the energy inefficiency levels of all typologies. The number of floors and roof type influence the overall height of the building, and together with the height of surrounding buildings, these characteristics are important to compute the space heating and cooling energy needs. As almost all roof types (97%) are sloped roofs with ceramic or concrete tiles, this criterion was not considered relevant for further distinguishing building typologies. However, the number of floors has a wider variety, with the bulk of the buildings having up to 2 floors (42%) or 3 to 4 (42%); therefore, three classes were kept for characterizing the building typologies, *i.e.*, "1 or 2," "3 or 4," and "equal or >5" floors. These criteria, combined with the analysis of the available data, enabled to identify six building typologies (TP), as illustrated in Table 5.1, accounting for 1 585 buildings in the Alfama district, which represents 85% of the total buildings in the area. The remaining 15% of the buildings have very distinct features, are not significantly widespread, and therefore are not considered in the analysis. A relevant criterion for the selection of typologies was the frequency of more than 7% representation in each civil parish of Alfama and the availability of data for its characterisation.

Table 5.1 - Main characteristics of the representative residential building typologies for Alfama District.

Typology	Construction period	Building type	Roof type	N° of floors	Number of buildings	Number of dwellings	Number of linked EPCs	Average area (m^2)	% EPC ≤ C class
TP1	Before 1919	House/multi-apartment building	Sloped	1/2 floors	330	619	65	45.3	100%
TP2	Between 1919 and 1960	House	Sloped	1/2 floors	321	552	122	48.0	100%
TP3	Before 1919	Multi-apartment building	Sloped	3/4 floors	409	1 316	656	54.0	97%
TP4	Between 1919 and 1960	Multi-apartment building	Sloped	3/4 floors	261	1 320	1 182	52.5	90%
TP5	Before 1919	Multi-apartment building	Sloped	5+ floors	133	946	1 091	77.4	90%
TP6	Between 1919 and 1960	Multi-apartment building	Sloped	5+ floors	131	1 251	1 126	66.4	96%

5.2.4 Energy Efficiency Retrofit Potential of Residential Buildings

Several authors, such as Lazzeroni *et al.* (2017), Liang *et al.* (2018), and Asdrubali *et al.* (2019), have assessed the effects of retrofit in the energy needs or consumption of buildings, spanning various geographical contexts and spatial scales, as well as considering different types of buildings and measures.

Herein, detailed information from 4 142 EPCs available for the district (ADENE, 2019) was used to characterise the energy performance of each residential building typology. Based on the main characteristics of each typology (Table 5.1), each energy certificate was associated with a specific building typology and the housing envelope elements (windows, walls, and roofs) corresponding to each EPC were analysed. The parameters of interest were recorded, such as the total area of each component, the type of element, and the coefficient of thermal transmittance (U-value). After analysing all the certificates associated with each typology for each building component, the average thermal transmission coefficients and the average total area of each component were used to estimate the nominal space heating and cooling energy needs. These were estimated before and after potential retrofitting interventions were estimated as well as the investment costs of the renovation measures applied to the building envelope. The energy needs were estimated following the methodology defined in the current National Energy Performance Regulation (Ordinance, N°349-B/2013), which derives from the EN ISO 13790 approach. The requirements set in the regulation were adopted, namely, the nominal conditions regarding the maintenance of an optimal indoor temperature of respectively 18°C in the heating season and 25°C during the cooling season, for the whole useful area of the dwelling and during the total duration of the respective season. The equations for calculating the space heating (Nic) and cooling (Nvc) useful energy needs, both in [kWh/m^2 .year], are the following:

$$Nic=(Q_{tr,i}+Q_{\upsilon e,i}-Q_{gu,i})/A_p \qquad [kWh/m^2 .year] \quad (1)$$

$$N\upsilon c=(1-\eta\upsilon).Q_{g,\upsilon}/A_p \qquad [kWh/m^2 .year] \quad (2)$$

$Q_{tr,i}$ is the heat transfer through transmission between the building and the surroundings in [*kWh*]; $Q_{\upsilon e,i}$ is the heat transfer through ventilation [*kWh*]; $Q_{gu,i}$ represents the total useful heat gain in the heating season in [*kWh*]; A_p is the building's indoor pavement useful area in [m^2]. η_υ is the utilisation factor of the heat gains [-]; and $Q_{g,\upsilon}$ represents the heat gains in the cooling season [*kWh*]. This process was carried out for the dwellings of all the subsections of Alfama. A subsection represents urban blocks within a civil parish to help identify distinct areas within.

Subsequently, a database with renovation measures was created using a market-based budget generation tool (CYPE, 2013), taking into account the type of materials that are traditionally used in the construction sector, as well as its suitability for the Portuguese buildings. For each measure, information on the physical and thermal properties, as well as its investment costs, including material and estimated man-hours for implementation was collected. Six measures were identified for windows (*e.g.*, aluminum and polyvinyl chlorine (PVC) framing with/without a thermal cut, low emissivity, and standard double glazing), 29 for walls (internal and external), and nine for roofs (*e.g.*, External Thermal Insulation Composite System (ETIC) systems, engineered polyurethane, agglomerated cork, expanded polystyrene). For more information about the considered technologies, see Duarte (2020).

The energy efficiency potential in the district was then assessed through a building fabric improvement scenario for each of the construction components (windows, walls, roofs). This scenario includes a selection for each component of the retrofitting measures that complies with the thermal performance requirements set in the regulation while involving the lowest investment costs. The following suitable options were identified: insulation of expanded polystyrene (EPS) and mineral wool (MW). EPS has a good insulating capacity and is permeable to water vapor. Mineral wool is an incombustible material and completely permeable to air and water vapor but does not absorb water. To estimate the impact of retrofitting measures in the district, the following options were selected as most adequate for being applied: mineral wool 10 centimetres thick (MW10) for the roof, PVC window frames with standard double glazing (CX PVC STD) for the windows, and expanded polystyrene 6 centimetres thick (EPS6) for the walls, through internal insulation. Historic listed buildings and buildings within historic districts often have façades worthy of preservation (*e.g.*, with tiles or other important visual features) (Build Up, 2020). In Lisbon historical districts, it is very common to have stonework on the door and windows which do not allow the use for example of ETICs (in external insulation) which would be more prominent than these visual details. With ETICs, buildings are more uniform on the outside with impacts on the existing aesthetic beauty in such districts being lost. For these reasons, the internal insulation of walls was selected, despite reducing thermal inertia and the internal floor area.

For walls and roof, insulation material is added to the existing structure; thus, for each building typology the two thermal resistances were summed, and the resulting value represents the final thermal resistance after the retrofit. For windows, the retrofit is a replacement of solutions; therefore, the resulting thermal resistance is equal to the one of the newly implemented solution. Table 5.2 shows the selected measures for each building component and its associated costs, where lambda (λ) is the thermal conductivity of the material and the R-value is a measure of resistance to heat transfer of the material, for the given thickness. A detailed description of the full methodology can be found in Duarte (2020).

Table 5.2 - Selected measures for buildings retrofit.

Building component	Selected improvement measures	Lambda [W m^{-1} K^{-1}]	*R*-value [m^2·K W^{-1}]	Investment costs [€/m^2] CYPE (2013)
Roof	Thermal insulation with mineral wool (MW10)	0.042	2.38	7.21
Windows	PVC window frames with standard double glass (CX PVC STD)	–	0.45	350.60
Wall	Expanded polystyrene (EPS6) through internal insulation	0.031	1.94	35.23

Windows investment costs consider a window with a size of 1.5 m^2.

5.2.5 Distributed Solar Photovoltaic Potential

One of the key measures identified in PED projects is solar power integration in buildings (Derkenbaeva *et al.*, 2020). This technology can provide a carbon-free energy source while increasing socioeconomic development by generating new investment opportunities. The goal herein is to evaluate the techno-economic potential of solar photovoltaic technologies, in terms of total electricity production and associated costs, to determine the feasibility of the Alfama district transformation, coupled with an opportunity to mitigate energy poverty through reduction of energy costs and larger use of sustainable energy in vulnerable households.

For the estimation of the electricity generation potential for PV projects, there are three approaches: sample, multivariate sampling, and complete census (Byrne *et al.*, 2015). On *the Sample-based*, three simple steps are taken: (a) a survey is conducted to obtain data on the available roof area; (b) average annual solar irradiation on inclined surfaces is determined; and (c) yearly PV production is calculated. It is a fast methodology to implement; however, the lack of variables makes this approach more attractive when calculating estimates rather than accurate and precise electricity production values (Byrne *et al.*, 2015). *Multivariate sampling-based* has a higher difficulty level and consists of five steps: (a) geographical division of the region; (b) rooftop sampling; (c) extrapolation through the use of rooftop area and population relationships; (d) calculations of constraints and detriments (shading, orientation, etc.), and (e) conversion of data into power and energy outputs. Although this method is generally seen as having a lower cost of implementation, the calculation of some variables such as the shading is extremely difficult to conduct, meaning this method is extremely time-consuming and less accurate (Byrne *et al.*, 2015). *Complete census* relies on the computing of the entire available rooftop area, usually performed through the use of innovative cartographic data sets that offer a digital model of the study region, or through the use of existing statistical data sets containing building information. One technique often used to measure solar radiation levels is Light Detection and Ranging (LiDAR) software (Huang *et al.*, 2015). This approach produces extremely accurate results. However, the increased amount of data makes this method the most time-consuming. A few examples of such application of methods are presented, *e.g.*, by the National Renewable Energies Laboratory (NREL) which provides a PV estimation tool PVWatts (NREL, 2020), using hourly meteorological data per year from the National Solar Radiation

Database. The work by Hong *et al.* (2017) using a sampling method calculated the rooftop solar PV potential for the city of Seoul. Phap *et al.* (2020) assessed the rooftop solar power technical potential of the city of Hanoi by using high-resolution remote sensing images technology. Eslami *et al.* (2021), utilizing a rich spatial dataset of solar irradiation augmented with electricity bills at the building level, estimated the cost and benefit of installing rooftop PV systems for each building of the city of Beirut (Lebanon).

The methodology used in this part of the work to assess the solar power integration potential follows a multivariate sampling-based approach, bringing together different tools and methods (PV GIS, EPCs, Google Earth, CENSUS data) for achieving a spatially detailed ballpark figure of production and investment needs for the district scale PV integration, and it can be broken down in several parts: investigation and characterisation of the buildings; solar irradiation assessment; available areas and orientation; and calculation of electricity production and costs for PV technologies.

The methodology considers the same six-building typologies used for EE assessment (see Table 5.1), with roof type, number of floors, and year of construction being the key characteristics of interest. Year of construction is an important characteristic since BIPVs need stable structures and building envelope to have a secure installation. BIPV includes the replacement of the traditional construction elements with multifunctional elements that generate electricity. This enables the dual function of producing renewable electricity through the use of PV and to provide a construction element for the finished building (Ritzen *et al.*, 2016). The installation of certain PV technologies as façade PV may cause structural problems on older buildings that have not been renovated but are an important structure for solar PV potential of Mediterranean cities as described in Brito *et al.* (2017). The number of floors influences the overall height of the building, thus being a critical factor to determine levels of shading from surrounding buildings. The slope of the roof is also a major feature in determining if a mounting system is needed, or if solar tiles can be used. Closely related, available roofing surface and orientation are the most important factors in determining solar energy generation capacity. To ensure the maximum potential, the available roof surface should have access to sunlight and face the optimal direction to secure the optimal irradiation angle.

5.2.5.1 Solar Exposure

The software Photovoltaic Geographical Information System (PVGIS) (JRC, 2021) was used to calculate the average monthly solar irradiation estimates for Lisbon (latitude 38.712° north, longitude−9.131 east) for direct normal irradiation, irradiation at an optimal angle, and diffuse solar radiation. The satellite CMSAF data for the year 2016 was retrieved and used for the assessment.

PVGIS is a free online tool that estimates the solar irradiation, taking into consideration shadowing. The solar irradiation information provided by PVGIS is the average direct solar irradiation at an optimum angle for Lisbon (31°) and optimal orientation (south-facing). Diffuse solar irradiation was used to calculate the annual generation of solar window-type technologies. Figure 5.2 shows a high fluctuation for irradiation levels with lows of about 60 kWh/m^2 for January and highs in the summer of about 205 kWh/m^2 (JRC, 2021).

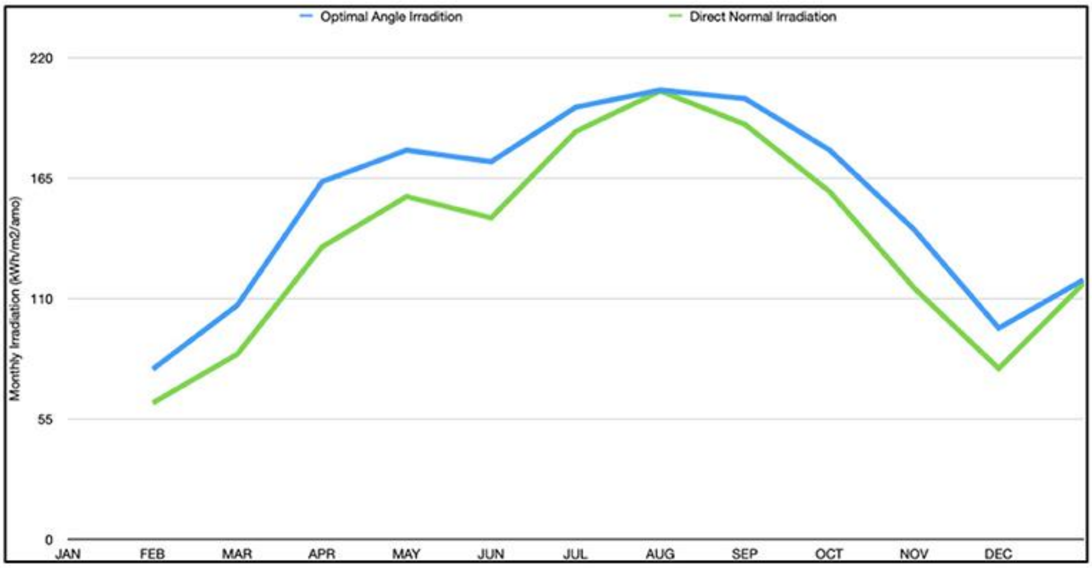

Figure 5.2 - Lisbon monthly solar irradiation estimates (2016) (adopted from JRC, 2021).

5.2.5.2 Orientation and Rooftop and Windows Area

Building orientation and rooftop availability determine the angle of solar exposure and the total surface available to install the modules. Those features were assessed through a visual analysis of the buildings in different regions of Alfama using Google Earth. The satellite images were used to evaluate rooftop characteristics. The main orientation of the buildings was gathered to identify a significant trend that could be assumed for the majority of the buildings. Little to no variation was found in the orientation of the buildings; in fact, most of them are facing south. Therefore, all the calculations were done based on the assumption that the buildings are south-facing. The next step was the matching between the orientation and rooftop availability information to the respective building typology (see section Representative Building Typologies).

From the EPC sample of the district (ADENE, 2019), we retrieve data on the floor surface, number of floors, and total window surface. The average surface of rooftops was computed for each building typology, using the building's footprint area as a proxy indicator. Three classes of rooftop surfaces were defined (*i.e.*, "I: 0–150 m^2," "II: 150–350 m^2," and "III: >350 m^2") as well as for window surfaces (*i.e.*, "A: 0–30 m^2," "B: 30–60 m^2," and "C>60 m^2"). These categories enable the identification of outliers, which have areas that are too large or too small in comparison to other buildings, indicating a fault in data recording or a building that has a completely different typology from the defined categories. Outliers are then removed from the assessment.

However, PV technologies will not be installed in the whole rooftop area. This is because only part of the rooftops will be exposed to sunlight, and there may be existing restrictions that prevent the installation of modules in certain areas. For the rooftop availability, a Google Earth visual inspection was done, taking an overview of the district and then taking a building's sample from each one of its subsections. Identified restrictions could include things like chimneys, water collectors, and parabolic antennas (*e.g.*, for television). Another constraint is that as the rooftops are pitched, one side of the rooftop could be privileged with more access to solar irradiation. This is especially true for the study at hand, as most of the buildings are south-facing. This means that only half of the total rooftop area will be facing the sunlight, so only half of the rooftop is suitable for PV technology installation. The calculation of the half-roof was done through the use of trigonometry following other studies such as Moreira (2016). Figure 5.3 clearly shows a multitude of situations that limit the potential of PV integration; for example, there are roofs completely unrestricted (in green), while others have shadowing (in orange) due to surrounding buildings, and roofs have high levels of restrictions (in red).

Figure 5.3 - Aerial view of the rooftop availability in the district area of São Vicente de Fora (northeast) (adopted from Google Earth).

5.2.5.3 Solar PV Electricity Generation

The total solar PV electricity production was estimated considering the average rooftop and window surfaces in Alfama district for the six residential building typologies based upon the results of the previous methodological steps, with varying PV technologies with different levels of maturity and adoption but that are already available on the market. Eight rooftop PV technologies (*i.e.*, building-integrated (BI) and tiles) and two window PV technologies were assessed, as depicted in Table 5.3. For each technology, total investment costs, annual and lifetime electricity production, and levelised energy cost were calculated. The installation costs of the modules of an additional 5% and O&M of 3%/year were included in the total investment costs, and a total lifetime of 25 years was considered for lifetime calculations. An average 10% discount rate was used. Finally, for the purpose of this paper's PED conceptual overview, the best technology in terms of overall costs, historic district applicability, generation, and LCOE were selected for each application (window and rooftop). Further details of the full methodology can be found in Luz (2020).

Table 5.3 - Key characteristics and prices of the considered module types.

Module name	Module type	Application	Efficiency (%)	Price [€ m^{-2}]	Module area (m^2)
TALLMAX[a]	Panel	Rooftop	17.50%	50.18	1.94
BLUESUN[b]	Solar tile	Rooftop	15.00%	117.94	0.35
PERC 60 305W[c]	B. I. panel	Rooftop	18.35%	97.98	1.66
PERC 60 320W[d]	B. I. panel	Rooftop	18.94%	116.32	1.69
BRAS PREMIUM[e]	Solar tile	Rooftop	17.16%	562.22	0.54
HCM60X9[f]	B. I. panel	Rooftop	19.56%	48.62	1.69
PERC 72 375[g]	B. I. panel	Rooftop	18.89%	115.53	1.99
PERC 72 385[h]	B. I. panel	Rooftop	19.11%	98.22	2.01
Onyx Solar[i]	Thin strip	Window	-	0.73 (€/W)	0.1–8.28
FY Solar[j]	Thin strip	Window	-	62.88	1.32

[a] *https://www.alibaba.com/product-detail/China-supplier-TALLMAX-72-cell-module_62056188419.html?spm=a2700.9099375.35.9.ff96jl Accessed on: 20/08/2020.*
[b] *https://www.alibaba.com/product-detail/Bluesun-solar-roof-tile-hook-2019_62183837021.html?spm=a2700.7724857.normalList.39.73992dacJGelGs Accessed on: 20/08/2020.*
[c] *https://www.solaris-shop.com/mission-solar-mse305sq5k-305w-mono-solar-panel/ Accessed on: 20/08/2020.*
[d] *https://www.solaris-shop.com/mission-solar-mse320sr8t-320w-mono-solar-panel/ Accessed on: 20/08/2020.*
[e] *https://www.baustoffshop.de/dach/mehr-fur-dach-fassade/solar/braas-solarsysteme/braas-pv-premium.html Accessed on: 20/08/2020.*
[f] *https://www.secondsol.com/en/anzeige/25513/pv-module/kristallin/mono/dah-solar/hcm60x9-330w Accessed on: 20/08/2020.*
[g] *https://www.foreverpureplace.com/Mission-Solar-MSE-PERC-72-Solar-Panel-375-Watt-PV-p/mse375sq9s.htm Accessed on: 20/08/2020.*
[h] *https://www.thepowerstore.com/mission-solar-mono-perc-365w-72-cell-silver-white.html Accessed on: 20/08/2020.*
[i] *https://www.onyxsolar.com/product-services/faq Accessed on: 20/08/2020.*
[j] *https://www.alibaba.com/product-detail/customizable-glass-transparency-solar-panel-BIPV_60361886776.html?spm=a2700.7724857.normalList.48.73992dacJGelGs Accessed on: 20/08/2020.*

5.3 Results

The results of this study set the scene for the conceptualisation of two of the major PED solutions to contribute to energy poverty mitigation in Alfama district while reducing GHG emissions and supporting the transition toward a carbon-neutral city. This section depicts the results for a highly detailed spatial assessment of building EE retrofitting measures and RES integration, unfolding the energy savings' potential of window, roof, and wall retrofit by district subsections and building typologies, as well as roof available surface and solar irradiation, enabling the identification of rooftop PV electricity generation potential for the historic district.

5.3.1 Residential Building Energy Efficiency Potential

The lion share of buildings in this historic district was built before 1960. Before 1930, the use of construction systems such as stone masonry walls, wooden beams in one direction between walls, and pottery floors nailed perpendicular to the beams (*i.e.*, masonry reinforced with wood), without insulation and with lime mortars bringing the stones together, was common. In the period 1930–1950 with the appearance of concrete, there was a constructive evolution but still very poor as no regulation was setting quality standards for thermal performance. Due to climate, culture, and lack of money, there was not much need for improved quality since it would increase costs; thus, roof slab serves as "insulation" and the buildings have wooden windows. All these characteristics set the scene for structural problems and low indoor thermal comfort, with significant potential for improvements (thermal, acoustic, against earthquakes).

Table 5.4 presents the nominal heating and cooling needs for a dwelling in each building typology before and after the application of the selected retrofitting measures. The current energy needs are generally higher in the dwellings of TP1 and TP2 typologies due to higher thermal transmittance of the building envelope, and because the roof is directly connected to the outside, which does not happen for most dwellings in multi-apartment buildings. The energy needs obtained for the retrofitting scenario were compared to the current needs.

Table 5.4 - Annual nominal heating and cooling dwelling energy needs before and after the retrofit.

Building typology	Current nominal heating needs (kWh/m^2.year)	Current nominal cooling needs (kWh/m^2.year)	Nominal heating needs after full retrofit (kWh/m^2.year)	Nominal cooling needs after full retrofit (kWh/m^2.year)	Heating need reduction (%)	Cooling need reduction (%)
TP1	167.7	57.6	34.1	41.8	79.7	27.4
TP2	120.1	33.1	12.8	17.9	90.2	46.1
TP3	89.8	35.8	20.6	30.3	78.2	15.4
TP4	76.8	14.9	10.9	11.6	85.8	22.3
TP5	75.5	31.7	19.0	30.3	74.8	4.6
TP6	55.5	12.9	7.7	12.7	86.1	1.6

Retrofit measures are more effective in reducing space heating energy needs, as the reduction of energy losses related to the improvement of thermal performance directly reduces the need for energy provision, whereas, for space cooling, this relation is not so straightforward. These needs are determined by a ratio between energy gains and losses, and retrofit can magnify energy needs if the reduction of losses is higher than the reduction of gains. The implementation of the combined set of measures shows a significant reduction of space heating energy needs, equal to 84% of the energy needs before the retrofit. On the other hand, space cooling energy needs are reduced by 19% (Table 5.5). The impact values on windows reflect the trade-off between the application of renovation measures to improve thermal comfort during both seasons (heating and cooling) in a Mediterranean climate, which is an aspect that should be evaluated carefully at the implementation stage. Although space heating energy needs are significantly reduced in all typologies, buildings built before 1919 have slightly lower reductions per dwelling (TP1 with 79.7% and TP3 with 78.2%, and TP5 with 74.8%), as the thick stone walls provide better thermal inertia and consequently a better energy performance from the start. Between the several building typologies, the difference between the higher and lower reductions of the heating energy needs is up to 15.4% (between TP2 and TP5), demonstrating that the building typology plays a relevant role in the efficacy of the retrofit. Space cooling energy need reduction is mostly connected to house typologies as the application of roof retrofit significantly reduces energy gains in those dwellings. Building orientation is also considerably relevant in dwellings with walls and windows facing south have higher energy gains and increased space cooling needs, explaining the low TP5 and TP6 space cooling energy needs reduction, respectively 4.6 and 1.6%.

Table 5.5 - Energy needs for space heating and cooling, and the impact of different individual renovation measures for each building components.

Current total energy needs (GWh/year)		Building component retrofitted	Total energy needs after retrofit [GWh/year]		Energy need reduction [GWh/year (%)]	
Heating	Cooling		Heating	Cooling	Heating	Cooling
34.3	10.9	Roofs	25.2	8.0	9.1 (27%)	2.9 (27%)
		Windows	30.8	11.5	3.5 (10%)	−0.5 (−5%)
		Walls	18.0	11.2	16.3 (48%)	−0.3 (−3%)
		All measures combined	6.3	9.0	28.9 (84%)	2.1 (19%)

Table 5.5 shows the energy needs for space heating and cooling and the impact of different individual energy renovations for each building component. Improved roof insulation resulted in an average reduction of space heating energy needs of 27% per dwelling (ranging from 14% on TP5 to 50% on TP2), 10% due to window replacement (ranging from 6% on TP3 to 13% on TP6), and 48% due to walls (ranging from 32% on TP1 to 60% on TP6). Regarding space cooling energy needs, roof measures enable a potential average decrease of 27% (ranging from 10% on TP5 to 58% on TP2). On the other hand, window replacement would increase energy needs by 5% (ranging from −2% on TP3 to −9% on TP6) and wall retrofit would lead to an increase of 3% for space cooling (ranging from −10% on TP6 to 1% on TP1).

Figure 5.4 depicts the spatial analysis of the resulting energy needs for space heating (left panel) and cooling (right panel) per dwelling in each subsection after all building components are retrofitted. From the analysis, 28% of subsections include dwellings with energy needs after retrofitting over 8.8 MWh for space heating and 15% of subsections with over 10.8 MWh for space cooling (two upper classes of the maps). The two categories where energy needs per dwelling are lower account for 39% of all subsections (*i.e.*, 53). The maps of Figure 5.4 also highlight that most of the subsections with lower heating energy needs after renovation measures are also the same where cooling needs are lower, probably due to the building typologies present in the subsection. Lower energy needs might translate into reduced energy consumption requirement and thus potentially lower vulnerability to energy poverty in these subsections. On the other hand, subsections that have higher energy needs after the building retrofit would need additional measures to reduce energy poverty, *e.g.*, a relevant integration of decentralised RES.

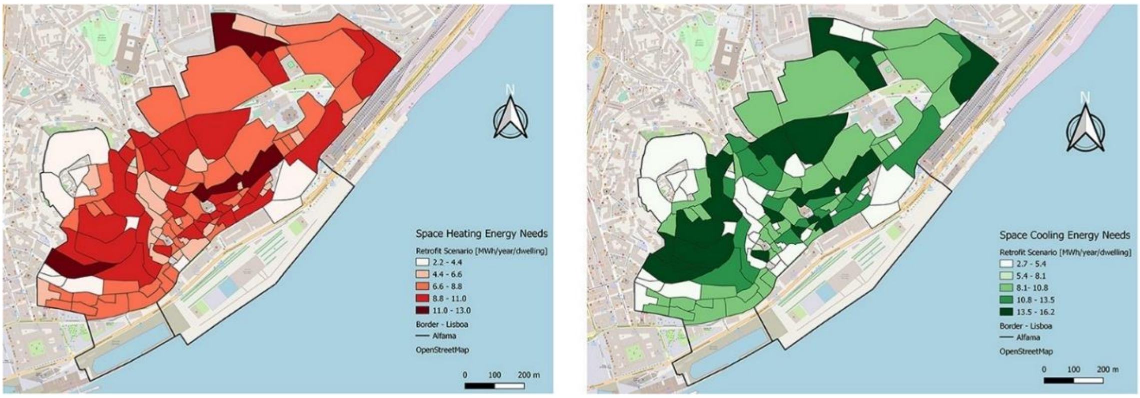

Figure 5.4 - Space heating (left) and cooling (right) energy needs per average dwelling in Alfama subsections after retrofitting measures.

Figure 5.5 discloses different levels of impact of the overall set of measures. This representation highlights the locations where the EE measures are most impactful, contributing to tackle the related thermal comfort and energy poverty problems. Subsections at the north and center south of the district have higher potential for energy need reduction. Most subsections have potential for space heating energy need reduction, whereas the dwellings of only a few subsections, especially in the western regions of the district, have potential for space cooling energy need reduction through building fabric retrofit. The subsections with high impact might be considered as priority hotspot locations for a cost-effective renovation, toward reducing the gap between energy needs and energy provision, while being also valuable locations for energy poverty mitigation. It is interesting to notice that the subsections with the highest heating energy need reduction are still the subsections that have higher energy needs. This highlights where the biggest vulnerability to energy poverty is present, and where a more detailed retrofit plan should be designed.

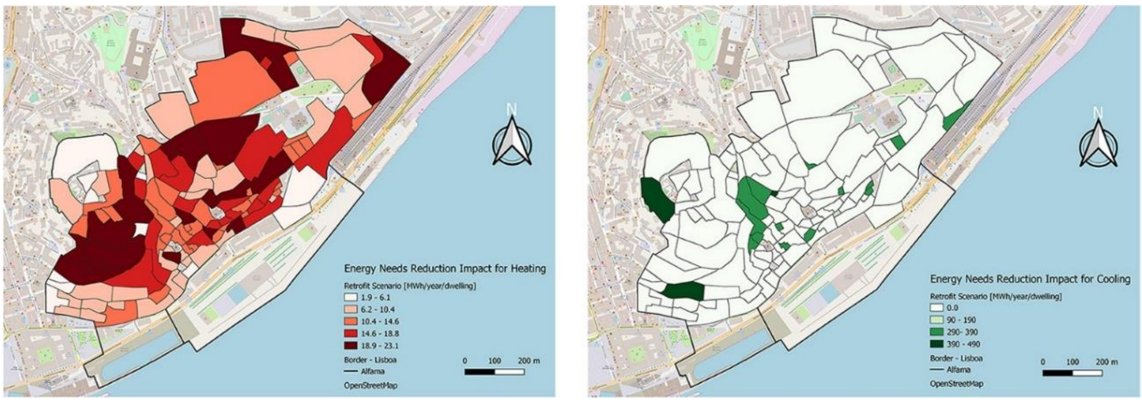

Figure 5.5 - Space heating (left) and cooling (right) energy needs reduction impact per average dwelling in Alfama.

5.3.2 PV Integration Potential in Residential Buildings

5.3.2.1 Rooftop and Windows Area

Figure 5.6 illustrates the composition of each building typology, in terms of the average rooftop area category and window area category. These are displayed as a cumulative bar chart for each building typology. The data shows trends for both these features in the different building typologies. Assessing the range for the window areas, the vast majority (96% and over) of buildings have an average window area in category A. Negligible amounts of buildings have average window areas in the range of categories B and C, evidently displaying that all the building typologies considered have relatively small available areas for the installation of window PV technologies.

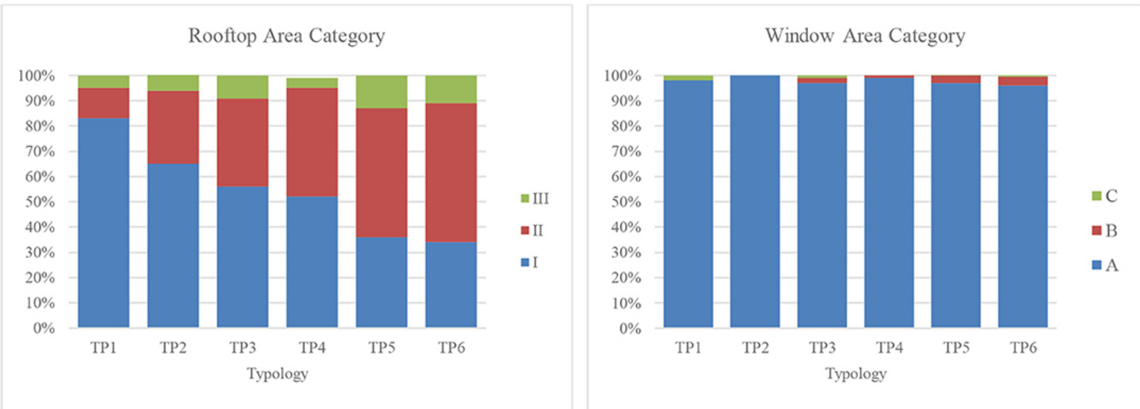

Figure 5.6 - Distribution of rooftop (I, II, III) and window area categories (A, B, C) by building typology for Alfama.

The rooftop area, however, shows a different trend. For TP1 and TP2 buildings, which represent houses/apartments with one or two floors, most of the buildings fall in the roof category I (0–150 m^2), whereas for building TP3 and TP4, it is spread almost evenly between categories I and II (150–350 m^2), providing a varied spread of average areas. For TP5 and TP6, which represent the tallest apartment buildings with 5+ floors, over half of the buildings have rooftop areas belonging to category II. Once the trends have been analysed, the average half roof area (without taking rooftop restrictions into account) and average available window area for each building typology were calculated.

The roof availability analysis for each building typology revealed roof restrictions as follows: 0% for TP3; 5% for TP1, TP2, and TP4; and 15% for TP5 and TP6. A single roof availability area for each building typology is assumed. This approximation is due to the lack of detailed data on roof characteristics.

5.3.2.2 Solar PV Electricity Generation

Individual technological evaluation results for investment costs, electricity generation, and LCOEs are depicted in Table 5.6. For window technology, the selected choice was FY Solar was the one enabling a continuous unbiased approach, as the source of information for solar irradiation is the same as the ones used for the rooftop PV technology calculations (*i.e.*, PV GIS) and not the manufacturer estimations. For the rooftop technology, the selection process was more complex since two different module types were chosen to be potentially implemented (solar tiles and building integrated panels). From the data gathered in the previous steps, it is shown that for solar tile technologies, the best choice is the Bluesun solar tile. Although the total production is less than if the BRAAS solar tile were to be used, the costs are significantly lower. These lower costs significantly impact the LCOEs, with 0.12 €/kWh for the Bluesun solar tile compared to a four-fold figure of 0.49 €/kWh for BRAAS solar tile. For building-integrated panels, more choices were available. After the analysis of the different electricity production levels, investment costs, and LCOEs, two technologies are seen to be better than the other ones—HCM60X9 and Tallmax. Due to the large area of each module for the Tallmax, HCM60X9 is the better choice as it is more adaptable to smaller rooftops or rooftops with a high level of restrictions.

Table 5.6 - Electricity generation, investment costs, and LCOE of solar PV technologies.

Module name	Type	Electricity generation (1st year) (GWh/year)	Lifetime electricity generation (GWh)	Module investment costs (M€)	Total investment costs (M€)	LCOE (€/kWh)
TALLMAX	Panel	63	848	12	14	0.04
BLUESUN	**Solar tile**	49	651	30	35	0.12
PERC 60 305 W	B. I. panel	24	316	24	28	0.20
PERC 60 320 W	B. I. panel	61	819	28	33	0.09
BRAS PREMIUM	Solar tile	55	744	137	161	0.49
HCM60X9	**B. I. panel**	63	845	12	14	0.04
PERC 72 375	B. I. panel	61	817	28	33	0.09
PERC 72 385	B. I. panel	62	826	24	27	0.62
Onyx solar	Thin strip	0.06	0.83	0.99	1.1	3.20
FY solar	**Thin strip**	0.05	0.68	0.91	1.0	3.57

For an integrated analysis of PV integration potential in different building parts, we concluded the two best combinations of window and rooftop technologies—FY-solar strips for window and HCM60X9 modules—which resulted in a combined electricity production of 63 GWh per year and a total lifetime of 846 GWh. The combination of FY-solar strips and the BLUESUN solar tiles has a potential of 49 GWh of generated electricity per year, with a total lifetime production of 652 GWh. The latest combination was ultimately selected as the best option for this district context, because the solar tiles have a lower visual impact, reducing the influence on the aesthetics of the historic district, thus increasing public acceptance. If compared to the current electricity generation levels in Portugal (2019), these annual figures would represent 0.09–0.012% of total gross electricity generation and 3.7–4.7% of PV generation. Figure 5.7 shows the potential of solar energy generation for this combination, mapped at the district subsection level. The map highlights that 83% of the subsections have a potential electricity generation lower than 0.6 GWh/year, while ~17% have values in the range from 1.2 to 2 GWh/year (darker purple). There is a higher potential for PV production in the subsections located in the northeast part of the district where most TP2 typologies have higher rooftop areas and also because it is the area in the district with more residential buildings. Lower potential for electricity generation is in the northwestern region where the castle and walls are located.

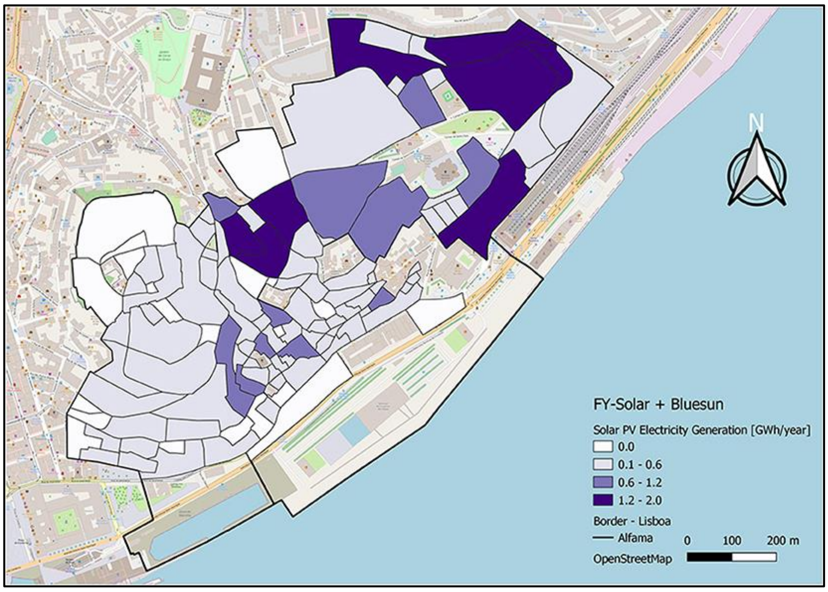

Figure 5.7 - Space heating (left) and cooling (right) energy needs reduction impact per average dwelling in Alfama.

5.3.3 Investment Costs

This section summarises the investment costs necessary for deep retrofitting measures and the RES generation through the integration of BIPV technologies in the buildings' windows and rooftops. The analysis provides insights into the relation between energy need reduction and the capital investment necessary to achieve that reduction, for different types of retrofit intervention and solar PV technologies (Figure 5.8).

The evaluated retrofitting measures for all residential building stocks in Alfama requires an estimated investment of 45M€, with 2.9M€ for roof retrofitting, 26M€ for window retrofitting, and 17M€ for wall retrofitting. The left panel of Figure 5.8 shows the total investment costs of building retrofit at the subsection level. Wall improvement is the most impactful measure for energy need reduction, with overall investment needed being the second. Roof retrofit has a cost-effectiveness of 0.32 and 1.0€/kWh for energy need reduction for space heating and space cooling, respectively. The retrofit of walls and windows results in 7.4 and 1.0€/kWh, respectively, regarding space heating. Considering only space cooling-related improvements, these interventions are not cost-effective. Overall roof retrofit is the most cost-effective measure for Alfama for both space heating and cooling and should be the first option to be pursued under a limited budget. As discussed in multiple publications (*e.g.*, Howden-Chapman, 2015;

COMBI, 2018; Bisello, 2020; Reuter *et al.*, 2020), energy efficiency renovations spawn far beyond direct impact on the environment (*e.g.*, energy consumption and GHG reduction) which should be acknowledged (for health, economy, social welfare) in district-scale ambitious energy efficiency transformations.

As for the PV production, however, the combination of FY-solar strips and HCM60X9 panels was found to be the most cost-effective choice, totaling 15M€ of needed investment with an LCOE of 0.04 €/kWh. The combination of FY-solar strips and the BLUESUN solar tiles were selected, as explained in the previous section, as more suitable to be applied in a historic district with several associated building regulatory restrictions. This combination requires a total investment cost of 36M€ and has an aggregated LCOE of 0.13 €/kWh. The right panel of Figure 5.8 illustrates the spatial distribution of the total investment costs for the integration of the selected set of PV solutions. It is found that 10% of the subsections entail a potential investment higher than 0.6M€. Locations with high investment costs are mostly found in the eastern part of the district due to their building types and higher presence of residential buildings. Approximately 46% of the subsections depict investments lower than 200k€.

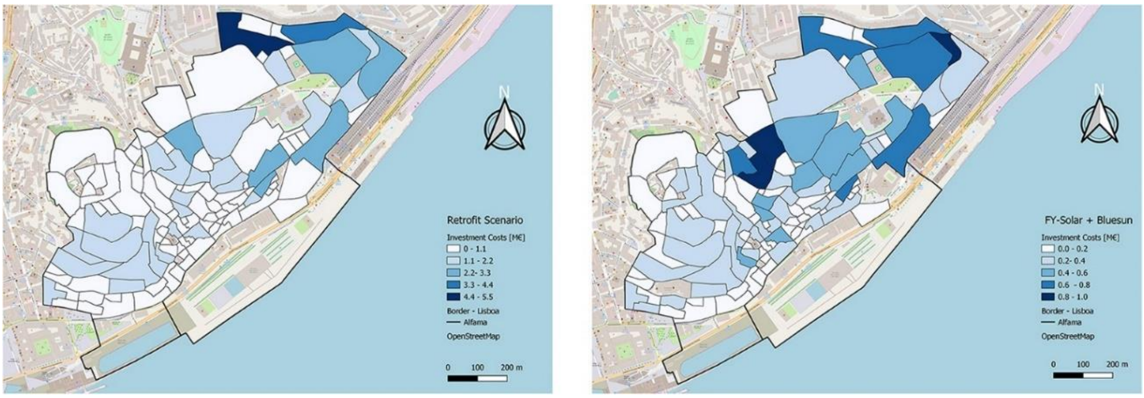

Figure 5.8 - Investment costs needed for full buildings retrofit (left) and solar PV integration (right) in Alfama subsections.

5.4 General Discussion

The work presented in this paper provides a first approach to implement a vision of a Positive Energy District in the Alfama historical district, focusing on two key components of the PED framework—EE measures to reduce energy needs and decentralised locally produced RES electricity. We argue that these two components entail a strategy for a structural and sustainable energy poverty mitigation, paving the way for a holistic and systemic district change (technically and socially) toward a sustainable energy transition. The case study highlights the common problems occurring in the Mediterranean historic city districts, and the methodology can be applied to evaluate the potential of PED implementations in many Southern European cities. Considering the current literature, this paper presents two key novelties that should be underlined: the technical and economic feasibility to adopt some key components of a PED concept in a historic district, while most projects focus on the design of newly built districts (Bossi *et al.*, 2020); and the exploration of the PED model as an opportunity to tackle and mitigate energy poverty.

The majority of European cities have buildings or blocks of historical interest, which have great potential to reduce their energy consumption and to cut GHG emissions (Eurocities, 2020), applying the PED concept. However, they present severe challenges to implement integrated PED solutions, either due to regulatory restrictions or due to standard financial bottlenecks that often limit the integration of RES and EE measures. Moreover, the social acceptance of interventions in historical districts may create barriers to the transition toward more sustainable cities. In many cases, the public opinion for the installation of PV panels or small wind turbines is extremely negative as the infrastructures built are considered to be damaging to the district's overall architecture and charm. Therefore, addressing these conflicts and barriers, developing innovative and creative solutions or designs (*e.g.*, technologies, financing schemes), and, on social features, educating the local population toward the benefits of using RES are of vital importance when transitioning the energy usage in historic districts unlocking their full potential.

The results achieved herein aimed to illustrate the high technical potential of historic districts to contribute to carbon neutrality and sustainable cities. For the case of Alfama, the oldest historic district of the city of Lisbon, energy efficiency measures on the dwelling's structure, including the renovation of the roof (*i.e.*, thermal insulation with mineral wool), windows (*i.e.*, PVC window frames with standard double glass), and walls (*i.e.*, expanded polystyrene, EPS6, through internal insulation), may reduce the energy needs around 84% for heating and 19% for cooling, when compared with the energy needs before the retrofitting measures. The required investment totals 45M€ for the full set of EE retrofitting measures in 6 004 dwellings and 15–36M€ for the two combinations (windows plus rooftops) of decentralised solar electricity generation. The investment for the retrofit of the building may represent between 56 and 75% of the total investment for the district, depending on the solar technologies selected. All these results unfold the importance of a deep-scale full package retrofit for reduction of energy needs while improving the living conditions of the occupants throughout the dwelling stock.

We argue that these levels of energy need reduction which enable to keep the thermal comfort at the set reference indoor temperatures in winter (18°C) and in summer (25°C) have a direct impact on energy poverty reduction, meaning that even if a family does not have the financial resources to heat or cool the household up to the ideal temperatures, the significant reduction of energy losses due to EE measures can increase the thermal comfort of the households. These results stress the need for acting first in the building's components, simultaneously with ventilation, which increases the building airtightness through insulation and better windows, while renewing the indoor air for good air quality conditions. Only then, under a PED concept, should the integration of technical systems (PV systems, boilers, heat pumps, etc.) be considered.

Nevertheless, we concluded a significant technical potential for solar electricity generation in the historic district, for two combinations of window and rooftop technologies. The most cost-effective technology combination is FY-solar strips for windows plus HCM60X9 BIPV panels for rooftops. However, due to its visual impact on the historic district rooftops and the potential low public acceptance, the combined solution of FY-solar strips for windows and BLUESUN solar tile for rooftops was spatially assessed. This combination has higher total lifetime costs; however, the aesthetic of the historic districts would be preserved since the solar tiles have a smaller profile and are designed to simulate rooftop tiles. This trade-off illustrates one of the current challenges historic districts are facing regarding locally produced electricity: the visual perception of PV panels.

The role of locally generated electricity in mitigating energy poverty should be underlined, as it brings an opportunity to lower energy bills. In particular, this could be especially relevant when the most adequate subsections for RES integration are closer or the same as the subsections that have high energy needs for space heating and cooling. In these cases, the PED model is an opportunity for a renewable energy community, a priority for the Portuguese government, as evidenced by the approval of the Decree-Law, 162/2019, which establishes the legal framework for the self-consumption of renewable energy and the constitution of energy communities, with potential positive spillover to the most vulnerable inhabitants through sharing surplus electricity generation. Furthermore, it is understood that the integration of renewables within the scope of, for example, Net Zero energy buildings is not profitable when it is performed building by building (Shehadi, 2020). Cost-effectiveness is much higher at district-scale interventions compared to individual buildings and should be explored moving forward to more ambitious renovation strategies.

The barriers that hinder the integration of PED solutions in historical city districts also affect the opportunities to tackle energy poverty. Although EU Directive sets minimum requirements of the energy performance of retrofitted buildings (European Parliament, 2012), legally protected buildings and buildings of historical interest are excluded from complying with energy efficiency requirements (Caro and Sendra, 2020). Therefore, a significant portion of the existing building stock is not covered by energy efficiency ambition (Dol and Haffner, 2010). Moreover, other practical reasons such as the heterogeneous geometry, peculiar materials, conservation strategies, and variety of protected elements (*e.g.*, façades, indoor finishes) of listed buildings are not suited to standardised values and procedures that are usually used by the construction industry, adding complexity to retrofit plans (Caro and Sendra, 2020). As a consequence, residents in historic districts are potentially more vulnerable to energy poverty than residents in newly built districts, therefore confronted with the related health, economic, and climate change risks. However, most of the EE measures and RES technologies do not comply with the specific regulation in Alfama. In this study, only technical constraints (such as building orientation and rooftop surface availability) were taken into account. In future research, the trade-off between compliance with local heritage regulations and compliance with the building's thermal component should be evaluated, to enable effective large-scale renovations. With the increasing availability of smart meters in the country providing more details on energy consumption profiles, a wider analysis including other important PED components such as energy flexibility with smart controls, as highlighted in IEA (2020) and JPI Urban Europe (2021), should be conducted. This research shows the technical potential hidden in historic districts, aiming to disclose the necessary policy, social, and financial discussion around the role of historic districts in the energy transition of cities.

The viability and sustainability of the business model behind EE measures is the biggest identified barrier, being more difficult to overcome than the existing technical limitations. For instance, split incentives, lack of capital financing, high upfront investment, lack of information and awareness about the costs and benefits, difficulty in the decision-making process, and lack of expertise (Vogel *et al.*, 2015; van Oorschot *et al.*, 2016; Bertone *et al.*, 2018; Bertoldi *et al.*, 2020) are limiting the regeneration of historic districts. For RES implementation, intermittency of sources and uncertainty of market subsidies add to the factors driving out investors (European Commission, 2014). In Portugal, the lack of available capital for upfront investment, together with ineffective, mostly loan-based support schemes, is a relevant obstacle preventing homeowners from investing in their assets. The energy gap between the energy needs for thermal comfort and measured energy consumption in Portuguese homes, as demonstrated by Palma *et al.* (2019), represents an increased challenge for an investment opportunity, especially for EE measures, since the capital return gains linked to energy savings are reduced or inexistent.

Despite the recent trend of fast-decreasing costs of PV, which is expected to proceed in future years opening a window of opportunity for this type of building PV applications, the highlighted investment numbers will require an innovative financial scheme to support not only building owners but also tenants, as these are among the most vulnerable to energy poverty. We argue that the social benefits of the investment should be evaluated, including benefits on health costs, air quality, climate resilience, and productivity. The quantification of potential social co-benefits (*e.g.*, reduction of energy poverty, community building, reduction of gentrification) from the adoption of the PED model could increase the ambition of the project and accelerate the implementation of these solutions in existing districts, and especially in historic districts, which usually present a more pressing need to solve the beforementioned social issues.

The European Commission through the Clean Energy for all Europeans Package (2019) brought a solid basis for renewable deployment and energy efficiency promotion, improving the regulatory structure and funding instruments, but the impact is still not enough, with renovation works only rarely addressing energy performance of buildings, and uptake of RES remains low (Arístegui, 2021).

In conclusion, the PED model is part of the pathway toward the goal of 100 climate neutral cities in Europe, which relate to the final goal of a climate-neutral Europe by 2050. The PED research field is at the beginning; however, it is important to include existing districts in the assessment, through analysis that covers the entire scale of the district, to achieve a relevant impact for a holistic and sustainable transformation. At the moment, the aspiration to be energy positive is difficult to reach in historic districts; however, high ambition is necessary to push research forward and enable to obtain a momentum of innovation and positive impacts. Moreover, historic districts generally have deep social problems and they play a relevant role in the European cultural landscape: deep demonstration projects that show the efficacy of the PED framework in historic districts could accelerate the energy transition in Europe and increase the value of sustainability.

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6

ASSESSING DIFFERENT SOLUTIONS FOR FUTURE ENERGY EFFICIENCY IMPROVEMENT AND ENERGY POVERTY MITIGATION

Part 1: Paper published in People, Place & Policy:

Palma, P., Gouveia, J, P. Mahoney, K., Bessa, S. (2022). It starts at home: Space heating and cooling efficiency for energy poverty and carbon emissions reduction in Portugal. People, Place and Policy. 1-20. https://doi.org/10.3351/ppp.2022.5344968696

Contribution: Writing – original draft, review & editing, Visualisation, Validation, Supervision, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualisation.

Part 2: Paper published in Sustainable Cities and Society:

Palma, P., Gouveia, J. P., & Barbosa, R. (2022). How much will it cost? An energy renovation analysis for the Portuguese dwelling stock. Sustainable Cities and Society, 78. https://doi.org/10.1016/j.scs.2021.103607

Contribution: Writing – original draft, review & editing, Visualisation, Validation, Supervision, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualisation.

Part 3: Paper to be submitted:

Palma, P., Gouveia, J.P., Climaco, N. (2024). Economic Analysis of decarbonising energy consumption in residential buildings. To be submitted.

Contribution: Writing – original draft, review & editing, Visualisation, Validation, Supervision, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualisation.

6.1 How much will it cost? An energy renovation analysis for the Portuguese dwelling stock

Abstract

The building sector is one of the critical pieces for the sustainable transformation in Europe. This study assesses the cost-effectiveness of renovation measures for reducing the Portuguese dwelling stock's space heating and cooling energy needs at national and regional levels. Three different scenarios with varying renovation levels were developed to identify the most effective interventions, and the building type and regions with the highest improvement potential. The energy needs were computed through a dwelling archetype bottom-up method, using EPC data. A market-based renovation measure inventory was conducted to estimate investment costs. Results show that a deep energy renovation of the dwelling stock entails a minimum investment of €71.7 billion. Roof renovation is the most cost-effective measure for improving heating and cooling thermal performance, respectively 3.5 and 0.8 kWh/€ in the scenarios with lower cost measures. However, renovation packages can add significant marginal increases in energy needs reduction. Results suggest it is more cost-effective to prioritise older house archetypes in the north and south inland regions in the heating and cooling seasons respectively. These results are informative for more nuanced and targeted policy schemes, enabling more effective use of public funding and increased impact of support measures.

6.1.1 Introduction

Buildings have been a cornerstone of urban settlements and civilisations, fulfilling the basic need for shelter and supporting a significant part of human activity and progress. They play a major role in achieving several sustainable development goals, crossing over different dimensions of the envisaged transformation (Frischmann *et al.* 2020). In the European Union (EU), the improvement of buildings' energy efficiency (EE) has been a long-standing priority, integrating concerted policy efforts to achieve greenhouse gases (GHG) emissions reduction and EE improvement targets by 2030, and carbon neutrality in 2050 (European Commission, 2019). From construction to demolition, the building sector accounts for about 40% of EU's energy consumption and 36% of GHG emissions, as approximately 75% of the existing building stock has low energy performance (European Commission, 2020a). The residential sector is particularly impactful, accounting for two-thirds of the final energy consumption in the EU building stock (Build Up, 2017). Several policies have been implemented at the European level to explore the sector's significant untapped potential, such as the Energy Performance of Buildings Directive (EPBD), which requires all new buildings to be nearly zero-energy buildings (nZEB) from the end of 2020 (European Commission, 2021). The Clean Energy for All Europeans package defined a path for eliminating all building emissions by 2050 (European Commission, 2020b), underlining the reduction of energy poverty as a policy priority. Energy poverty is a severe and persistent issue in the EU, with 6.9% of people (approx. 31 million people) still claiming not to be able to keep their homes adequately warm in the winter (Eurostat, 2021a). Energy inefficiency is particularly significant in the south of Europe, as the building stock presents lower energy performance than northern and central countries on average (Anagnostopoulos & De Groote, 2016; iNSPiRe, 2014). Several of these countries also present some of the highest percentages of inability to heat the home, which is symptomatic of a more significant energy poverty issue amongst the population (Eurostat, 2021a). The global COVID-19 pandemic has created a combination of circumstances that potentially exacerbate vulnerability (Ding, Ivanko, Cao, Brattebø & Nord, 2021).

Despite the ongoing efforts to boost this sector's EE (European Commission, 2020c), the EU building stock energy renovation rate stands below 1% per year (European Commission, 2020e), with only 0.2% of buildings per year undergoing deep renovations (European Commission, 2020d). There are several constraints to building stock renovation which prevent higher renovation rates, such as split incentives for owners and renters, lack of awareness regarding the costs and benefits, and lack of interest and engagement of residents (Bertoldi, Economidou, Palermo, Boza-Kiss & Todeschi, 2020; Gangale & Mengolini, 2019; van Oorschot, Hofman & Halman, 2016). Regulations can also be limiting, especially in older buildings in historic districts, where stricter regulations protect and preserve the historically valuable urban fabric and building façades (Build Up, 2020). Nonetheless, high upfront investments and lack of available private funding are arguably the most common constraints to the roll-out of building renovation

(Bertoldi *et al.*, 2020; Bertone *et al.*, 2018; Vogel, Lundqvist & Arias, 2015). Large projects can benefit from economies of scale, highlighting the potential of integrated district efforts (Michelsen, Rosenschon & Schulz, 2015). In this context, the EC has recently approved a new renovation strategy, aiming to address several barriers to building renovation and to double renovation rates (European Commission, 2020d). Aside from the direct benefits such as reductions in energy needs, energy consumption and GHG emissions, renovations can also positively impact health, the economy, and social welfare (Bisello, 2020; Hyland, Lyons & Lyons, 2013; Reuter, Patel & Eichhammer, 2020).

Given that financing is such an instrumental part of boosting building renovation and considering the substantial amounts of capital being deployed in Member-states for this purpose, namely through the Recovery and Resilience Facility, it is crucial to understand how much capital is necessary to upgrade the residential building stock energy performance to required levels. Furthermore, it is paramount to identify the most cost-effective renovation measures (RM) for higher impact and improved use of funding (Hashempour, Taherkhani & Mahdikhani, 2020). Renovation programs are tailored at the national and regional levels, thus there is a need for regionally specific studies for a detailed and nuanced assessment of renovation potentials and impacts, such as the one presented herein, for bridging the persistent informational gap between research and policy.

6.1.2 Literature Review

Several authors have focused on analysing the cost-effectiveness of RM on energy demand and consumption reduction for different building samples in various geographical contexts. Multiple case-studies were conducted to evaluate the effect of various building envelope RM, individually and in packages, producing differential results. Kuusk, Kalamees and Maivel (2014) identified wall renovation as the most impactful for reducing final energy consumption in Finnish apartment buildings, whilst underlining that a retrofit package can upgrade energy performance to the level of new buildings. Tadeu *et al.* (2016) highlights roof insulation as the most cost-effective intervention for building envelope, with better results for older dwellings with low space heating systems. Ferrari and Beccali (2017) estimate a decrease in primary energy consumption and GHG emissions of up to 40%, following the retrofit of a public building. Paiho *et al.* (2015) estimated the costs of EE and RMs for a district in Moscow, reporting higher values for external wall renovation. Dodoo *et al.* (2017) calculated higher cost-effectiveness for basement wall insulation and window replacement for a Swedish building. However, the authors emphasise that cost-effectiveness is dependent on the particularities of buildings studied, particularly their characteristics and current condition. In their study for Israel, Friedman, Becker and Erell (2014) report that renovation is more effective for cities with extremer climates, both cold and hot. La Fleur *et al.* (2019) found that renovation is less effective in previously renovated buildings than buildings without intervention. This conclusion is corroborated by Hoos *et al.* (2016), who found that renovating high-energy consumption buildings, not previously renovated, is more cost-effective for reducing consumption. These are generally older buildings, which may have lower energy use reduction due to regulations protecting their architectonical value and preventing specific RM (Liu *et al.*, 2016). Patiño-Cambeiro *et al.* (2019) evaluated packages of EE measures in building envelope interventions for universities in Spain and stated that building envelope renovation can have a significant impact on energy reductions but implies considerable investment, which is a common finding in the analysed studies.

Only a few authors have focused their attention to whole building stocks, analysing renovation scenarios for different building archetypes. For Luxembourg's public building stock, Hoos *et al.* (2016) calculated a cost-effectiveness of between 20 and 25 kWh/€ of final energy for dwellings, considering total renovation. Streicher, Mennel, Chambers, Parra and Patel (2020) estimated a cost-effectiveness of approximately 9 kWh/€ for final energy demand reduction in the scenario considering full refurbishment for 6700 archetype buildings in Switzerland. Both authors focus on the reduction of final energy consumption, including HVAC systems, which enables a more direct evaluation of EE in buildings. However, it is more challenging to trace its real impact of RM when considering energy consumption, since other factors come into play, such as occupant behaviour (Chen *et al.*, 2015), which can result in different outcomes such as the "rebound effect" (Haas and Biermayr, 2000; Lin and Liu, 2015).

In Portugal, Palma *et al.* (2019) estimated the residential stock energy performance gap for all the country's regions and pinpointed the most ineffective regional residential dwelling stocks. Building on this work, Gouveia and Palma (2019) assessed the effect of energy renovation interventions on the energy performance gap. Cost-effectiveness analyses have focused chiefly on particular case studies and small building samples. Ferreira *et al.* (2014) investigated the cost-effectiveness of renovation packages, including HVAC equipment and renewable energy systems, for a building in a neighbourhood in the north of Portugal, finding out that the cost-optimal RMs are identical to the ones necessary to achieve the zero-energy balance. Vasconcelos *et al.* (2016) assessed RMs in a reference building through Life-Cycle Cost Analysis (LCCA). The authors identified roof retrofit as the most effective solution and observed synergies between different RMs regarding costs and consumption. Almeida *et al.* (2018) analysed the influence of embodied energy in the cost-effectiveness of renovation packages for several European case-studies, through a LCCA, not finding any differences in RMs relative ranking. Terés-Zubiaga *et al.* (2020) evaluated the renovation potential from a cost-effectiveness perspective at the district level to support decision making, using a Portuguese social housing neighbourhood as case study. The authors highlighted the importance of including building envelope renovation for achieving zero energy districts whilst adhering to cost-effectiveness requirements. Focusing on building stock renovation at district or regional scales can be beneficial due to economies of scale and resource use efficiency, whilst enabling municipalities to tap into the sector's potential (Paiho *et al.*, 2015; Paiho *et al.*, 2019; Rose *et al.*, 2021). Lastly, the recently approved national LTRS (Portuguese Republic, 2021), assessed the impact of the cost-optimal package of EE measures on primary energy consumption of the Portuguese residential building stock at the national level. The strategy estimated a total investment of €40 400 million to achieve full renovation.

Aiming to move further and tackle the existing lack of regionally detailed assessments, this study conducts a snapshot assessment of energy RM cost-effectiveness at regional Nomenclature of Territorial Units for Statistics (NUTS) 3 scale. It assesses the deep renovation of the Portuguese dwelling stock to improve its energy performance to nZEB level, whilst developing a more comprehensive range of archetypes to encompass the diversity of its characteristics. The study focuses on the residential stock, due to strong evidence of low energy efficiency and subsequent high levels of energy poverty in the population, which stress the need for in-depth studies to identify the causes and effective solutions. The goal of this study is to identify the RM and dwelling types with the highest potential for reducing energy needs at lower costs across the country's regions. This approach assesses the impact of RMs both individually and jointly, for three different scenarios based on different energy performance requirement levels and buildings suitability for RM implementation. The focus on energy needs reduction is particularly relevant because it is the first step for achieving nZEB levels. On the other hand, in a country with a temperate climate such as Portugal, increasing insulation in the building envelope is an effective strategy for increasing inside thermal comfort and eliminating building pathologies (Decree-Law no., 101-D/2020). The insights from this study can be helpful in the current European and national contexts, where there is a strong push for energy renovation through increasingly available funding, for the achievement of energy and climate targets.

6.1.3 Materials and Methods

This section presents the case-study characterisation in subSection 3.1, focusing mainly on the Portuguese residential building stock's current state. The methodological approaches applied for the building stock's characterisation, RM inventory, energy needs and investment cost calculation, and cost-effectiveness assessment are addressed in subSection 3.2.

6.1.3.1 Case Study - Portugal

Portugal was chosen as a case study due to the deteriorating dwelling stock and the pressing need for its renovation, highlighted by the LTRS (Portuguese Republic, 2021). There were circa 3.6 million classic residential buildings and 6.0 million dwellings in Portugal in 2020 (INE, 2021). The residential building stock is old (INE, 2011) and has low energy performance - approximately 71% of all the energy certified residential buildings (about 1.67 million), have an energy performance rating equal or lower than C (below B- level, the standard for new buildings) (ADENE, 2020). Class C means the ratio between nominal annual primary energy needs and the maximum limit value, calculated according to the method defined in the regulation, should range between 1.01 and 1.51 (Ministerial Order no., 15793-C/2013). New buildings must have at least a B minus class. Around 70% of residential buildings were built before 1990 (INE, 2011), before the establishment of the first Portuguese energy performance regulation. Older buildings commonly have a stone masonry structure and wooden roofs and floors, whereas reinforced concrete in the bearing structure is common nowadays (Magalhães & Freitas, 2017). Generally, older buildings have a historical and architectural value which is preserved by regulations. This is a frequent constraint to the implementation of certain thermal improvement RMs (Magalhães and Freitas, 2017). In some regions, restrictions are even stricter, as interventions must also follow the traditional regional construction procedures and building materials.

The building stock's poor quality reduces its effectiveness in maintaining comfortable indoor temperatures in different climate conditions and seasons. Portugal is amongst one of the warmest countries in the European Union with high temperatures in the summer, with the fifth-highest number of CDDs (*i.e.* 269), and the third with lower HDDs (*i.e.* 1008) in 2020 (Eurostat, 2020b). Furthermore, the country is located in one of the most climate change-impacted regions of Europe (Ducrocq, 2016). Cooling and heating degree-hours will vary inversely in the future - total heating degree-hours are predicted to decrease, whereas total cooling degree-hours are bound to increase by 2050 (Meteonorm, 2020). There is an expected increase in average temperature and frequency and intensity of heatwaves, especially in the south of Europe (Barbosa *et al.*, 2015; Castaño-Rosa *et al.*, 2021).

In the policy arena, building renovation is considered a priority for reducing GHG emissions and increasing EE by national strategy instruments such as the National Energy and Climate Plan 2030 (Portuguese Republic, 2019a) and the Roadmap for Carbon Neutrality for 2050 (Portuguese Republic, 2019b). The LTR characterises the building stock, identifies market failures, and proposes lines of action and policy, including an investment mobilisation strategy (Portuguese Republic, 2021). There are currently several financing instruments to promote building renovation in private housing in the country, namely subsidy schemes implemented at the national level, providing low-interest loans, bank guarantees, or non-repayable grants to improve buildings' energy performance. The recently approved national Plan for Recovery and Resilience, stemming from a European debt issuance mechanism to face the crisis, will unlock €620 M for buildings' EE over the next five years, €300 M of which for the residential sector (Portuguese Republic, 2020). There are also support schemes at the municipal level, mainly targeting vulnerable households in degraded dwellings, aiming to improve living conditions. Tax benefits are conceded for renovations works and projects in defined urban rehabilitation areas in each municipality.

Despite the implementation of these schemes, national statistics from the last ten years show a low reconstruction rate of buildings - an average of around 0.01%/year in the last five years (INE, 2019), emphasising the need for increased focus on buildings EE improvement. Most building renovation policies targeting the residential sector are top-down, lacking effectiveness to deliver the relevant results. There is still a significant untapped potential for renovation in the Portuguese building stock that could bring further benefits for the country and population. The increase of residential buildings' EE is particularly relevant for addressing energy poverty, which looms large in the country (Eurostat, 2021a, 2021c).

6.1.4 Methodological Approach

The methodology approach employed in this study can be divided into five different steps: 1) Characterising the dwelling stock through defining dwelling archetypes at regional level; 2) Developing a database for RM, with data on RMs' cost and energy properties; 3) Defining the renovation scenarios, considering different RMs according to their cost, compliance with regulations, level of energy performance, and the building archetypes' age; 4) Computing energy needs and estimating the total cost per archetype; 5) Assessing the cost-effectiveness of each scenario per NUTS3 region. The methodology framework is displayed in Figure 6.1 and will be further detailed in the following subsections.

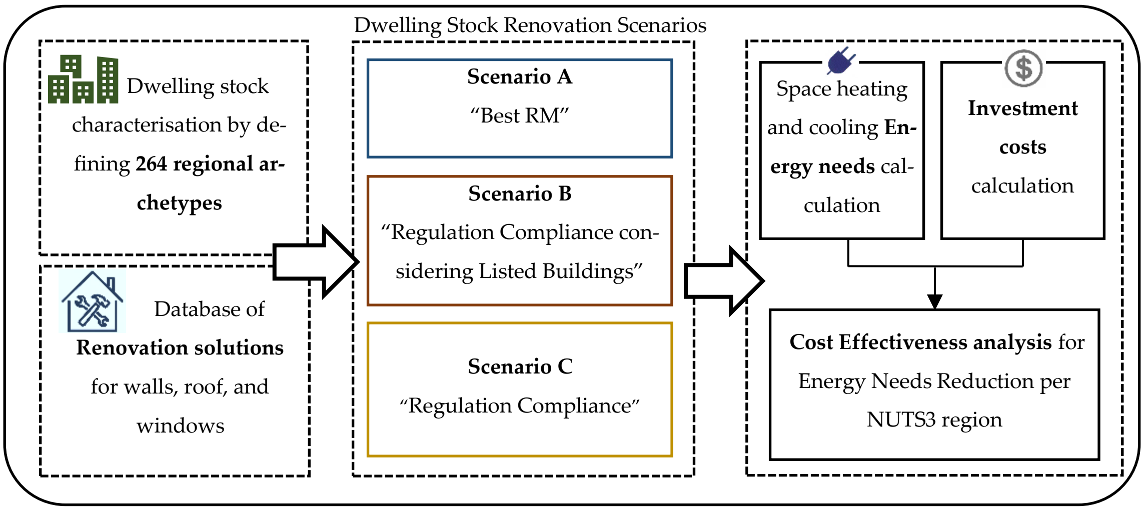


Figure 6.1 -Methodological Framework.

6.1.4.1 Dwelling Stock Archetypes

In the first step of the methodology, a process of archetyping was conducted to identify the different types of dwellings that compose the Portuguese residential dwelling stock. Reinhart *et al.* (2016) describe that the process has two distinct stages: segmentation, where the building stock is divided into different groups which share identical characteristics, and characterisation, where the parameters and properties that determine the buildings energy performance are quantitively defined. In the segmentation phase, the dwelling stock was classified into 264 dwelling archetypes, 11 per 24 NUTS3 regions, according to the type of building which they are classified as (house or apartment building) and construction period. The NUTS3 region of Azores was not considered because the EPC data is managed by a regional entity that does not disclose it. The selected NUTS3 regions are displayed in Figure 6.2. The following 11 archetypes were, according to the type of building: House constructed pre-1919; House constructed between 1919 and 1945; Apartment building constructed between 1919 and 1945; House constructed between 1946 and 1960; Apartment building constructed between 1946 and 1960; House constructed between 1961 and 1980; Apartment building constructed between 1961 and 1980; House constructed between 1981 and 2005; Apartment building constructed between 1981 and 2005; House constructed between 2006 and 2011; Apartment building constructed between 2006 and 2011. Subsequently, the raw data from approximately 525 thousand Portuguese dwelling stock EPCs, issued from December 2013 to October 2017, were used to regionally define the dwelling archetypes according to building elements like thermal transmittance (U-values), floor areas, solar gain heat coefficient, height, and thermal inertia. Data analysis and cleaning were performed before setting up the archetypes, described in Gouveia and Palma (2019). The resulting dwelling archetypes are provided as supplementary material.

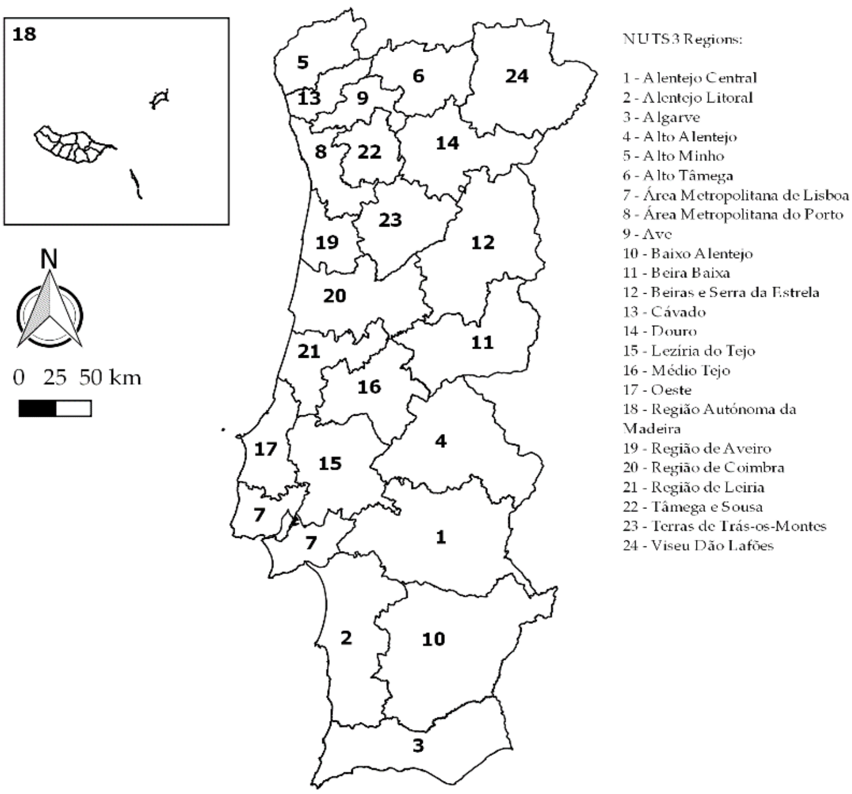


Figure 6.2 - Analysed Portuguese NUTS 3 Regions.

6.1.4.2 Energy Renovation Measures Database

Subsequently, a database with information regarding the physical and thermal properties of materials (thickness and conductivity) and the investment costs of RMs was created. The RMs correspond to insulation materials chosen because of their everyday use in Portugal's construction sector and adequacy for Portuguese buildings. RMs were collected according to the building fabric element - roof, external walls, and windows. Floor insulation was not considered as it is not an effective solution for reducing energy needs. The material properties were collected from established documentation used in thermal regulation calculations (Santos Matias, 2006) and used to calculate the thermal resistance of each insulation solution. The investment costs, including material and estimated person-hours for implementation, without taxes, were drawn from a market-based budget generation tool (CYPE, 2013). All the considered RMs for the roof and wall and the respective thermal conductivity, thermal resistance, and investment cost are displayed in Annex B1. The RMs for window and glazing replacement and the respective solar factor, thermal resistance, and investment cost are shown in Annex B2.

6.1.4.3 Energy Renovation Measures Database

Three different building renovation scenarios were analysed in this study, with variations regarding the type of RMs applied, resulting in different intervention costs and energy needs reduction. The scenarios are the following:

• Scenario A, considering the best possible RMs currently available in the market regarding their thermal performance parameters. This is the scenario where capital investment is highest.

• Scenario B, considering the lowest cost RMs that comply with the thermal performance requirements expressed in the current national residential building energy performance regulation (Ordinance no. 349-B/2013). This scenario also considers internal insulation of walls for the dwelling archetypes pre- 1960. This is based on the assumption that these are listed buildings, where internal insulation is prioritised due to the strict regulations for applying external insulation. External insulation is considered for the other archetypes.

• Scenario C, assessing the lowest cost RMs that comply with the regulation's thermal performance requirements. It assumes the implementation of external insulation for walls in all archetypes.

Generally, there can be legal constraints regarding external insulation of walls since it modifies the buildings' façade. There can also be some social constraints - in the case of apartment buildings, the application of external insulation in dwellings might require the owner's agreement. Moreover, a complex outer surface of a building might also present some practical challenges for the implementation. None of these challenges are faced when installing internal insulation, which is generally cheaper and simpler to install (Build Up, 2020). Although it is technically more demanding and generally costlier, external insulation has several advantages such as preventing thermal bridges; improving the preservation of the buildings' walls from climate events; reducing outside noise; lessening the disruption that the retrofit work forces on the occupants; preventing damp from entering the building and interstitial condensation more effectively.

In each of the scenarios, for the roof and walls, the calculated thermal resistances from the RM database were cross-referenced with the regulation's U-values of the typical Portuguese buildings, accounting for the NUT2 region and climate zone, to select the renovation

RM with the necessary thermal resistance to guarantee the requirements of each scenario. As the insulation material is added to the existing insulation, the thermal resistances of the selected RM and the current solution for each archetype were summed, with the resulting value representing the final thermal resistance after the renovation. Roof renovation was only considered for house archetypes, since in apartment buildings only the top dwelling is more significantly affected. For the windows, implementing a new solution implies substituting the window frame and glazing and hence the resulting thermal resistance and solar factor are the ones of the selected RM.

6.1.4.4 Energy Needs and Investment Costs

Aiming to assess the cost-effectiveness of the three scenarios, energy needs reduction and the investment cost associated with implementing the selected RMs were computed through an excel-based tool developed by the authors for each dwelling archetype and per NUTS3 region. Each archetype's space heating and cooling useful energy needs were calculated according to a steady bottom-up method based on the methodology and requirements for nZEB defined in the current National Energy Performance Regulation (Ordinance n◦349-B/2013), which derives from the EN ISO 13,790 approach. Useful energy needs represent the energy requirement to maintain a comfortable indoor temperature in the heating and cooling seasons. It is an input in end-use equipment, independent of the HVAC systems in use. Therefore, it is a different output than final energy consumption, which is the energy consumed by the end user delivered by the HVAC equipment, depending on its efficiency and operation (Hulscher, 1991). These energy needs were computed for nominal conditions, *i.e.*, considering the maintenance of an optimal inside temperature of 18 ◦C in the heating season and 25 ◦C in the cooling season, for the dwelling's whole useable area and during the total duration of the respective season. They were calculated before and after the renovation for each scenario to estimate the variation related to the RMs' application. Space heating and space cooling useful energy needs generic equations for a dwelling archetype are displayed respectively in Eq. (1) and Eq. (2).

$$N_{ic} = (Q_{tr,i} + Q_{ve,i} - Q_{gu,i})/A_p \qquad [kWh/(m^2.year)] \qquad (1)$$

$$\mathrm{N_{vc}} = (1 - \mathrm{\eta_v}).\mathrm{Q_{g,v}}/\mathrm{A_p} \qquad [\mathrm{kWh}/(\mathrm{m}^2.\mathrm{year})] \qquad (2)$$

where Qtr,i represents the heat transfer through conduction between the building and the surroundings in [kWh]; Qve,I is the heat transfer through ventilation in [kWh]; Qgu,I represents the total useful heat gain in the heating season in [kwh]; Ap is the building's indoor useable floor useful area in [m_2]; ηv is the heat gains utilisation factor; and Qg,v represents the heat gains in the cooling season [kWh].

The archetypes' energy needs were calculated using EPC data of construction parameters such as indoor useable floor areas and height, and thermal performance parameters such as heat transfer coefficients of building elements and solar factor of windows. The total primary dwellings per archetype were subsequently used to compute total and regional dwelling stock energy needs (INE, 2011). Since this is an engineering-based bottom-up deterministic model, uncertainties are difficult to display (Booth *et al.*, 2012). The process of data cleaning explained beforehand was an effort to reduce the major source of uncertainty, the EPC data. Despite this shortcoming, only with a white-box model was it possible to assess and predict the impact of different combinations of interventions (de Rubeis *et al.*, 2021; Lim and Zhai, 2017), using detailed measurable data from an official source.

Although occupant behaviour is an important factor for buildings' energy performance (Cuerda *et al.*, 2020; Steemers and Yun, 2009), especially when considering single dwellings, it was not considered in the energy needs calculations. Considering occupant behaviour, which is extremely diverse considering a country's dwelling stock, is not the goal of this study, but rather to assess a typified energy performance of dwellings at the level of the entire stock, independently of the people who occupied them. The energy needs calculation follows the regulations requirements regarding climatised area and period and it is supported by EPC data, which do not take this factor into account. The cost investment for each building element's intervention was calculated by multiplying the selected RM's cost per unit of area (m^2) and the total area of the corresponding building element for all dwellings of the respective archetype. The cost-effectiveness is the GWh of energy needs reduction achieved with 1M€ investment, per unit of area (m^2) of a particular archetype dwelling. No discount rates or lifetime assumptions are considered since the study provides a current steady snapshot of the building stock renovation cost-effectiveness.

6.1.5 Results and Discussion

The analysis was tailored to generate results bridging the different geographical scales, renovation scenarios, and the various dwelling archetypes. The results are presented and discussed in the following sections, at country-scale, in Section 6.1.5.1. and regional scale, in Section 6.1.5.2. All the results are provided in the supplementary data.

6.1.5.1 Country-level Analysis

The three scenarios consider building envelope energy RM that enable different thermal performance improvement levels in the dwelling stock. Renovation solutions with greater thermal performance are associated with higher implementation costs. Consequently, Scenario A corresponds to the highest total cost for renovating the entire dwelling stock with the best possible solutions currently available in the market, with a total of €99 600 million of investment. Scenario C has a higher cost than Scenario B (€73 500 to €71 700 million), as implementing external insulation of walls is more costly than installing internal insulation.

These costs can be compared with the investment costs indicated for the building envelope in the LTRS, estimated at €40 400 million. It is essential to highlight the difference in the methodologies, and the goals of both studies. The LTRS introduces an analysis of primary energy consumption, focusing on the monetary savings and payback to prove the economic viability of building renovation over the next 30 years. This study assesses the potential for energy needs reduction at the current context and cost-effectiveness of RMs to achieve that potential, aiming to inform decision-makers about regions and RMs that should be prioritised. In terms of the RM selection, the LTRS analysis is similar to scenarios B and C, which present considerably higher investment costs, over 30 billion, and higher energy reduction, over 14 thousand GWh. The most significant reason for this difference is the thermal comfort standard – in the LTRS, RMs were selected for thermal comfort to be at an acceptable level, according to EN 15,251:2007, a less demanding requirement compared to this study, which considers the criteria of the Portuguese regulation, the permanent maintenance of a set optimal indoor temperature in both seasons. Although considering that the adaptive comfort can be adequate to analyse the Portuguese context, it can hinder an objective comparison between households in regions with different climates.

This study goes deeper into the analysis and provides an individual assessment of RMs. In Scenario A, windows are the most expensive renovation intervention, accounting for 53% of the total cost. In Scenarios B and C, wall insulation represents the higher portion of the cost, 56% and 55% for wall outside and inside insulation, respectively. The cost of every renovation RM for each scenario and the respective percentage of the total cost are displayed in Figure 6.3.

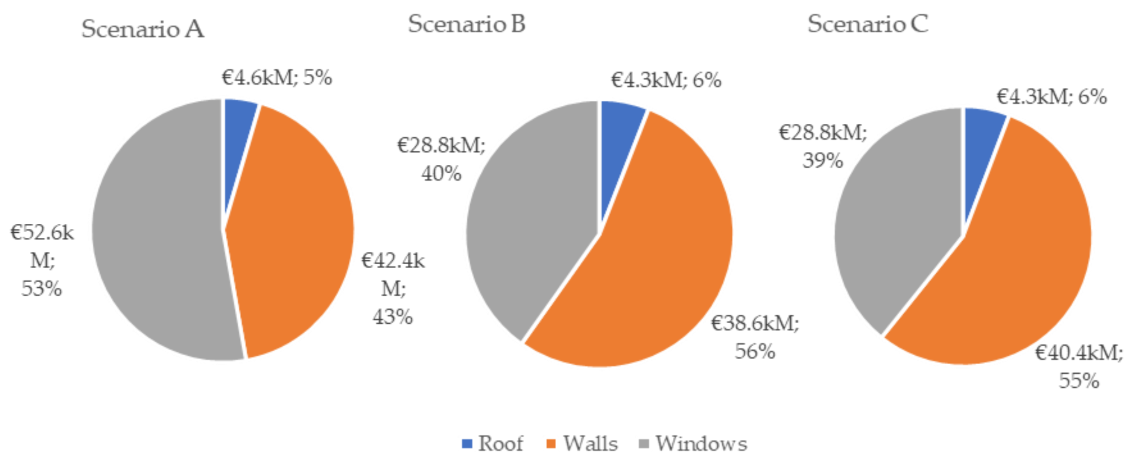


Figure 6.3 - Cost of every scenario in million euros per building component renovation.

Looking at the energy needs reduction at national level, Scenario A is the most impactful scenario, with 86.1% overall annual reduction of space heating needs and 41.4% decrease of space cooling energy needs. Reductions in Scenario B and Scenario C are slightly lower, 79.0%

and 76.9% respectively for space heating needs and 25.2% and 23.4% respectively for space cooling (Table 6.1).

Table 6.1 - Space Heating and Cooling Energy Needs Variation and Investment Cost of the RM assessed in Scenarios A, B and C.

Renovated Building Element	Space Heating Energy Needs Variation (%)			Space Cooling Energy Needs Variation (%)			Investment Cost (kM€)		
	Scenario A	*Scenario B*	*Scenario C*	*Scenario A*	*Scenario B*	*Scenario C*	*Scenario A*	*Scenario B*	*Scenario C*
Walls	-43.3	-41.8	-34.9	6.5	6.0	4.4	42.4	38.6	41.1
Roof	-39.9	-38.0	-38.0	-32.4	-30.9	-30.9	4.6	4.3	4.3
Windows	-3.1	-6.3	-6.3	-15.7	2.3	2.3	52.6	28.8	28.8
Total	-86.1	-79.0	-76.9	-41.4	-25.2	-23.4	99.6	71.7	73.5

Nevertheless, for space heating energy needs reduction, Scenario B is the most cost-effective for the package of RMs, with 0.32 GWh energy needs reduced per M€, above Scenario C (0.31 GWh/M€) and Scenario A (0.25 GWh/M€), meaning that the added increase in investment from choosing the best RMs does not improve the energy performance at the same rate as the other scenarios. On the other hand, the best RMs scenario (Scenario A) results in higher cost-effectiveness for space cooling energy needs reduction, with a figure of 0.035 GWh/M€, compared to Scenario C (0.028 GWh/M€) and Scenario B (0.029 GWh/M€). RMs can have a different thermal performance impact on the buildings' space heating and cooling energy needs. This is related to the balance between the heat losses and the energy gains of these building elements, as defined in the regulation's method. For space heating, only internal gains and solar gains through the windows make up the total energy gains, according to the methodology; hence when a wall or roof solution with a lower U-value is applied, heat loss reduction directly decreases energy needs. For space cooling, energy needs are estimated using a ratio between energy gains and heat losses. Solar gains through the roof and walls are accounted for in the total energy gains, which means the implementation of better insulation reduces both heat gains and heat losses through these building elements. Thus, reducing space cooling energy needs is not so straightforward. Occasionally, the resulting ratio after the renovation increases total space cooling needs, as energy gains reduce in a lower proportion than energy losses. For this reason, the cost-effectiveness of RM for space cooling energy needs reduction is significantly lower than for space heating. In the cooling season, the superior cost-effectiveness of Scenario A is related to the application of low emissivity glazing, which has a significant impact on energy needs.

The cost-effectiveness results obtained are considerably lower than those estimated in the studies of Hoos *et al.* (2016) and Streicher *et al.* (2020). This is expected since the authors considered the replacement of HVAC systems, calculating the impact of renovation in energy demand and consumption, which is greater than on energy needs. Several factors dictate the difference in cost-effectiveness, such as the type of RMs and implementation costs, which vary according to the economic context. It is relevant to highlight that the authors took on simpler representations of the corresponding building stock in central European countries with more severe winters, which can also be contributing factors for higher cost-effectiveness results.

When looking at the individual interventions, wall renovation is the most effective in reducing space heating energy needs in Scenario A and Scenario B, with reductions standing at 43.3% and 41.8% (Table 6.1). Applying internal insulation in older archetypes can lead to a more significant general space heating reduction (7% higher), compared to 100% external insulation across the dwelling stock. From an energy standpoint, internal insulation seems to be the better option, although external insulation has other benefits that should be considered when deciding which one to apply.

Roof renovation is also an effective option, impactful for both space heating and cooling. It results in the highest reductions in space cooling energy needs in every scenario, 32.4% in Scenario A and 30.9% in Scenarios B and C, whilst guaranteeing space heating energy needs reduction in the order of 39.9% and 38%, respectively. These results are aligned with the work of Gouveia *et al.* (2021), who estimated a heating energy needs' reduction of 48%, and 27% respectively from wall and roof renovation and also 27% reduction in space cooling energy needs from roof insulation for residential buildings in a historic district of Lisbon.

Considering total energy needs (heating and cooling jointly), roof insulation enables a higher reduction overall in all studied scenarios. Moreover, it is also by far the most cost-effective option in every scenario for space heating energy needs reduction, with 2.5 GWh/M€ in Scenario A and 3.4 GWh/M€ in B and C, compared to 0.29, 0.31 and 0.25 GWh/M€ for wall renovation respectively (Figure 6.4), the second most cost-effective RM. This is justified by the considerably lower investment costs compared to wall renovation. This finding is aligned with the analysis conducted by Vasconcelos *et al.* (2016), who also identified roof renovation as the most cost-effective.

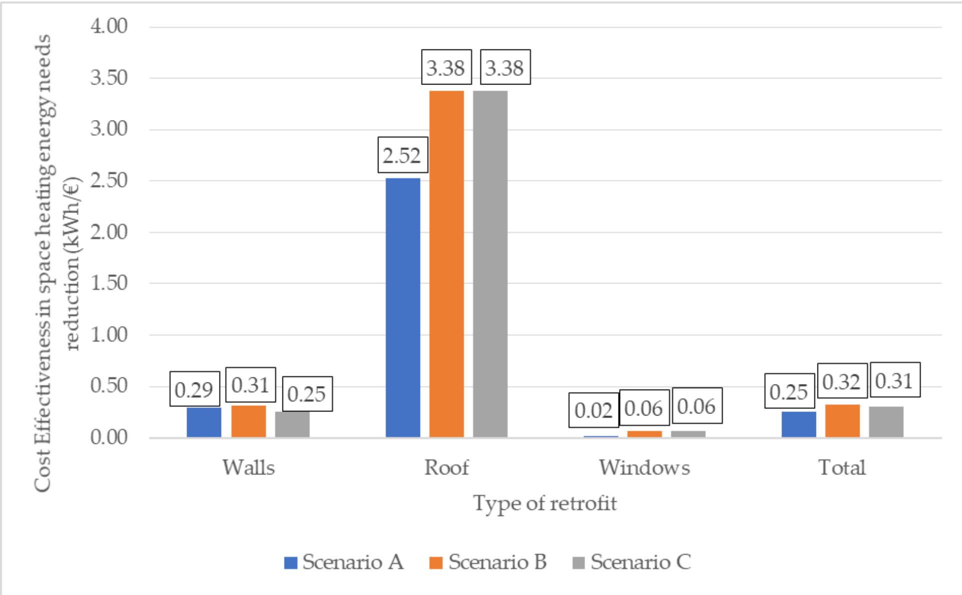


Figure 6.4 - Cost-effectiveness of RM for reducing space heating energy needs in the three scenarios.

Whilst wall renovation is not cost-effective for space cooling energy needs decrease, window improvement can have a positive effect, mainly in Scenario A (Figure 6.5). In this scenario, window replacement yields a 15.7% decrease in space cooling energy needs and a cost-effectiveness of 0.025 GWh/M€, the highest in all 3 scenarios. After roof insulation, window replacement is the best option for improving dwelling energy performance in the summertime.

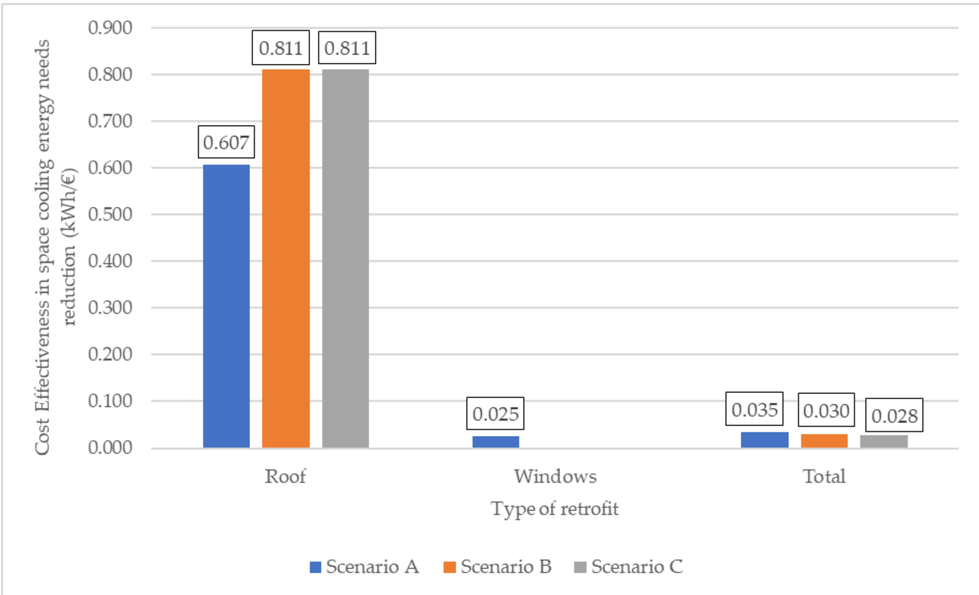


Figure 6.5 - Cost-effectiveness of RM for reducing space cooling energy needs in the three scenarios

It is relevant to highlight that roof RMs' cost-effectiveness considerably surpasses the cost-effectiveness of renovation packages. However, the combined intervention adds a marginal increase in energy needs reduction, especially for space heating. For Scenario A, the renovation package has a positive marginal effect for both space heating and space cooling, with increases of 46.3% and 9.0% in energy needs reduction. In Scenario B and C, this marginal increase is also significant – 41.0% and 38.9%. However, due to the contrasting effect that RMs may have on winter and summer energy needs, the package retrofitting action produces lower reductions of space cooling energy needs reduction than only roof insulation, respectively less 5.6% and 7.5%.

As for individual archetypes, whether it is for heating or cooling, dwellings in house archetypes have higher cost-effectiveness results than those in multi-apartment buildings mainly due to roof insulation improvement, the most effective RM, which is not considered for multi-apartment buildings archetypes, as it only affects the top dwelling. Figure 6.6 and Figure 6.7 show that the newer the archetype, the lower the cost-effectiveness of RM, except for multi-apartment from 1980 to 2005 archetypes, which is slightly more cost-effective than the same archetype of the previous period. This pattern is directly connected, for the most part, to the thermal performance parameters, which determine energy needs. It would be expected that the older archetype would always have higher energy needs reduction than the newer ones, as regulations increase energy performance requirements over the years. Nevertheless, both these periods include dwellings constructed before any regulations were in place and therefore a considerable variety of characteristics can explain these discrepancies. Moreover, a significant proportion of dwellings with an EPC were for sale or rented, suggesting they have been subject to some renovation work. Overall, it may also mean that cost-effectiveness might even be underestimated herein, as the thermal performance level of average dwelling archetypes might be lower than the one depicted by the EPCs.

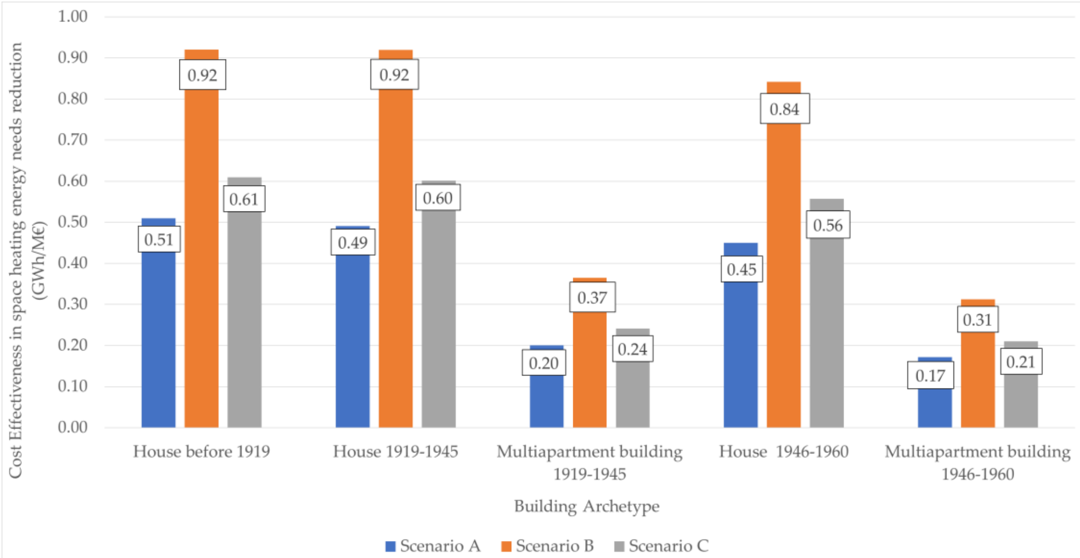


Figure 6.6 - Cost-effectiveness of total renovation for reducing space heating energy needs of archetypes until 1960 for the three scenarios.

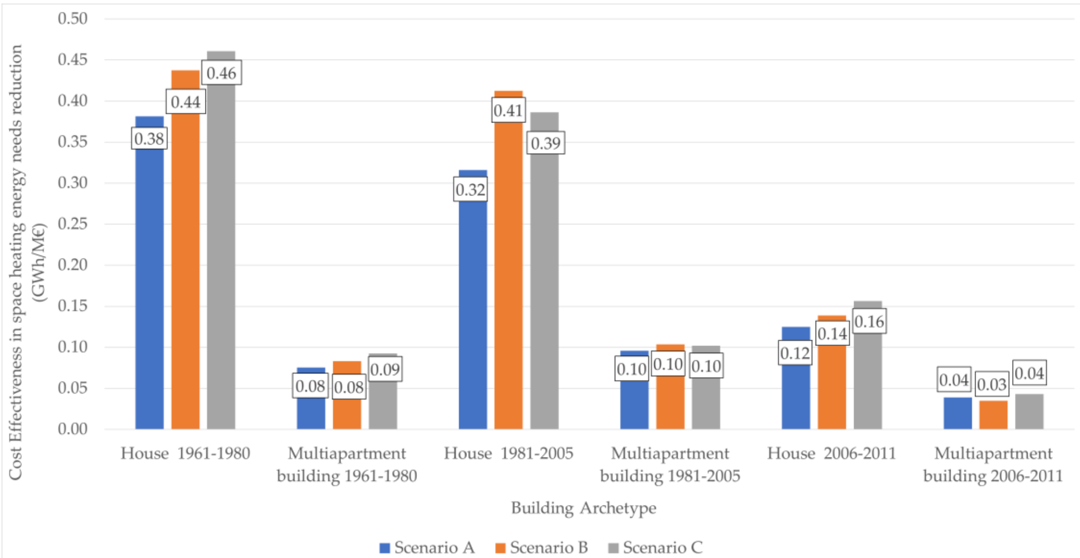


Figure 6.7 - Cost-effectiveness of total renovation for reducing space heating energy needs of archetypes after 1960 for the three scenarios.

Across all scenarios, the most cost-effective package of renovation interventions can be achieved in the oldest archetype, houses pre-1919, and in the period between 1919 and 1945, for both space heating and cooling. This is due to the application of mineral wool solutions, which provide considerable improvements in thermal performance to regulation levels at low cost, and the significant potential of these archetypes for energy needs reduction. This observation is corroborated in the Long-term national Strategy for the renovation of the building stock, buildings (Portuguese Republic, 2021). With internal insulation of walls, Scenario B constitutes the most cost-effective scenario for these archetypes due to the lowest cost of this kind of application. In Scenario A, the greater improvement of energy performance in the heating season does not compensate for the higher costs, making it the least cost-effective option for dwelling in every archetype, just as for the dwelling stock.

As for space cooling, as displayed in Figure 6.8, in the house archetypes pre-1960, Scenario B presents better results because total costs are lower, due to the considerable impact of roof renovation on energy needs and because cheaper internal wall insulation is considered for the archetypes pre-1960. Due to Scenario C's higher costs, the cost-effectiveness of this scenario and Scenario A for the same archetypes is similar. Nevertheless, the situation differs for newer house archetypes, with higher energy performance - as potential energy needs reduction decreases, the relation between cost and impact of Scenario A's RMs surpasses one of the other scenarios. Moreover, only Scenario A proves to be minimally effective in reducing cooling energy needs in the newer multi-apartment buildings. Renovation packages are not cost-effective for apartments from pre-1981 for all scenarios, thus not being displayed in Figure 6.8.

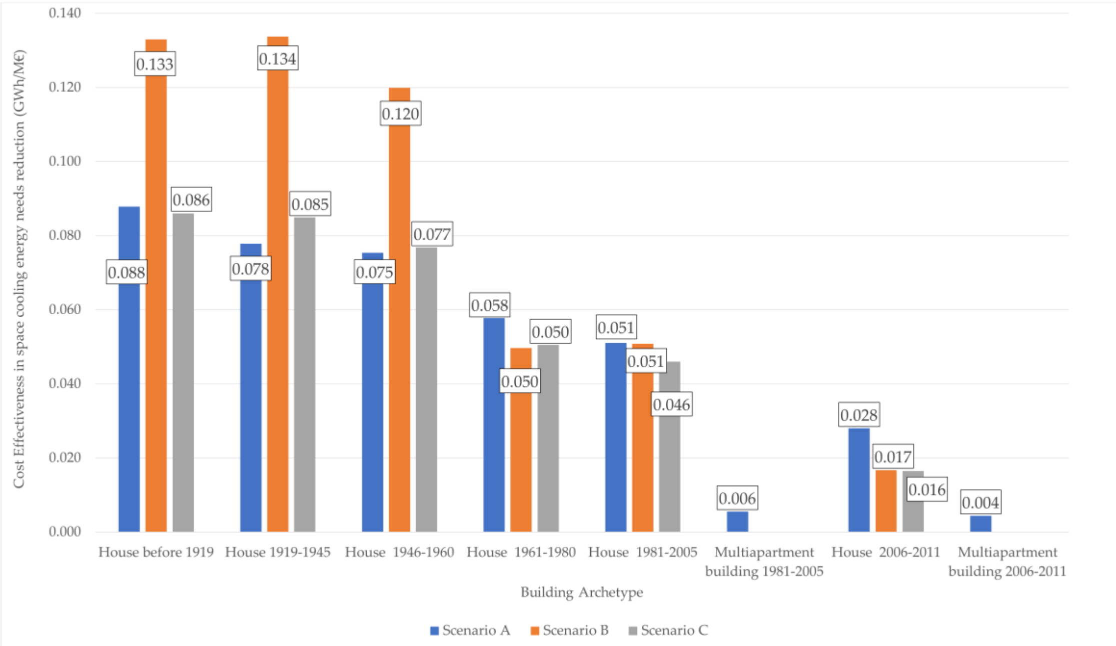


Figure 6.8 - Cost-effectiveness of total renovation for reducing space cooling energy needs across all building archetypes for the three scenarios

If considering only energy needs reductions without taking costs into account, house archetypes from 1960 to 1980 and from 1981 to 2005 are the ones with the highest total potential, due to higher nominal needs and simultaneously high number of dwellings in this type of building, in all scenarios. Wall renovation presents the best results for reducing space heating energy needs in multi-apartment dwellings from the archetypes between 1919 and 1980, with an average of 83.5%, 81.9% and 73.6% reduction for Scenario A, B and C, respectively. This is due to the lowest energy performance of these archetypes built before any thermal performance regulation was in place. Roof renovation is also the most impactful RM for space cooling, with reductions over 40% for the house archetypes older than 2005, for all scenarios. It is mostly evident for the 1919–1945 archetype, where energy needs drop by over 50%. Window replacement is more effective for the multi-apartment dwellings between 1960 and 1980 in Scenario A.

6.1.5.2 Regional Analysis

Regionally at the NUTS3 level, for reducing space heating needs, RM are more cost-effective in the north inland of the country, particularly in the regions of Alto Tâmega, Beiras e Serra da Estrela and Terras de Trás-os- Montes, for the three scenarios (Figure 6.9). Dwellings in these regions have the highest energy needs for space heating, due to the combination of a severe winter climate, with lower average outside temperatures and higher HDDs - over 1850, compared to the national average of 1362 (Ordinance no. 349-B/2013)- as well as lower energy performance of ageing buildings, mostly of house archetypes. Terras de Trás-os-Montes stands out as the region with the highest potential in both Scenario B (0.69 GWh/M€) and C (0.64 GWh/M€), due to the combination of sufficiently effective renovation of all building elements, but particularly roof insulation, which has a cost-effectiveness of 9.60 GWh/M€, the highest in all regions. Window replacement is also the highest in this region for the same scenarios, with a cost-effectiveness of 0.18 GWh/M€.

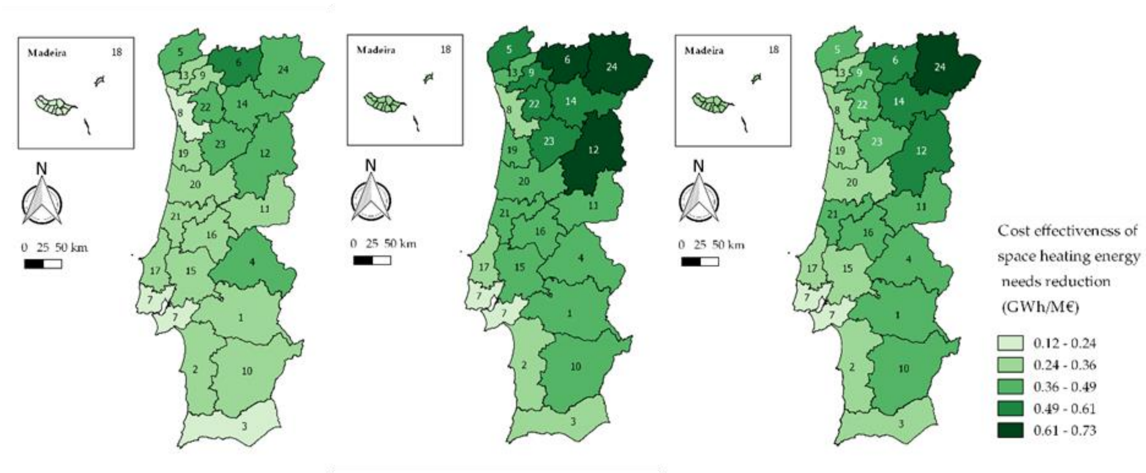
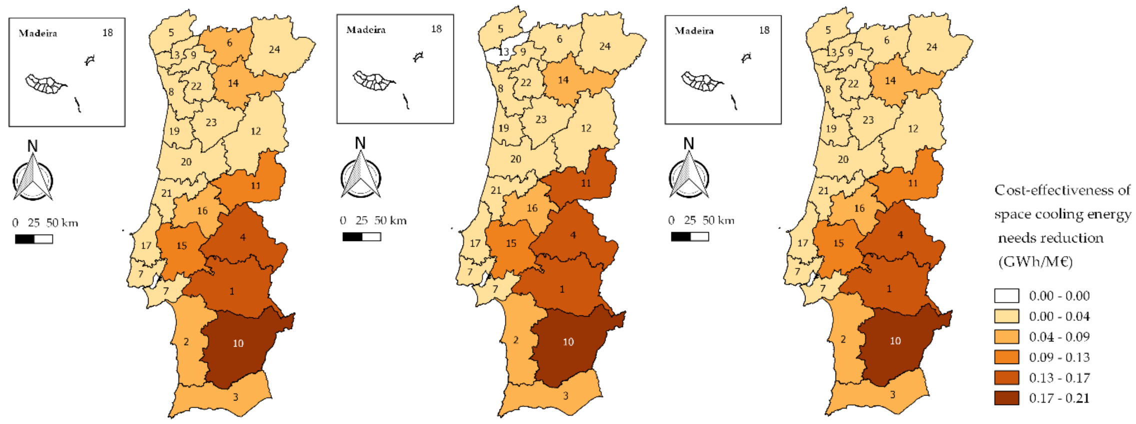


Figure 6.9 - Cost-Effectiveness of the RM packages in space heating energy needs reduction, per NUTS3 regions of Portugal, for Scenario A (left), Scenario B (centre) and Scenario C (right)

For Scenario A, Alto Tâmega is the region with the highest potential, primarily due to wall renovation (0.47 GWh/M€) and roof insulation installation (3.77 GWh/M€). These RMs are less effective in south littoral, like the Metropolitan Area of Lisbon and Algarve, and the Metropolitan Area of Porto, in the north coast, as the winter climate is milder, and dwellings are newer and are mainly located in apartment buildings.

On the other hand, when considering the improvement of buildings' thermal performance in the summer, RM should be firstly targeted at dwellings in the inland south of Portugal, as they are more cost-effective for reducing space cooling energy needs, especially in the regions of Alentejo Central, Alto Alentejo, and Baixo Alentejo. The renovation packages' cost-effectiveness in the different NUTS3 regions for the three scenarios can be consulted in Figure 6.10. These results can also be explained partly by the drier and warmer climate conditions in these regions, with the highest outside temperatures in the country averaging 24.5 ◦C, higher than the national average of 21.9 ◦C (Ordinance n◦349-B/2013). Moreover, house archetypes are frequent in these regions, representing around 85% of all dwellings, where the use of roofs consisting of tiles without a mortar substrate and insulation is common, a low-energy performing solution, as stated by Gouveia and Palma (2019), making roof renovation the most impactful RM for improving energy performance in the summer in all scenarios. This RM is most cost-effective in Scenario B and C, in the Baixo Alentejo region (2.47 kWh/€). It is also in Baixo Alentejo where a full renovation is more effective in every scenario, with a higher value in Scenario B (0.22 GWh/M€), followed by Scenario C (0.20 GWh/M€) and Scenario A (0.18 GWh/M€). Looking at wall renovation, although not very effective, internal wall insulation presents better results in Beira Baixa, in the central region of the country, with a value of 0.08 GWh/M€. Window replacement is at its most effective in Beira Baixa and Alto Alentejo, for scenario A, registering a value of 0.08 GWh/M€. The cost-effectiveness of individual renovation of walls, roof and windows in each scenario, for space heating, is displayed in Annexes B3, B4, and B4; and for space cooling in the Annexes B6, B7, and B8.



NUTS3 Regions: 1 - Alentejo Central; 2 - Alentejo Litoral; 3 – Algarve; 4 - Alto Alentejo; 5 - Alto Minho; 6 - Alto Tâmega; 7 - Área Metropolitana de Lisboa; 8 - Área Metropolitana do Porto; 9 – Ave; 10 - Baixo Alentejo; 11 - Beira Baixa; 12 - Beiras e Serra da Estrela; 13 – Cávado; 14 – Douro; 15 - Lezíria do Tejo; 16 - Médio Tejo; 17 – Oeste; 18 - Região Autónoma da Madeira; 19 - Região de Aveiro; 20 - Região de Coimbra; 21 - Região de Leiria; 22 - Tâmega e Sousa; 23 - Terras de Trás-os-Montes; 24 - Viseu Dão Lafões

Figure 6.10 - Cost-Effectiveness of the RM packages in space cooling energy needs reduction, per NUTS3 regions of Portugal, for Scenario A (left), Scenario B (centre) and Scenario C (right).

It is relevant to note that, because costs are calculated per unit of area, the cost-effectiveness also reflects the potential for energy needs savings. In that sense, an archetype with higher cost-effectiveness also has greater potential for energy needs reduction in absolute number. However, when considering a whole region, the total potential energy needs reduction is connected to the number of dwellings in the building stock, *i.e.*, the building stock's size, which means the Metropolitan Area of Lisbon and Porto are top-ranked as the regions with the more significant potential.

Therefore, besides the cost-effectiveness, the total percentage potential for energy reduction, which presents a different expression and distribution, might also be a useful indicator at regional level for local authorities. For space heating, considering all archetypes, greater energy needs reduction for wall insulation can be achieved in the three scenarios in the Metropolitan Area of Lisbon, ranging from 44.3% (in Scenario C) to 55.7% (in Scenario A). Roof renovation works better for improving thermal performance in Baixo Alentejo, with energy reductions from 47.4% (in Scenarios B and C) to 49.8% (in Scenario A). All regions of the Alentejo region have significant potential for roof intervention. Window replacement results in higher reduction in the Autonomous Region of Madeira (-10.1%). In the summer, Baixo Alentejo is also the region with greater reduction potential, between 60.2% and 68.7%. The most impactful RMs are roof renovation in Baixo Alentejo (from 47.4% to 49.8%) and window replacement in Oeste (21.6% in Scenario A).

Furthermore, the results enable a more detailed analysis for identifying in which dwelling archetypes specific RMs should be prioritised for each region, which is not possible to discern when considering the regions as a unit. External insulation implementation for walls has its peak cost-effectiveness value (0.81 GWh/M€) for space heating energy needs reduction in dwellings in house archetypes from 1919 to 1945, in the region of Ave, in the north coast part of the country. Internal insulation presents higher cost-effectiveness figures across the whole north of Portugal, peaking in the region of Terras de Trás-os-Montes (1.67 GWh/ M€), in houses pre-1919. It is less effective in the new archetypes in the centre of Portugal. The cost-effectiveness of roof insulation for improving energy performance in the heating season is high all over the country, but it is at its highest for Scenarios B and C, in Terras de Trás-os- Montes, for house archetypes before 2005, with an average of 12.26 GWh/M€. In the summer, it has its peak value (6.22 GWh/M€) in house typologies pre-1919 in Baixo Alentejo. Window replacement has improved cost-effectiveness for reducing space heating needs in older houses (pre-1980), mainly in Terras de Trás-os-Montes and Beiras e Serra da Estrela regions, with a value over 0.20 GWh/M€ in Scenarios B and C. For space cooling, it is more effective in dwellings of the archetype apartment building built between 1980 and 2005, in Beira Baixa and Alto Alentejo.

6.1.6 Implications for Policy

In the current European policy context, especially with the formulation and adoption of the Green Deal and adoption of the Renovation Wave strategy, there is a considerable push for Member-States to leverage building stock renovation towards the improvement of energy performance, with broader goals of reducing GHG emissions and energy poverty levels in the population. In Portugal, efforts for promoting renovation, mainly in the form of policy schemes and tax incentives, have not been able to tear down the persistent barriers that prevent the deployment of large-scale renovation works for the residential building stock. These efforts generally stem from central administration bodies and are designed at national level, failing to target energy inefficiency hotspots, whether they are building blocks, neighbourhoods, or regions. The detailed regionally specific outcomes of this study provide data and information at both national and regional scales to potentially feed into the policymaking process and contribute to designing more effective and accurate policy schemes. It addresses the informational barrier - regional governments generally lack data and studies on the potential for renovation of the building stock, which may prove useful, as funds are often even more limited at this level. Regional and local level building renovation action might be essential to unlock extensive deep renovation across countries. As the impact of renovation interventions is disaggregated by region, type of RM and type of building, the cost-effectiveness analysis might enable prioritisation of regions and the selection of particular RMs in detriment of others, for the elaboration of more detailed and tailored schemes. It might support a weighted allocation of support in the developed policy schemes, namely regarding the mobilisation of financial resources, increasing the efficiency of capital use, either on national or regional level. Moreover, the results of the potential percentage of energy needs reduction can be a useful indicator for assessing the progress towards achieving reduction targets, and for possible future regional efforts to match energy demand and supply. This is especially relevant for developing Positive Energy Districts at local scale, which are regarded as one of the keys for achieving on carbon-neutral cities and carbon neutrality for Europe (European Commission, 2018). Boosting energy renovation rates of the residential building stock is also crucial for tackling energy poverty, especially in vulnerable groups, as the improvement of building energy performance may ultimately improve thermal comfort and even bring down energy bills (Arístegui, 2021). Nevertheless, in Portugal, energy needs reductions do not necessarily translate into lower final energy consumption and reduced energy bills because energy demand for thermal comfort in homes is not being met (Palma *et al.*, 2019). Therefore, it has been a challenge to attract private capital for supporting building renovation in Portugal. It is paramount to develop innovative and viable business cases for energy renovation of residential buildings in Portugal. Rose *et al.* (2021) highlight the importance of financial models that face persistent barriers such as split incentives. The various positive externalities or co-benefits - thermal comfort improvement, air pollution reduction, improved environmental standards, increase in market value, decreasing the incidence of diseases - might provide opportunities to harness investment and light the beacon for large-scale renovation. This study can support and complement future cost-benefit analysis for quantifying the impact of these co-benefits, aiming to highlight the economic viability of deep renovation in the country from an energy performance standpoint, connected to those externalities.

As shown by the study’s findings, tackling the demand side with building renovation to nZEB level entails a very significant capital investment, which is not available in the current situation and potentially will have to be gradually deployed over the following years. As renovation rolls out, it is necessary to address the supply side by integrating renewable energy to cover the remaining energy needs., if decarbonisation goals are to be achieved.

The findings of this study are specific for the Portuguese case-study and difficult to extrapolate to other countries, as each country's building stock varies considerably in its characteristics and construction techniques. Nevertheless, the methodology can be transferred to other European countries, northern and southern, as it is grounded on replicable reliable methods such as the definition of a comprehensive archetype-based representation of the stock through raw data from EPC, available in most EU countries; an energy needs calculation method based on an international standard adopted by the EU; and a market-based RM database. The replication of this method for other countries would be beneficial as there is a lack of studies comparing building stock energy performance in different member states. There is also a dearth of cost-effectiveness assessments to direct European and Member-states policy, especially relevant in the context of the current renovation wave. Because buildings are such an impactful and crosscutting sector, these results are relevant for different readerships, as it holds a place of prominence in the development and transformation of society, especially when addressing energy paradigms and public policy development.

6.1.7 Conclusions

This study develops a comprehensive cost-effectiveness analysis of building RM for renovating the dwelling stock in Portugal, highlighting the most cost-effective interventions and dwelling types at different spatial scales. The approach uses a bottom-up archetype-based method to estimate energy needs reduction and a retrofit measures database to calculate investment costs. Three dwelling stock renovation scenarios, with different thermal performance requirements and necessary investment costs were assessed. This study unveiled a necessary minimal investment cost 71.7 billion euros to improve dwelling stock thermal performance to nZEB standards. Overall, the findings showed that roof renovation should be prioritised when tailoring support schemes, standing as the most cost-effective RM in every scenario. The mix of internal and external wall insulation in the dwelling stock also shows promising results for reducing energy needs in the heating season. Results suggest that older houses archetypes should be prioritised, especially for space heating needs reduction. Although presenting lower cost-effectiveness values than individual roof renovation, renovation packages result in marginal increases in energy needs reduction. Results highlight that renovation measures for reducing energy needs in the heating season should be prioritised in the northern inland regions of the country, whereas in the summer, renovation is more effective in the southern inland regions.

These findings can be of significant value for national and regional governments to channel the limited funding available for targeted policy schemes with increased impact at lower costs. Therefore, the knowledge advanced by this study can help filling an existing informational gap and promoting the necessary renovation wave nationally. The study also introduces a transferable methodologic framework, from which important insights may be generated for other European Member-States. Only with deep and comprehensive renovation, as well as broad democratic renewable energy integration, can the dwelling stock become one of the keys for the sustainable transformation of society, whilst guaranteeing the provision of adequate housing conditions for the population.

Despite the merit of producing diverse and comprehensive results that enable detailed analyses at different scales, this approach has limitations that should be addressed. It is a deterministic approach, whose uncertainty is inherently difficult to compute. In fact, predictions might be significantly different from measured data due to uncertainties with the definition of dwelling archetypes. Therefore, it would be beneficial in the future to develop statistical models, in case-studies for instance, to assess the relationship between the input parameters and the output, computing confidence levels and confirm the findings of this study. The conjunction of these two approaches can provide important information with a higher level of reliability. Furthermore, this approach represents a static snapshot of the current situation and does not aim to assess evolution over time, thus not considering discount rates and building stock evolution, which would also impact the investment estimation and cost-effectiveness rates.

In this study, the residential stock was spotlighted due to its low energy performance and implications for increased energy poverty. Although no building EPC raw data was available for the public and commercial stocks, further work could address the energy performance in these buildings since a significant part of the population spend numerous hours in these environments daily, with potential consequences to their health and wellbeing.

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6.2 It starts at home: Space heating and cooling efficiency for energy poverty and carbon emissions reduction in Portugal

Abstract

Climate change mitigation, the economy's decarbonisation, and energy poverty reduction are major challenges globally and for the European Union. However, competing agendas might create trade-off situations that hinder the achievement of these goals. Energy efficiency promotion in the residential sector, through the replacement of space heating and cooling equipment, can be an important solution to simultaneously contribute to reducing energy poverty and carbon emissions whilst improving households' comfort and wellbeing. This paper analyses the regional impact of replacing space heating and cooling equipment on energy poverty levels in the population using the Energy Poverty Vulnerability Index. Moreover, the impact on carbon emissions is also investigated. Results show that increasing equipment efficiency to regulation levels is only effective in reducing winter energy poverty, with a decrease in municipal vulnerability levels of about 18 per cent. Implementing a "deep change" in the heating and cooling equipment stock is significantly effective for reducing winter and summer energy poverty, respectively, 47.8 per cent and 26.3 per cent in average municipal levels, while significantly decreasing potential CO_2 emissions by 3554 kilotons. This transformation should be coupled with the improvement of buildings' energy performance and presents various significant challenges regarding financial investment and social justice that should be addressed by authorities at different scales. This study demonstrates the relevance of exploring the impact of space heating and cooling equipment replacement measures on energy poverty, efficiency and carbon emissions at the regional level while providing a replicable method for investigating this subject and producing valuable insights into other geographical contexts.

6.2.1 Introduction

Energy poverty is a severe social issue affecting populations across the globe in distinct ways. It is deeply linked to the sustainable development of society, particularly United Nations' Sustainable Development Goal 7, which underlines the need for ensuring "affordable, reliable, sustainable and modern energy for all" (United Nations, 2022). Energy poverty can be defined as the inability of households to meet adequate energy needs, taking different forms depending on context. In developing countries, it is mainly reflected by the lack of access to modern energy services such as electricity (Li *et al.*, 2014). In 2019, 770 million people still lived without access to electricity, mostly in Africa and Asia (IEA, 2022). These people must rely on harmful fossil fuels and inefficient rudimentary equipment for space heating and cooking. The use of such fuels increases CO_2 emissions and deteriorates indoor air quality, with serious ill effects on the health and safety of the population (WHO, 2021). In developed countries, the term energy poverty is more frequently used to describe the inability to afford the necessary level of energy services to maintain an adequate indoor temperature (Li *et al.*, 2014). Despite affecting populations globally, this form of energy poverty looms large in the European Union (EU), affecting over 34 million people, with severe impacts on the population's wellbeing, contributing to health problems such as cardiovascular and respiratory diseases, as well as being a cause of stigma and social exclusion (EPAH, 2022). Alleviating energy poverty, together with energy efficiency improvement and decarbonisation of the economy, are primary policy goals for the EU (European Commission, 2019), as highlighted in the 2030 energy and climate framework and further reinforced by the European Green Deal and the Fit for 55's legislative package. The main root causes of this social issue are the energy inefficiency of homes, low incomes, and high energy prices (Dobbins *et al.*, 2019). The global energy crisis of 2021 and, more recently, the Ukraine invasion and the sanctions imposed on Russia, have caused a significant recent spike in energy prices, especially natural gas, with increased negative impacts for households and particularly for the energy poor. The European Commission has recently approved the REPowerEU plan, aiming to assure European independence from Russian fossil fuels before 2030, by mitigating the impact of rising energy prices, diversifying gas sources, and boosting a clean energy transition (European Commission, 2022a).

Simultaneously, the building stock is also a major target for decarbonising the economy and reducing energy demand, representing about 40 per cent of the EU's energy consumption and 36 per cent of its greenhouse-gas emissions, considering the whole life cycle (European Commission, 2020a). The residential sector accounts for two-thirds of the final energy consumption (Build Up, 2017). Increasing the energy efficiency of buildings can be achieved through passive measures, such as improving the building envelope energy performance for reducing energy needs. Alternatively, active energy consumption measures can be applied such as the use of more efficient electric appliances and HVAC equipment for reducing energy consumption. Both types of measures are highlighted and prioritised by the European

Commission in the Energy Performance of Buildings Directive (EPBD) 2010/31/EU. The REPowerEU plan underlines the importance of energy efficiency for the EU's energy transition and independence, encouraging the roll-out of heat pumps for increasing energy savings and reducing gas consumption in buildings (European Commission, 2022b). Active measures in homes have been shown to be effective in ameliorating energy poverty (Boardman, 2013).

Research shows there is potential for synergies between climate change and energy poverty mitigation policies, especially when the focus is energy efficiency promotion two policy goals is paramount for mobilising large-scale energy efficiency measures that could lead to the resolution of both issues, with positive effects on energy security and employment. Chakravarty and Tavoni (2013) report that reducing global energy poverty may increase consumption. Still, this increase would not hinder the attainment of climate targets. It could be mitigated with efficiency improvement, thus achieving both goals would not result in a bottleneck. Bouzarovski (2013) highlights that systemic energy efficiency policies can help address both objectives of fighting climate change and addressing energy poverty.

However, these two highly interlinked agendas can compete and create trade-off situations (Großmann, 2019) if policy frameworks do not evenly integrate both goals. Ürge-Vorsatz and Tirado-Herrero (2012) found that the most relevant trade-off identified is the possible worsening of energy poverty resulting from climate policy increasing energy prices through carbon pricing. Sunderland and Croft (2011) state that energy poverty significantly contributes to making the distribution of social impacts a key factor in climate change policy analysis.

Massera (2020) identifies potential redistributive consequences of the green transition and decarbonisation policies, with vulnerable layers of society being more exposed to energy poverty. The "yellow vests" case in France in 2021 is an example of this instance, where the increase in diesel prices and fuel tax aimed at protecting the environment and fighting climate change resulted in large protests and turmoil. Previously in 2018, in Bulgaria, citizens also protested the rise of fuel prices and taxes for more polluting cars, accusing the government of injustice and negligence due to the policy's regressive nature. As the author clearly states, they should not deter decarbonisation efforts but should highlight the need to consider the different parties and interests. Who will pay for the energy transition is an important debate, particularly regarding decarbonising the building stock, placing energy poverty at the centre of discussion, and not leaving any groups behind.

Carley and Konisky (2020) point out the existence of winners and losers of the energy transition. Energy justice arises in this conversation, defined as the access to affordable, sustainable, and safe energy to sustain a decent life and participate in society. There are three central tenets to consider: distributional, *i.e.*, the just distribution of burdens and benefits; procedural justice, regarding the inclusion of people in the energy decision-making process, to guarantee processes are equitable, fair, and inclusive; and finally, recognition justice, referring to the recognition of historical and ongoing inequalities. Other types of energy justice have also been identified. Cosmopolitan justice is the acknowledgment of different ethnic groups as part of a community based on collective morality (Sovacool *et al.*, 2016). Restorative justice focuses on reparations of past harm rather than just punishing the offender (Heffron and McCauley, 2017). Corrective justice implies that those who have committed environmental harm in processes related to energy should be responsible for the correction of this harm. Finally, intergenerational justice refers to the management of not only present-day energy decision impacts but impacts on future generations (McHarg, 2020).

Existing problems of energy justice can hinder the adoption of energy efficiency measures. These interventions are often seen as a one-size-fits-all solution, hiding structural injustices regarding urban planning, territorial development, access to housing, agency, and social inclusion, and discrimination, which affect its distributional impact (ENGAGER, 2021). For example, injustices can occur in the process of identifying the vulnerable population. The energy-poor are often identified by analysing income and energy burdens. This is not a straightforward task because the energy-poor can have lower or higher than average energy burdens. Roberts *et al.* (2020) highlight increased energy needs among the most vulnerable; conversely, Tirado-Herrero (2017) identifies that spending on energy among the energy-poor is insufficient to meet health and wellbeing needs. It is paramount to focus on an adequate level of energy services rather than solely on energy consumption or energy bills when identifying the population to support and when evaluating and monitoring the impact of measures. Households' varying purchasing power also plays an important role in the roll-out of domestic energy efficiency measures, as interventions often require the ability to invest in new equipment. It is an important factor to consider in the design of support schemes, to assure a just distribution of benefits. Preston *et al.* (2010) state the importance of linking households' expenditure on energy efficiency measures to accessible grants and subsidies.

It is necessary to fully grasp the benefits of energy efficiency measures and policies for reducing energy poverty and achieving decarbonisation goals whilst considering the implications for energy justice associated with the implementation of these solutions. This paper aims to explore the impact of energy efficiency measures in the complex context of energy poverty and carbon emissions in the Portuguese residential sector, considering the differences in territorial settings and vulnerability configurations. The country was selected due to the high estimated levels of energy poverty and low energy efficiency indicators of the building stock.

6.2.2 Literature Review

There is a lack of studies bringing together quantitative analyses of energy poverty vulnerability and carbon emissions reduction connected to the implementation of energy efficiency improvement measures in the residential sector. On the other hand, there are several studies and methods that focus on these two tasks separately. Measuring energy poverty has been a challenge undertaken by several researchers over the last few years. It is crucial to understand the depth and extent of this issue, aiming to produce effective policy for its reduction. Energy poverty metrics can be divided into four different types: consensual-based approaches, based on the self-reported experiences of occupants such as the EU-SILC indicators developed in studies such as the Thomson and Snell (2013) and OpenEXP (2019); Expenditure-based, in which energy expenditure is contrasted with income (*e.g.* Boardman, 1991; Moore, 2012; EPAH, 2021); Direct measurement of domestic energy services compared to a required set value, used in studies such as Calì *et al.* (2016); Kampelis *et al.* (2017); and Gouveia *et al.*, (2019). Other supporting indicators of demographic, energy, health outcomes, physical infrastructure, and policy nature (Rademaekers *et al.*, 2016) are also used in energy poverty studies. Although not directly describing the issue per se, they provide information on factors that influence energy poverty vulnerability. Most studies dedicated to assessing energy poverty, defined as the inability to attain thermal comfort, focus on European contexts, as seen in Siksnelyte-Butkiene *et al.* (2021), but increasing attention is being paid to this form of energy poverty in other continents, in countries like Chile (Pérez-Fargallo *et al.*, 2020), Australia (Churchill *et al.*, 2020) and Japan (Okushima, 2019).

Computing carbon and other greenhouse gas emissions in buildings has been a relatively common enterprise in research, together with energy indicators, with the application of different modelling techniques. The Life Cycle Assessment approach has become the reference methodology for analysing the environmental performance of buildings (Piccardo and Gustavsson, 2021). Modelling choices of system boundaries, materials and energy technologies, and supply can significantly influence the model's outcomes (Dixit *et al.*, 2012). When it comes to energy consumption inside the buildings, carbon emissions are generally calculated using emissions factors associated with each energy carrier or fuel. These emissions factors result from the conversion of each fuel or energy carrier’s primary energy units, using the respective carbon intensities (Dixit *et al.*, 2014).

There are several case studies assessing the impact of energy efficiency measures, both building fabric renovation and HVAC equipment replacement, on energy demand and energy consumption and carbon emissions reduction, spanning different spatial scales, building stock, and types of measures (Domingo-Irigoyen *et al.*, 2015; Niemelä *et al.*, 2017; Streicher *et al.*, 2020, Gouveia, *et al.*, 2021).

Nevertheless, there are very few studies analysing the impact of this kind of measure on the energy poverty levels of a population, also considering the effect on carbon emissions in the residential sector. Zhao *et al.* (2021) researched these topics in conjunction, estimating energy poverty levels in 30 Chinese provinces and the impact of energy poverty on CO_2 emissions. The authors found that energy poverty can increase CO_2 emissions, but the effect is heterogeneous across regions. There is a bidirectional causal connection between the two issues in regions with high levels of energy poverty, whereas, in regions with less vulnerability, energy poverty increases emissions. Subsequently, Dong *et al.* (2021) investigated whether a low-carbon energy transition could support energy poverty mitigation, using panel data from 30 Chinese provinces. The study focused mainly on the impact of natural gas consumption, finding that the use of natural gas was correlated with lower energy poverty levels, although with variations across regions.

Taking into consideration the current European policy landscape, it becomes increasingly relevant to focus on the energy poverty-CO_2 nexus, developing European case studies to investigate the connection between these two energy policy cornerstones, and potentially disclose opportunities for measures or policies that could create a positive dual effect for achieving the proposed goals of reduced emissions and energy poverty eradication. Acting upon this thought and aiming to bridge the identified lack, this study proposes an approach to assess the effect of large-scale HVAC equipment replacement on regional energy poverty levels, as well as the potential variation in CO_2 emissions. It uses a previously developed index for estimating regional energy poverty vulnerability – the EPVI (Gouveia *et al.*, 2019), to analyse all 308 Portuguese municipalities, considering the entire occupied dwelling stock. This research aims to produce valuable insights for policymaking at different scales, namely identifying the most effective technologies for energy poverty and greenhouse-gas emission reduction and pinpointing the regions that should be priority targets due to higher vulnerability and/or higher potential for improvement.

6.2.3 Case-study

Portugal was selected as a case study because of its severe energy poverty levels and the low energy efficiency of the building stock and its HVAC equipment. Currently, according to EU SILC indicators, which are usually used as proxies of energy poverty, Portugal has the 4th highest rate of citizens reporting their inability to maintain dwellings adequately warm during the winter (17.5 per cent) and the 2nd highest percentage of the population living in homes with a leaking roof, damp walls, floors or foundation, or rot in window frames or floor in the EU (25.2 per cent) of all 27 European member-states in 2020 (Eurostat, 2022a; Eurostat, 2022b). One of the main root causes of these energy poverty levels is the ageing and low energy-performing Portuguese residential building stock. Approximately 68 per cent of all the energy certified residential buildings from 2014 to 2021 (about 1.43 million) have an energy performance rating equal to or lower than C (below B- level, which is the standard for new buildings) (ADENE, 2022), whereas only 13.5 per cent present the highest rate A. This is a consequence of the fact that approximately 70 per cent of residential buildings were built before 1990 (INE, 2011), before the establishment of the first Portuguese energy performance regulation. The average deep renovation rate was approximately 0.01 per cent/year for the five years prior to 2019 (INE, 2019), considerably below the EU average renovation rate of one per cent (European Commission, 2020b) and target of three per cent (BPIE, 2020). Inefficient heating and cooling equipment also contribute significantly to the low EPC rates. According to DGEG (2021), about

26.4 per cent of improvement measures proposed in EPCs pertain to HVAC systems replacement.

Moreover, the ownership and use of decentralised, low-efficiency heating systems such as fireplaces and electric oil heaters are widespread (INE/DGEG, 2021). Biomass is the most commonly used energy carrier for indoor space heating (INE/DGEG, 2021), as evidenced in Figure 6.11. District heating is virtually inexistent in the country. Space cooling equipment ownership is still low, at around 32.7 per cent nationally (INE/DGEG, 2021) when compared to countries with a similar climate (Castaño-Rosa *et al.*, 2021). Space cooling is provided only through electricity, and cooling fans are more commonly used equipment, providing ventilation rather than cold air. Furthermore, there is considerable geographic variation in the ownership and type of heating and cooling equipment across Portugal, particularly between rural and urban settlements (Gouveia *et al.*, 2019). This variation is related to cultural factors, energy infrastructure, and fuel availability (Horta *et al.*, 2019), resulting in distinct consumption patterns and instances of underconsumption.

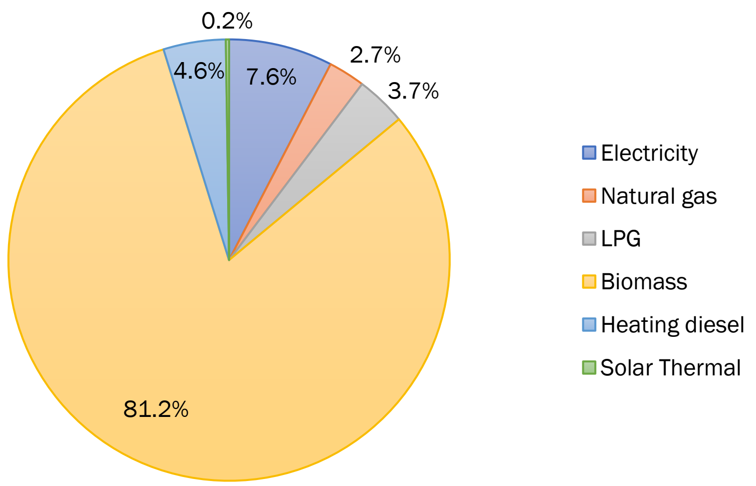

Figure 6.11 - Energy consumption per energy carrier for space heating in Portugal (data from INE/DGEG, 2021)

Portugal is among one of the warmest countries in the EU with high temperatures in the summer, with the fifth-highest number of CDD cooling degree days (*i.e.*, 269) and the third with lower HDD (*i.e.*, 1008) in 2020 (Eurostat, 2022c). Furthermore, the country is located in one of the most climate change-impacted regions of Europe (Ducrocq, 2016), with predicted increases in total CDD, frequency and intensity of heatwaves, and a decrease in HDD (Sanchez-Guevara *et al.*, 2019; Meteonorm, 2020).

In the policy arena, building renovation and increased energy efficiency are considered a priority in the national strategy instruments such as the National Energy and Climate Plan 2030 (Portuguese Republic, 2019a), the Long-term National Strategy for the Renovation of the Building Stock (Portuguese Republic, 2021), and the Roadmap for Carbon Neutrality for 2050

(Portuguese Republic, 2019b). Recently, a national Plan for Recovery and Resilience, stemming from a European debt issuance mechanism to face the crisis, will unlock €620M for buildings' energy efficiency, €300M of which for the residential sector, and a total of €774M to invest in new public housing (Portuguese Republic, 2020).

6.2.4 Methodology

The energy poverty levels for both winter and summer were estimated using the EPVI developed by Gouveia *et al.* (2019), composed of two sub-indexes. The first is the sub-index energy gap, representing the difference between the theoretical final energy consumption for thermal comfort conditions and the actual final energy consumption, as in Palma *et al.* (2019). The theoretical consumption is calculated through a bottom-up dwelling typology approach based on a set of buildings' characteristics (*e.g.*, area, walls, roof, bearing structure), where a total of 264 representative typologies are defined using regional data harvested from approximately 525 thousand EPCs. The energy needs of every typology are calculated according to a steady-state method based on the requirements and methodology defined in the current National Energy Performance Regulation, implemented in 2013 (DRE, 2013), which derives from the EN ISO 13790 approach. It considers the maintenance of an optimal inside temperature of 18°C in the heating season and 25°C during the cooling season for the whole useful area of the dwelling and during the total duration of the respective season. The theoretical consumption is then computed using data on the occupied dwelling stock per typology and the ownership percentages and efficiencies of the different space heating and cooling systems. The actual final energy consumption for space heating and cooling is estimated using municipal statistics (DGEG, 2022a) on total final energy consumption per energy carrier and representative municipal energy matrixes for each country's climatic zones.

The second sub-index portrays the adaptive capacity of the population to implement measures to cope with thermal discomfort. It is calculated using socioeconomic indicators such as unemployment rate, income, dwelling ownership rate, population share with a university degree, population's age, and building conservation state. The sub-index is the weighted sum of these indicators, and the weights were selected according to feedback from national experts in this field. The median income after income tax was used instead of the gross average monthly income included in the original study. Income inequality in Portugal is high, evidenced by a GINI index of 31.2 per cent, the 9th highest in the EU in 2020 (Eurostat, 2022d) and the median income is less distorted by outliers, representing more adequately the financial means of the population to heat or cool their homes.

The EPVI ranges from 1 (less vulnerability) to 20 (highest vulnerability). It is a linear, equal average of the energy gap sub-index and the symmetrical value of the adaptive capacity sub-index. More information and detail on the index development can be consulted in Gouveia *et al.* (2019).

The effect of the improvement in the efficiency of HVAC systems in the theoretical final energy consumption and subsequently on the EPVI values was assessed for two different scenarios: Current Situation; Scenario A, where heating and cooling equipment ownership rates were maintained, but the efficiencies were improved to the level required by the residential buildings' energy performance regulation (DRE, 2013); and Scenario B, based on the pathways to 2050 of the "Yellow Jersey" scenario set in the Portuguese Carbon Neutrality Roadmap (Portuguese Republic, 2019b), which considers a socioeconomic evolution compatible with carbon neutrality, supported on structural change in the production chains, integration of circular economy models and growth of medium cities. Following an optimisation modelling of the entire energy system, this scenario considered the necessary national split of HVAC equipment ownership for achieving carbon neutrality objectives. The regional ownerships needed in this study were altered proportionally from the current situation scenario to reach the established national ownerships for 2050. Current climate indicators provided in the regulation for the current situation were considered for both scenarios.

The increases in HVAC efficiency are explored as a proxy of a deep energy efficiency program for replacing the old and inefficient HVAC equipment currently being used. The HVAC efficiencies before the increase in energy efficiency and in the two tested scenarios are shown in Table 6.2. The split of equipment ownership rates for the current situation and the two scenarios is displayed in Table 6.3. The data for the ownership rates split is from the 2011 Census, as it is still the only data available at the regional level.

Table 6.2 - HVAC equipment efficiencies in % and Coefficient of Performance (for air conditioner and heat pumps) (Palma *et al.*, 2019; Ordinance nr. 349-B/2013; Portuguese Republic, 2019b)

HVAC system for space heating	Current situation	Scenario A	Scenario B
Open fireplace	35	75	75
Fireplace with heat recovery	60	75	75
Closed biomass stove	55	75	75
Biomass boiler for central heating	70	75	75
Solar Thermal	-	-	100
Diesel boiler for central heating	75	89	-
Natural gas boiler for central heating	75	0.89	-
Electric heater	99	100	100
LPG heater	85	85	-

Heat pump	2.20	4.30	4.30
HVAC system for space cooling	**Efficiency before HVAC substitution**	**Energy Efficiency scenario 1**	**Energy Efficiency scenario 2**
Air conditioner	2.38	3.00	3.00
Fan	100	100	-
Heat pump	2.30	3.00	3.00

Table 6.3 - National space heating and cooling equipment ownership (%) (INE, 2011; INE/DGEG, 2011; Portuguese Republic, 2019b)

Heating System	Current Situation/ Scenario A	Scenario B
Open fireplace	21.7	2.2
Fireplace with heat recovery	8.4	
Closed biomass stove	4.5	
Biomass boiler for central heating	1.3	
Solar Thermal	-	1.1
Diesel boiler for central heating	3.2	0.0
Natural gas boiler for central heating	6.0	0.4
Electric heater	54.5	10.8
Liquified Petroleum Gas (LPG) heater	0.4	0.0
Air conditioning (Heat pump)	2.2	85.6
Cooling system		
Air conditioner	7.0	2.0
Fan	68.0	0.0
Heat pump	25.0	98.0

The CO_2 emissions resulting from the real final energy consumption and the theoretical final energy consumption before and after the energy efficiency measures were computed using default emissions factors from the IPCC's Guidelines for National Greenhouse Gas Inventories for Stationary combustion in the residential and agriculture/forestry/fishing/fishing farm categories (IPCC, 2006), for LPG (butane and propane), natural gas, and diesel, and the

Portuguese energy supplier Energias de Portugal S.A. (EDP, 2021) for electricity. The electricity emission factor is derived from an energy mix of 72 per cent non-renewable energy (10 per cent of coal, 49 per cent of natural gas, 12 per cent of fossil cogeneration and one per cent of solid waste) and 28 per cent of renewable energy (one per cent of wind energy, eight per cent of hydric energy, 11 per cent of other renewable energy and eight per cent of renewable co-generation) (EDP, 2021). The methodology follows a similar approach to the one of Gouveia and Palma (2019). The difference in the total carbon emissions was estimated and analysed for the different scenarios in light of the variation in energy poverty levels.

6.2.5 Results and Discussion

The results show unequivocally that the increase in energy efficiency in residential homes in Portugal positively affects energy poverty levels when assessing vulnerability with the multidimensional approach for regional assessment advanced by Gouveia *et al.* (2019). Average municipal EPVI values for space heating and cooling seasons decreased from 10.0 and 11.4, respectively, to 8.2 and 11.2 in Scenario A, with 17.8 per cent and 1.0 per cent decreases. In Scenario B, percentage decreases are even higher, respectively, 47.8 per cent and 26.3 per cent, with EPVI average values of 5.2 and 8.4. These findings indicate a more significant effect of equipment replacement and efficiency increases in the winter energy poverty season as the equipment currently in use has lower efficiency. Inefficient equipment includes fireplaces, biomass stoves, and diesel boilers. On the other hand, although real consumption is considerably lower in the summer season, the equipment stock composed of fans and air conditioners is more efficient. The maps displaying EPVI values for the current situation, Scenario A and Scenario B, are shown respectively in Figure 6.12, Figure 6.13, and Figure 6.14. Both in the heating and cooling seasons, higher EPVI values can be found in the interior of the Portuguese mainland and the islands in the current situation. In Scenario A, higher average municipality reductions in winter EPVI are observed in the centre littoral regions of Leiria, Aveiro, and Coimbra (29 per cent, 27 per cent, and 27 per cent, respectively) and the centre inland region of Beira Baixa (28 per cent). This is explained by higher ownership rates of biomass systems in house and apartment typologies, which have lower energy efficiency. In Beira Baixa, open fireplaces are particularly common.

In contrast, in the central coastal regions, all types of biomass equipment can be frequently found, as well as natural gas boilers in apartment buildings. In the summer, as the equipment ownership split was considered the same for every municipality, the highest decreases are found in Lisbon and Porto regions (minus two per cent and minus three per cent) due to the greater size of the dwelling stock, magnifying the effect. Reductions of EPVI levels are considerably lower than for space heating because the cooling systems' stock already has an efficiency very close to regulation requirements. Only replacing less efficient systems for new and substantially more efficient systems can result in a substantial change at a larger scale, as observed in Scenario B. In this scenario, summer EPVI reductions are considerably higher, especially in the urban centres of Lisbon and Porto, where actual consumption levels are more significant, and together with a decrease in theoretical consumption, result in lower energy gaps and vulnerability. Additionally, municipalities in northern regions like Alto Minho and Ave would benefit significantly from an energy efficiency upgrade given that energy demand for space cooling due to climate conditions is low; hence efficiency upgrades could reduce energy needs and the energy gaps and vulnerability in a tangible form. Regarding space heating in Scenario B, the change of equipment stock is transversally impactful across the country, with significant reductions in energy needs and ultimately vulnerability levels to a value lower than five in about 59 per cent (182) of all 308 municipalities, which is a considerable achievement.

The Açores and Madeira's islands are the regions where energy efficiency measures are less effective for space heating because there is a widespread use of portable electric heaters in both dwelling typologies, which have a higher efficiency than most of the other systems in the stock. Moreover, real consumption in the municipalities of both islands is generally meagre. Thus, efficiency increases and even equipment replacements are not so impactful in reducing winter EPVI levels and summer EPVI to a lower degree in both scenarios.

Looking at CO_2 emissions at the national level, displayed in Table 6.4, there is a large gap between current emissions and the emissions that would result from the necessary consumption to attain thermal comfort in all Portuguese dwellings, around 2565 kiloton for space heating and 1112 kiloton for cooling. The increase of efficiency in Scenario A does not significantly reduce this gap in percentage - 79.8 per cent to 78.5 per cent for heating and 84.7 to 84.1 per cent for cooling - resulting in reductions of around 195 kilotons and 43 kilotons. Considering the current energy performance of the residential building stock, consumption levels and CO_2 emissions would have to increase significantly to guarantee thermal comfort for the population. On the other hand, in Scenario B, emissions drop to around 779 kilotons for space heating, 16.5 per cent above the emissions with the current consumption, which means even in a scenario of carbon neutrality and a very favourable and efficient equipment stock, consumption levels and emissions would still need to rise to guarantee energy sufficiency in Portuguese homes. However, for space cooling, CO_2 emissions associated with the necessary thermal comfort consumption drop to 198 kilotons, below current emissions, which means an increase in cooling energy consumption and CO_2 emissions would not be needed.

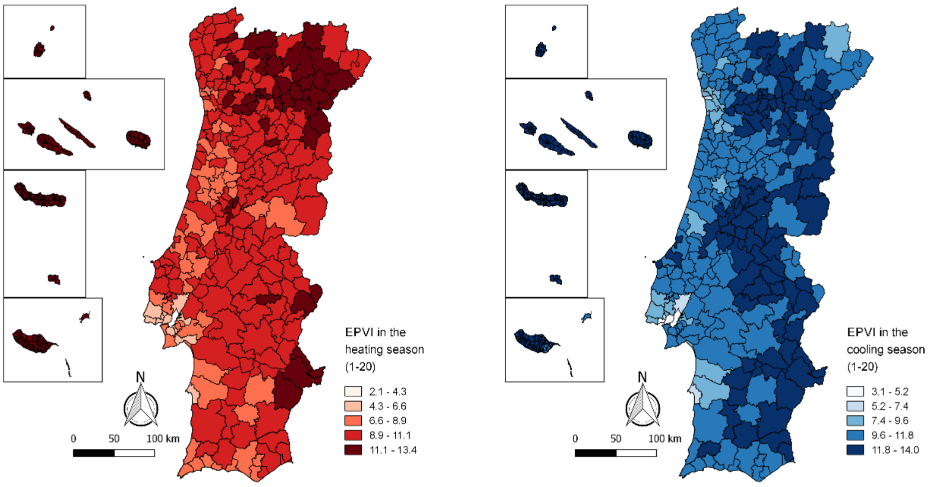

Figure 6.12 - EPVI in the heating season (left) and cooling season (right) in the current situation

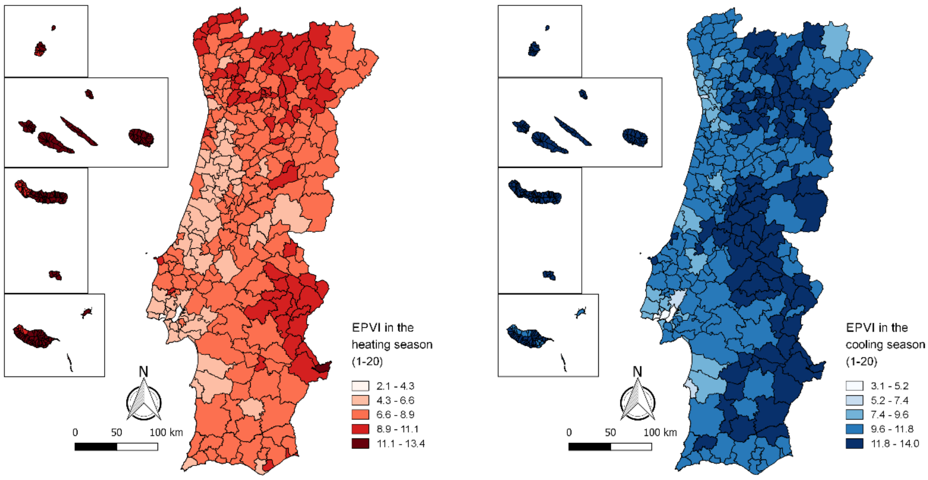

Figure 6.13 - EPVI in the heating season (left) and cooling season (right) in Scenario A

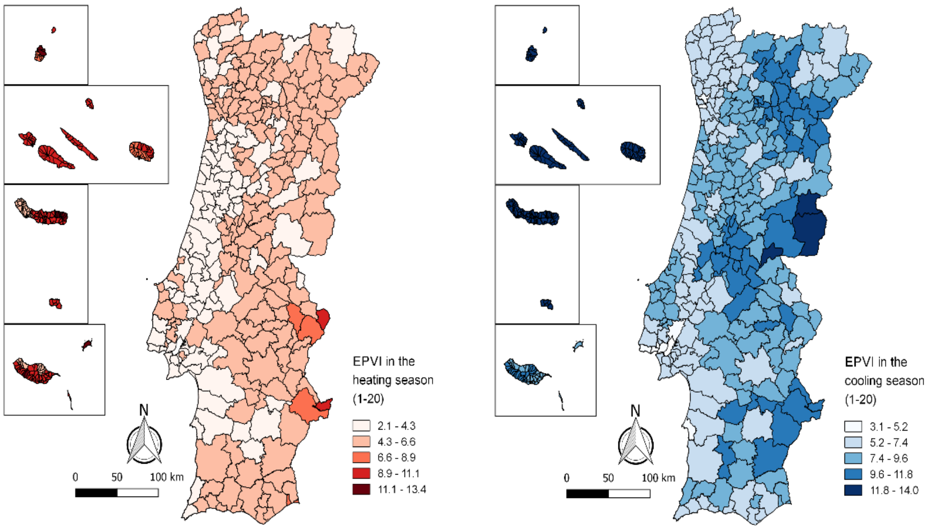

Figure 6.14 - EPVI in the heating season (left) and cooling season (right) in Scenario B

Table 6.4 - Total carbon dioxide emissions in the current situation, Scenario A and Scenario B~

CO_2 emissions (kton)	Space Heating	Space Cooling
Current Situation (Real consumption)	651	202
Current Situation (Theoretical consumption)	3217	1314
Scenario A (Theoretical consumption)	3021	1270
Scenario B (Theoretical consumption)	779	198

It should be noted that, whilst heating and cooling equipment replacement and increase of efficiency is an essential part of the solution, it should not be the only effort towards increased thermal comfort, decarbonisation, and reduction of energy consumption. The increase in the population's quality of life and economic development may lead to excessive energy consumption in the long run. Indeed, the Building Renovation Strategy raises concerns about the so-called "rebound effect" (Portuguese Republic, 2021). Moreover, the roll-out of the necessary equipment for Scenario B is of great magnitude, with heavy investment and inherent environmental impacts. Efficiency systems like heat pumps and air conditioners still pose challenges to climate change mitigation, as they use f-gases, which have a global warming effect up to 23 000 times greater than CO_2 (European Commission, 2022c), and avoiding them can be a major climate change solution (Project Drawdown, 2020). Therefore, it is also crucial to tackle the problem upstream, *i.e.*, reducing building stock energy needs by increasing energy performance via renovation interventions. In Portugal, due to the very high energy gaps (Palma *et al.*, 2019) resulting from the lower energy performance of an old building stock and historical underconsumption, this renovation might not reduce consumption in the short term. However, it will improve the thermal comfort of occupants and provide other positive externalities such as better indoor air quality, which, together with efficiency upgrades in heating and cooling systems, might result in energy consumption savings in the medium or long term.

At the policy level, efforts have derived mainly from the central administration under the recent scope of the Recovery and Resilience Plan. There are currently two programs supporting building renovation and energy efficiency measures in the residential sector. The first one is directed at the general population, providing 85 per cent of the investment (VAT excluded) after the implementation of both kinds of measures. The other program distributes vouchers of €1300 + VAT before the intervention to homeowners that benefit from the social energy tariff. The €300 million allocated for the residential sector until 2025 represent nevertheless a small percentage of the necessary investment, falling short of making a significant impact. Palma *et al.* (2022) reported a minimum total investment of €70 billion euros to renovate the Portuguese residential building stock to the optimal regulation standards. Conducting a small theoretical exercise, considering an average cost of €1200 for installing two regular split heat pumps in a dwelling, increasing ownership by 25 per cent would require an investment of roughly 1.25 billion euros. Also, there are over 800 thousand social energy tariff beneficiaries in Portugal (DGEG, 2022b). As the EU mandates Member-states to achieve energy savings in energy-poor homes, the energy gaps between ideal and actual consumption in the residential sector in Portugal are a substantial barrier to creating sustainable business models around energy savings. The energy-poor population does not have the financial resources to conduct interventions in their homes, thus sustained state financial support after 2025 at central level is essential to drive permanent transformation in the sector.

Regional and local governments have tax incentives in historical areas and mainly support the renovation of rundown buildings but often have problems regarding funding availability. Nevertheless, due to their closer relationship with the people, they can play an important role in increasing energy literacy, supporting the population in accessing the state programs, and collaborating with central administration to guarantee higher adoption and effectiveness of these support programs. The results of this study highlight the regions where energy efficiency support measures can have a higher impact, which can be useful for prioritizing and mobilizing efforts at both national and regional levels.

The private sector, particularly energy companies, should also be accountable for this transformation through obligations, as proposed by the EU in the energy efficiency directive, as they have large revenues and households suffer from high energy prices in the country. However, these obligation schemes should not be based on energy savings but rather on renovation interventions and equipment replacement, focusing instead on energy needs reduction, energy sufficiency, and thermal comfort improvement. This approach would benefit from the collaboration with local authorities to target those most in need.

While this energy transition is of utmost importance, it should assure energy justice across the country. There are households in situations associated with different types of energy injustice. Firstly, it can be argued that there is an issue of distributional justice in energy policy, as the percentage of support for each measure does not vary according to the socioeconomic status of the recipient, and the subsidies for vulnerable consumers can be significantly lower in absolute value compared to the program targeting the general population, depending on the measures adopted. Hence, there is an imbalance in the support framework resulting in inequality of opportunity, connected to a deeper problem in adequately recognising and taking into account socioeconomic inequalities. Outside the scope of support schemes, the fact that highly efficient equipment is more costly also contributes to increasing injustice. As Europe tries to move away from gas, a significant increase in demand is ramping up heat pump prices, which also exacerbates inequality (Euroactiv, 2022). There are Portuguese people in energy poverty across the whole country (Panão *et al.*, 2021), but there is generally higher vulnerability in rural regions (Gouveia *et al.*, 2019), thus, geography and territory should also be considered in policy design, as these factors shape injustice. This study highlighted the varying levels of energy poverty and the potential impact of measures across regions that are not considered in support provision and funding allocation. It can also be argued that there is a systemic problem of procedural justice when it comes to policymaking, as people are rarely engaged in the decision-making processes, potentially due to considerable levels of energy illiteracy in the country (ERSE, 2020) and relatively low efforts from governments to promote citizens' participation in the discussion.

There is also a set of ongoing historical and recent inequalities that should be recognised and addressed for the needed transformation to be conducted fairly. Across the country, there is still high ownership of fireplaces and other biomass-burning equipment across regions, and a part of the population still access firewood at very low or no cost, as it might be a common resource in the countryside. Replacing these fireplaces with higher efficiency equipment could mean improved efficiency but would result in added costs to these families. In apartment buildings, some newer systems are also challenging to install and require the approval of neighbours. Various efficient technologies such as monobloc heat pumps might require a considerable amount of space in the dwellings, which prevents their implementation in smaller dwellings, creating a housing inequality. Furthermore, as elderly people frequently inhabit these homes, digital difficulties in handling these new systems could also prevent smooth utilisation. Digital illiteracy is a relatively recent problem of injustice, crossing over different areas within this domain. For instance, it is also a significant handicap for accessing support programs, as the application process can only be conducted using online platforms. Ashby *et al.* (2020) state that policymakers often design programs to their image, though not reflecting the needs of the vulnerable, which may be the case also for ongoing support programs in Portugal. Therefore, to address that lack, state support schemes for vulnerable households should have a nuanced approach, considering geography, context, vulnerability profiles and ongoing injustices, to deliver more effective support interlinking efforts at national and regional levels. This will help not to leave anyone behind in the efforts of tackling energy poverty, boosting energy efficiency, and achieving the set energy and climate targets for 2050.

Finally, reflecting on the contribution of this paper on a broader level, it links three critical social and political subjects at a worldwide and European scale - energy poverty, decarbonisation, and energy efficiency, by analysing the potential transversal impact of a particular solution, the replacement of domestic HVAC equipment. It underscores the need for looking at this kind of measure as part of the solution for these three societal challenges, not only in Portugal but also in other geographical contexts, with an energy justice lens. It advances a context-specific but replicable methodology, that could inspire the development of similar studies. In fact, the study of the direct causal nexus between these subjects in the residential sector is still an underexplored subject in literature. Developing knowledge in this area could ultimately benefit local and national governments in their policy design and contribute, even if contextually, to tackling these major global challenges.

6.2.6 Conclusions

Climate change mitigation, decarbonisation, and reduction of energy poverty are three of the most critical challenges that the world and the EU currently face. While various policies are tackling each of these issues, it is crucial to support integrative and comprehensive actions which tackle all these challenges, such as increasing energy efficiency in buildings.

This study proposes a methodology to assess the impact of energy efficiency upgrades, namely the replacement of domestic space heating and cooling equipment, on regional energy poverty and CO_2 emissions. Results show significant reductions in energy poverty levels, especially when considering equipment replacement and profound change in the national equipment stock. Due to historical, cultural, and financial reasons, underconsumption of energy is prevalent, resulting in a substantial gap between the real consumption and the necessary consumption to achieve indoor thermal comfort in every Portuguese home. This means that thermal comfort conditions would subsequently entail higher carbon emissions. Comprehensive upgrades of heating and cooling equipment would significantly reduce the consumption and emission gaps for space heating and even reduce necessary emissions below the current levels for space cooling.

Increased and consistent state support at both central and regional levels is crucial for boosting energy efficiency in the residential sector, as a considerable investment is necessary and the circumstances of energy use in the sector do not enable suitable business models. Private energy companies could be part of the solution via energy retrofit and inefficient equipment replacement obligation schemes. It is paramount that this transformation accounts for energy justice issues of the different vulnerable groups of the population to ensure a just energy transition and achievement of energy and climate targets. The outcomes of this study, although specific to Portugal, emphasise the need for investigating heating and cooling systems replacement at a wider scale, as it can have a triple positive impact in simultaneously tackling the major challenges of energy poverty alleviation, decarbonisation, and energy efficiency in other geographical contexts.

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6.3 Economic analysis of decarbonising energy consumption in residential buildings

Abstract

The drive for a green fair energy transition that accomplishes the significant decarbonisation of energy consumption, and the alleviation of energy poverty is currently one of the policy priorities of the European Union. Harnessing the necessary investment and producing tailored policy that mobilises investment towards impactful and efficient measures are two of the main challenges to be addressed. Assessing the magnitude of the efforts that need to be conducted is an important starting point to plan national strategies that are effective in achieving these goals. This study aims to conduct an exploratory and critical analysis of the economic efforts necessary for decarbonising energy consumption in residential buildings in Portugal. The analysis is supported by the best available data, statistics, and scientific studies, as well as a review of the national policy plans and strategies that outline pathways and targets for achieving this goal. The report includes a quantitative analysis of the costs of replacing equipment in multiple residential sector energy services such as space heating and cooling, domestic water heating, cooking equipment, and lighting. Qualitative considerations regarding the context of the populations and territory are also considered. This study discusses potential funding sources and support mechanisms to achieve the objectives. Current challenges and barriers to decarbonisation are also identified, and potential technological solutions are evaluated based on the advantages and disadvantages of their application. It outlines possible technical responses to the goal of decarbonising energy consumption in Portuguese households, considering the different characteristics and needs of the population. The study estimates total necessary investment in equipment replacement ranging from €26.2 and €28.5 billion euros for total fossil fuel phase-out, significant biomass consumption reduction, minding energy justice issues for particular segments of the population, and deep energy efficiency increase. Reducing fossil fuel use in domestic hot water production represents the largest cost burden, followed by reducing biomass consumption for space heating. The conclusions and key outputs can inform and guide decision-makers and other social actors engaged in building this future at various scales, especially at the central level for national-scale planning.

6.3.1 Introduction

6.3.1.1 European Context

Fighting climate change is one of the biggest challenges facing humanity today. Overcoming this challenge requires a transformation of the economy towards a more sustainable and ecological model, with a significant reduction in environmental impacts, greater efficiency in the use of resources, and an increase in people's quality of life. With this goal in mind, the European Union (EU) has set itself the target of achieving climate neutrality by 2050 (European Commission, 2023) through an economy with zero net greenhouse gas (GHG) emissions, reinforcing its commitment to climate action in line with the Paris Agreement. The European Parliament approved the goal of carbon neutrality in the 2019 resolution on climate change and the 2020 resolution on the European Green Deal. In the European Green Deal (European Commission, 2019), the European Commission (EC) put forward a set of proposals covering the various sectors of the economy to meet the target of reducing GHG emissions by 55% compared to 1990, taking decisive steps towards achieving the desired climate neutrality by 2050.

The energy sector is one of the most important for the necessary transition, accounting for 75% of GHG emissions in the EU (European Commission, 2021a). The European Green Deal describes the decarbonisation of the energy system as a critical step in this process, highlighting the large-scale replacement of fossil fuels, such as natural gas and coal, with renewable energy sources and the importance of investing in energy efficiency (European Commission, 2019). Decarbonisation requires a substantial transformation of the energy system and how energy is obtained, transported and consumed. The form and nature of this transformation are still the subject of much debate due to its political dimension and potential impact on people's lives. While measures such as reducing dependence on fossil fuels, promoting the electrification of energy consumption and expanding electricity production from renewable sources are relatively consensual, other solutions such as hydrogen and so-called renewable gases appear more controversial (Zachmann *et al.*, 2021).

Focusing on the energy demand side, buildings are a fundamental pillar of the energy transition since, considering all stages of their life cycle, they account for 40% of energy consumption and 36% of GHG emissions (European Commission, 2020a). The residential sector represents a significant share, around 28% of final energy consumption in the EU in 2021 (Eurostat, 2023a). Through the European Green Deal, the Renovation Wave strategy and the Recovery and Resilience Plan, the European Commission strongly emphasises the need to reduce emissions and energy consumption in buildings. The renovation of buildings and the replacement of equipment for space heating and cooling and domestic water heating are the solutions that can effectively contribute to reducing energy needs and decarbonising the sector (EEA, 2022). The package of measures called "Goal 55" (Fit-for-55), which aims to update the legislation in force in line with the targets set and boost the green transition, proposed the revision of the Energy Performance of Buildings Directive (EPDB). This revision, also outlined in the "Renovation Wave" strategy, has as one of its main objectives to help at least double building renovation rates, currently below 1% (European Commission, 2021b), and to make buildings more efficient and future-proof. The revision introduces the term "zero-emission building", *i.e.* a building with a high energy performance, in line with the primary objective of energy efficiency, which requires small amounts of energy to be produced by local renewable sources. All new buildings must meet this standard from 2027, and all renovated buildings must meet this standard from 2030. Among other measures, this revision also ends subsidies for fuel boilers from 2027 to promote the adoption of zero-emission renewable heating systems (European Parliament, 2022).

Although improving energy performance through renovation should be the basis of the sector's transformation, electrification is considered the main way to decarbonise energy consumption in buildings, namely through the installation of equipment such as heat pumps, which allow for very significant efficiency gains (Zachman *et al.*, 2021). Of the energy uses in the residential sector in the EU in 2020, space heating is the most consuming, accounting for around 63% of final energy, followed by water heating, which accounts for 15% (Eurostat, 2023b). Historical efforts to replace fossil fuels with energy from renewable sources for heating and cooling have been slow and too focused on the use of biomass. However, the development of heat pump technology and industry has brought about a change of pace in the industry and its implementation in buildings (EEA, 2023a). The International Energy Agency predicts an exponential increase in heat pumps, a technology with solid environmental credentials which, if supplied with renewable electricity, can reduce heating emissions by up to 90% compared to a gas boiler, depending on the electricity production mix. A study by the European Climate Foundation states that if 60 million heat pumps were installed in the EU by 2030, it would be possible to achieve a 40% reduction in gas consumption in buildings compared to 2022 and a 46% and 40% reduction in CO_2 and nitrogen emissions respectively (ECF, 2023). In conjunction with building renovation, it would also contribute to an average 20% decrease in household expenditure on heating. The International Energy Agency calls for implementing "carrot and stick" policies, such as a ban on the sale of gas boilers from 2025, to accelerate the adoption of this type of equipment (IEA, 2021). On the other hand, converting fossil fuel boilers to biomass systems can lead to a "fuel lock-in" situation, as they last for several years, with implications for the availability of forest resources, air quality and people's health (EEA, 2023a).

The European Scientific Advisory Board on Climate Change also recommends that member states promote the electrification of final energy consumption sectors (EEA, 2023b). The use of green hydrogen, produced by renewable electricity, for heating is also a solution that has been the subject of recent analysis (Zachman *et al.*, 2021) and its potential role in decarbonising buildings is also highlighted by the International Energy Agency, as are district heating networks (IEA, 2021). The European Energy Agency states that district heating for heating and cooling should be carefully evaluated in each case and in relation to other local and cost-effective sources (EEA, 2023a). Studies indicate that hydrogen is not a relevant energy vector for decarbonising home heating by replacing fossil fuels or mixing it with natural gas (Rosenow, 2022). The expected increase in electricity demand must be matched by renewable electricity so that there is no transfer of emissions between the buildings sector and the electricity production sector.

The decarbonisation of buildings is imperative, but it is also an arduous path, with challenges that are difficult to overcome: the implementation of energy efficiency standards, the promotion of building renovation and the guarantee of improved energy performance, the creation of effective support and financing programs, access to technologies for the transition to renewable energy for space heating and domestic water (Baker *et al.*, 2022) are just a few examples of the set of challenges that will have to be faced to achieve the goal of decarbonising buildings.

6.3.1.2 National Context

In Portugal, the decarbonisation of buildings is a political objective that is framed and reiterated in various strategies and instruments in the area of energy and climate and is an essential pillar on the road to meeting the targets set out in the National Energy and Climate Plan 2021-2030, approved in 2020. The plan sets the country an overall GHG reduction target of between -45% and -55%, incorporating renewable energy into the gross final energy consumption of 47% and a 35% reduction in primary energy consumption by 2030 (Government of Portugal, 2020). At a sectoral level, the NECP sets a target of 35% GHG reduction in the residential sector by 2030. It also targets 80% of electricity consumption and 38% of heating and cooling by renewable energy. The plan states that the strengthening of electrification will be associated with the decarbonisation of production by investing in onshore/offshore solar and wind technologies, in parallel with distributed production with a focus on renewable energy communities, storage, and optimisation of the transmission and distribution network, concentrated solar thermal pilot projects, stimulated geothermal energy and wave energy.

The decarbonisation of heating and cooling should be achieved through consumption electrification and reduction of fossil fuel consumption, with a potential increase in biomass, namely through the creation of decentralised thermal power stations and renewable gases such as biomethane and hydrogen. Regarding buildings, the relevant role of heat pumps is mentioned and highlighted as one of the most efficient ways of heating and cooling to promote the electrification of energy consumption and increase thermal comfort in homes. Solar thermal is also highlighted as an important solution for heating domestic water and, in conjunction with other solutions, as an equally important option for space heating. Urban thermal networks are considered an unviable option due to the country's climate, and there are no plans to invest in this solution.

To increase energy efficiency, the NECP reinforces the need to renovate buildings and make them more efficient due to the various benefits resulting from this commitment, highlighting the importance of the new energy certificate, the revision of the Energy Certification System for Buildings, the reformulation of the financing/support mechanisms for the renovation of buildings, and NZEBs (Nearly Zero Energy Buildings) Reducing the carbon intensity of buildings are one of the lines of action of the NECP, which outlines three measures to achieve this: rehabilitating buildings to increase their useful life; promoting sustainable construction techniques and sustainable buildings, favouring the use of secondary raw materials, recycled materials and promoting improved energy efficiency; and promoting the electrification of buildings and the incorporation of renewables. Reducing EP is part of the NECP's strategic objective of ensuring a fair, democratic and cohesive transition, reinforcing the role of the citizen as an active agent in decarbonisation and the energy transition. The plan also proposes to encourage and stimulate the use of heating and cooling production systems that use renewable energy, listing solar thermal systems, boilers adapted to renewable gases, biomass boilers and heat recovery systems and solar photovoltaic systems associated with heat pumps as well as hybrid systems combining two or more technologies, as optimal solutions for space heating in the domestic, services, industry and public services sectors". The need for a program to promote the replacement of household appliances and other inefficient electrical equipment in the domestic sector to reduce the energy consumption of the domestic equipment stock is also underlined.

The Roadmap for Carbon Neutrality (RNC) 2050 (Government of Portugal, 2019) is another central document in the energy transition and progress towards decarbonisation in Portugal's economic sectors.

Regarding residential buildings and the services sector, the expected increase in energy demand for cooling is due to rising average temperatures and increased electrical use. Still, it estimates significant GHG reductions by 2050, around -96%, as shown in Table 6.5.

Table 6.5 - Evolution of emissions from the residential and services sectors and integration of renewables in space heating and cooling (from Government of Portugal, 2019)

Buildings **Unit: Mt $C0_2$eq**	**2005**	**2015**	**2020**	**2030**	**2040**	**2050**	**Δ 2050/2005**
	5.89 | 71.44	3.22 | 52.94	3.6 | 49.73	3.07 | 28.15	1.05 | 14.15	0.09 | 7.11	-98% | -90%
Residential	2.72	2.08	2.43	2 | 2.01	0.73 | 0.71	0.09 | 0.11	-97% | -96%
Services	3.17	1.14	1.18	1.07 | 0.89	0.32 | 0.3	0.00	-100%

Renewable Energy in Space heating and cooling (%)	32%	34%	34%	41% | 49%	60% | 58%	66% | 68%	-

The RNC 2050 identifies four factors as the most decisive for achieving this sector's decarbonisation goal: Energy efficiency, electrification, insulation and rehabilitation, solar thermal and heat pumps. It projects an increase in thermal comfort in the cold and hot seasons due to the growing trend towards electrification, more efficient equipment such as heat pumps, and higher building renovation rates. Renovation is projected to result in a 26% reduction in heating energy consumption in 2040 and around 50% in 2050 in the residential sector, so the increase in thermal comfort will not be linked to a sectoral increase in actual final energy consumption. To this end, urban regeneration needs to become the priority, as it also plays a central role in the fight against EP. A possible decrease in final energy consumption per square metre of between -7% and -20% is projected due to the adoption of higher-performance electrical equipment, such as LEDs and equipment in the most energy-efficient classes. Gas consumption will become residual in homes from 2040 onwards, at around 1%, as seen in Figure 6.15. The same is true for biomass, whose share is reduced to 5%, although it may remain relevant in rural areas, with a more decentralised and sporadic distribution. By 2050, it is expected that more than 90% of water heating needs will be met by solar thermal, around 11% of total energy consumption, and heat pumps will meet 55% of space heating and cooling needs. It is important to note that the increased use of heat pumps results in increased demand for fluorinated gases with high global warming potential values. R-410A is the most widely used refrigerant in heat pumps, with an estimated global warming potential of 2088 (European Commission, 2020b). Investing in alternatives with a lower greenhouse effect is crucial to mitigate this impact. The evolution of carbon neutrality by 2050 in the residential sector is presented in Figure 6.16

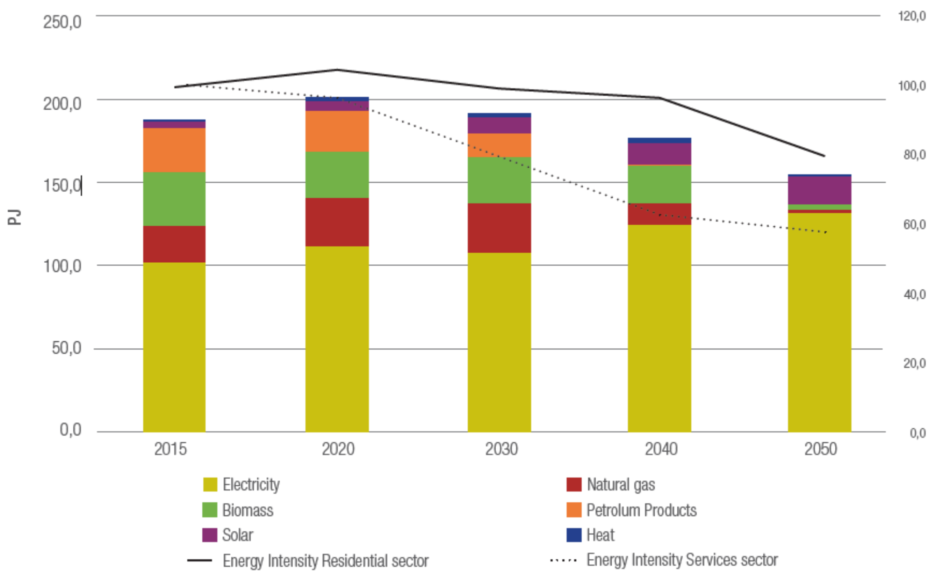

Figure 6.15 - Evolution of final energy consumption and energy intensity in buildings in the residential and services sectors (Government of Portugal, 2019)

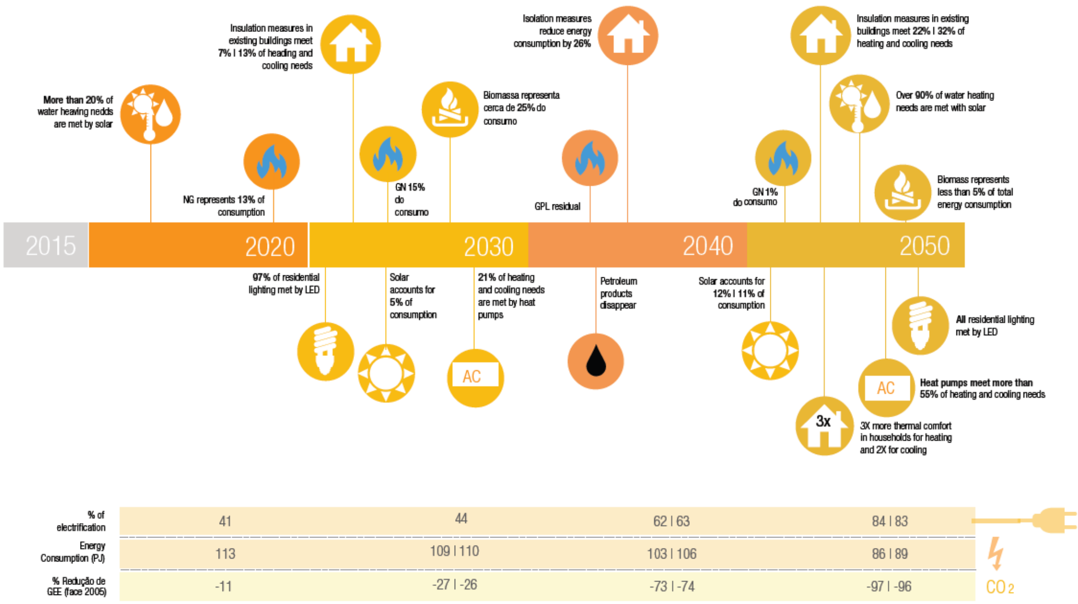

Figure 6.16 - Evolution of carbon neutrality by 2050 in the residential sector (Government of Portugal, 2019)

It also marks net zero energy buildings and Positive Energy Districts as future solutions integrated into smart cities, constituting technological advances to promote greater sustainability and efficiency in energy consumption and other resources with less environmental impact. Greater integration of natural elements and even new uses, such as urban farming, are also identified as part of future models with multiple benefits.

Stemming from the NECP 2030, the Long-Term Strategy for Building Renovation (LTRS), approved in 2021 (Government of Portugal, 2021), focuses mainly on the energy renovation of buildings in terms of the passive envelope and their equipment, prioritising energy efficiency, and the integration of renewable energy sources. The strategy develops an economic analysis of the impact on the inhabitants' energy needs and thermal comfort, of packages of measures to improve the insulation of façades, roofs and windows, and the replacement of existing systems with more efficient alternatives that promote renewable energy. It applies a bottom-up approach based on the definition of building typologies, dwelling occupancy and energy use profiles, and geographical location, considering current market conditions. The package of measures prioritises passive-type measures to guarantee an acceptable level of thermal comfort in homes, meet the minimum requirements of the current building energy performance regulations for each climate region, and select the most cost-effective measures. The LTRS projected that 65% of residential buildings will have undergone an intervention in their passive or active components by 2030 and 100% by 2040. It also envisages 50% of electrical self-sufficiency and 50% of domestic hot water (DHW) needs supplied through solar thermal. The investment needed in the residential sector would be in the order of €26 760 million in 2030, €42 441 million in 2040 and €40 877 million, for a total of €110 078 million. For the same sector, around €40 373m would be needed for the passive component, €365m for lighting, €14 588m for heating and cooling systems, €11 960m for solar thermal and €18 861m for solar photovoltaic plus storage systems.

The cost-effectiveness analysis of renovation scenarios for occupied residential buildings in Portugal by Palma *et al.* (2022) estimates values in the same order of magnitude as those presented in the LTRS. For the scenario with the lowest-cost measures that meet the requirements of current legislation, the authors calculated a necessary investment value of €71 200 million. For the scenario that considers the best solutions on the market, the investment rises to €99 600 million. Both estimates illustrate the major challenge of renovating Portuguese residential buildings to acceptable levels of energy performance. In conjunction with the RNC 2050 and NECP 2030 targets, LTRS has established a set of objectives for the residential building stock for the 2030, 2040, and 2050 horizons compared to 2018 levels, as shown in Table 6.6.

Table 6.6 - Objectives for residential buildings compared to 2018 (Government of Portugal, 2021)

Indicator	2030	2040	2050
Primary Energy Savings (%)	15	37	40
Local Renewable Energy (%)	10	35	73
Renewable Energy (%)	57	62	98

CO_2 emissions reduction (%)	16	56	85
Building area renovated (m^2)	299 524 729	513 059 967	514 265 282
Renovated Buildings (%)	70	100	100
Hours in Discomfort reduction (%)	26	34	56
Weighted average investment (€2020/m^2)	82	165	258
Savings (€2020/m^2)	88	191	279

Approved in 2024, the National Long-Term Strategy for Combating Energy Poverty 2023-2050 is an unprecedented instrument in energy policy in Portugal, introducing for the first time a definition for the concept of energy poverty, defining a set of indicators for measuring and monitoring it and national targets until 2050, and proposing a set of measures to mitigate this problem. This strategy highlights its alignment and complementarity with the other strategies mentioned above, reinforcing the role of decarbonisation, electrification, renewable energy integration, and energy efficiency in the residential sector, reinforcing the need for incentive mechanisms that consider the inability of the most vulnerable households to invest in measures, guaranteeing more favourable and equitable conditions for citizens and, in this way, contribute to the fight against energy poverty.

Decarbonising and reducing the carbon intensity of buildings is a clear objective of all the strategies mentioned, and all of them mention the need to reduce fossil fuel heating equipment. Seven EU member states already have a strategy to decarbonise their heating systems: Sweden, Finland, Denmark, France, Austria, Belgium, and the Netherlands have already announced their intention to eliminate all fossil fuel heating systems by 2050. There is currently no plan to ban fossil fuel heating systems in Portugal. However, the need to significantly reduce fossil fuel consumption in the medium term is mentioned across the board. A ban on the sale of gas water heaters and boilers from 2025 could become a reality, depending on what is agreed in the revision of the directive on the energy performance of residential buildings and its transposition into national legislation. However, if such a ban is adopted, it must be accompanied by mechanisms to support replacement with more efficient electrical technologies to make the transition socially just.

The Recovery and Resilience Plan (RRP) is currently the main instrument driving the implementation of the energy transition in Portuguese homes. It is a national program with an implementation period until 2026. It aims to put the country on the path of sustained economic growth and in line with the European Union after a critical period of the pandemic. The RRP implements reforms and makes investments in line with the Sustainable Development Goals and the pillars of the European 2030 strategy. One of the dimensions of the plan is precisely the Climate Transition, guaranteeing the RRP's commitment to the climate targets and the goal of carbon neutrality in 2050. Within this dimension, component C13 concerns Energy Efficiency in Buildings, the main objective of which is the rehabilitation of buildings, incorporating and operationalising measures included in strategies such as LTRS and the national strategy for combating EP, and provides for a total investment of 300M€ (Government of Portugal, 2023a), distributed across different programs. The REPOWER Europe, the European Commission's support for ending dependence on Russian gas, has led to the update of the RRP, which foresees a potential additional investment of 120 M€ in energy efficiency for residential buildings.

The funds allocated to these programs correspond to a residual percentage of the amounts estimated in LTRS and in the study by Palma *et al.* (2022), which are necessary to promote the decarbonisation of residential buildings based on the renovation of buildings, increased energy efficiency of equipment and the integration of renewable energy systems. It is also important to note that the different levels of adherence to the programs reveal difficulties in providing support and opportunities to the different segments of the population fairly and equitably, to the obvious detriment of the most vulnerable households.

For these reasons, it is urgent to understand how much effort will be needed to decarbonise energy consumption in Portuguese homes and how this path can be followed, with a view to fairly including all families, whether vulnerable or not. The analysis developed in this work focuses on the active component of consumption, *i.e.* equipment, leaving out the passive element in the building, which has already been the subject of extensive analysis in the LTRS and Palma *et al.* (2022). The following RQ is thus defined: What is the feasibility of decarbonising energy consumption for Portuguese families by replacing fossil fuel equipment (diesel, natural gas and LPG) with electricity and renewable energy sources?

6.3.1.3 Goals

To outline possible ways to achieve the desired result - the decarbonisation of energy consumption in Portuguese homes, it is first necessary to understand the current situation regarding consumption in the domestic sector and identify the challenges that need to be overcome to achieve the goal. Four objectives are defined to build the path towards decarbonising energy consumption:

1. *Eliminate energy consumption from fossil fuels*

The first objective concerns the consumption of fossil fuels. The indicator to be analysed is the breakdown of final energy consumption in households in 2021, shown in Figure 6.17. Total consumption for energy purposes in households was 34 945 GWh (DGEG, 2023). It can be seen that around 22.6% of final energy consumption is still directly provided by fossil fuels, corresponding to a total of 7 869 GWh with direct consequences in terms of GHG emissions and air pollution. This identifies the first general objective - eliminating energy consumption from fossil fuels. This objective is justified by the considerable negative impact that the consumption of fossil fuels has on the environment and populations through the release of greenhouse gases such as CO_2, which cause global warming, and their contribution throughout their life cycle to various other environmental problems such as soil degradation, water pollution, air pollution and ocean acidification (NRDC, 2022). Fossil fuel pollution resulted in the deaths of 8.7 million people globally in 2018 (Vohra *et al.*, 2018). It should be noted that this 22.6% of consumption corresponds almost entirely to the energy consumed for DHW, space heating and cooking, energy uses that are difficult to replace and which, given society's growing standards of comfort, may even tend to increase.

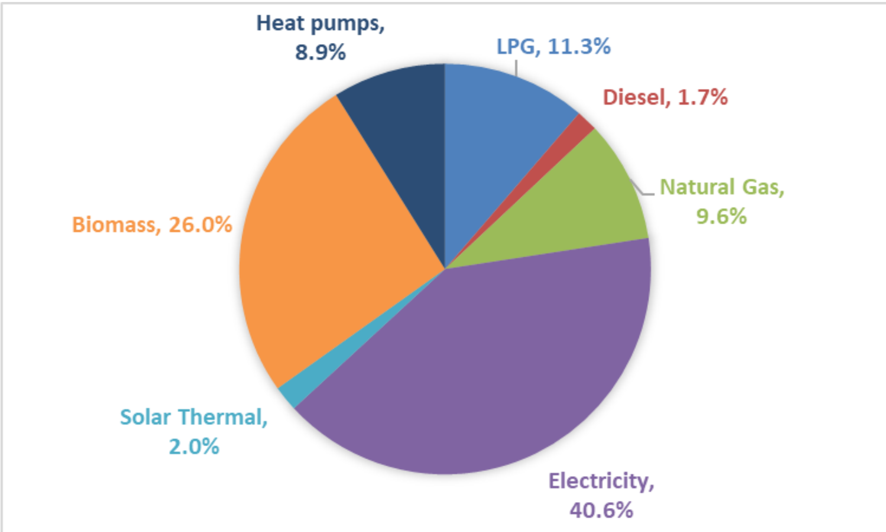

Figure 6.17 - Breakdown of final energy consumption in dwellings by fuel type (data from DGEG, 2023)

2. Reduce Biomass consumption

Biomass also represents a significant part of final energy consumption in the Portuguese residential sector, for cultural reasons, easy access and price. This energy source predominates in many Portuguese homes throughout the country, especially in the interior. Using firewood for space heating, water heating and cooking in homes is ingrained in Portuguese culture. Many families have access to this resource free of charge, as they live in rural areas where it is abundant, either on their land, if they own it, or on adjoining or neighbouring land. Regular and/or regionally representative data on the quantity and distribution of the resource and its use is scarce, and the widely spaced estimates of the Directorate General for Energy and Geology (DGEG) energy balances are the only data available.

Biomass is considered carbon neutral in the international accounting of emissions, but several experts dispute this decision (Ter-Mikaeilian *et al.*, 2015; NRDC, 2021; Ahmer, 2022).

The IPCC states that automatically considering biomass carbon neutral is incorrect (IPCC, 2021). In addition to CO_2, burning biomass produces harmful pollutants such as carbon monoxide, methane, volatile organic compounds, nitrogen oxides and particulate matter, negatively impacting air quality and the population's health. Smoke from burning biomass contributes to around 40,000 premature deaths in Europe related to respiratory and cardiovascular problems (Tomlin, 2021).

At the same time, biomass's important role as a strategy for tackling EP should not be overlooked (Stojilosvka *et al.*, 2023). Although fireplaces are inefficient systems when compared to other solutions, a percentage of households in energy poverty enjoy free firewood, which allows them to mitigate their situation of vulnerability, and an additional expense with the energy consumption of another system is not seen as favourable, even with improved thermal comfort and indoor air quality. Other types of biomass fuels have been adopted in the meantime, such as pellets, which are typically certified in terms of their quality, burn more efficiently and produce less pollution. They should also ideally have a certification of sustainable origin. These fuels are easy to handle and supply, but they are more expensive and more susceptible to (European) market prices than firewood, implying additional costs. Another factor to highlight is the difficulty some households have in changing their practices and adapting to new equipment other than a fireplace, and a lack of digital literacy may also contribute to this difficulty. In RNC 2050, the path towards carbon neutrality foresees a significant reduction in the biomass energy percentage.

3. Increase consumption from renewable energy sources

Eliminating fossil fuel consumption and reducing biomass consumption necessarily involves promoting the electrification of consumption by replacing existing equipment with more efficient alternatives that run on electricity. However, a second step towards decarbonisation is to increase energy consumption from renewable sources, whether electricity or heat. In this sense, it will be necessary to reinforce the capacity of the electricity grid at the expense of renewable energies, as well as to promote the installation of systems that directly use renewable energy (*e.g.* solar thermal), the installation of small electricity-producing units in homes for self-consumption, or even the creation of renewable energy communities. Hanke *et al.* (2021) point out that local photovoltaic production projects and energy communities contribute to democratisation and energy autonomy, the promotion of citizen participation and a sense of community spirit, empowerment of the population, increased awareness of the importance of the energy transition and even local economic development.

4. *Increase energy efficiency of domestic equipment*

Finally, replacing equipment and the source of energy consumption must not ignore another of the fundamental pillars of decarbonisation, increasing the efficiency of final energy consumption in homes. This is a determining factor, highlighted in all national strategies on the topic, which makes it possible to guarantee the same or even higher levels of energy services but using less energy. In addition to the passive aspect of the thermal quality of housing construction, which, although a priority, is not the focus of this work, it is necessary to promote the efficiency of the equipment that transforms final energy into useful energy, and it is important to note that more efficient equipment often still has significant investment costs. This increase should not jeopardise the pursuit of the previously mentioned objectives.

6.3.2 Methods

The first step in achieving the set goals was characterising energy access, energy consumption, type of energy services, equipment stock, and dwelling types. Data from the National Statistics Institute (INE) and the Directorate General for Energy and Geology, as well as from the 2020 Household Energy Consumption Survey (INE/DGEG/ADENE, 2021), were used for this purpose.

6.3.2.1 Energy Access and Consumption

The Survey on Energy Consumption in the Domestic Sector (ICESD) data (INE/DGEG/ADENE, 2021) shows that access to electricity is not a barrier to the desired transition since 99.7% of households have a connection to the public grid. Only 2.1% of the population produces electricity from renewable energy sources, although this figure is growing rapidly. Increasing electrification will mean the need to update the electrical infrastructure associated with housing, either by increasing the capacity of the electrical installation in the building itself or by increasing the power requested from the grid, which may require more investment, typically in low voltage.

Another relevant indicator is the type of dwelling, which can be a deciding factor due to how easy it is to implement different solutions since specific technical systems can only be implemented in certain types of buildings and/or may require considerable space for installation. On the other hand, the restrictions found in apartments, for example, could encourage the use of shared solutions or gains in scale through the joint purchase of equipment, as is the case for various passive measures. In 2020, as shown in Figure 6.18, around 46.7% of the population lived in apartments, 36.5% in detached houses and 17% in semi-detached houses (Eurostat, 2023c).

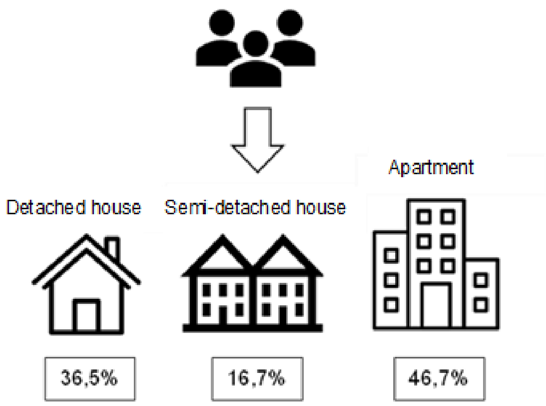

Figure 6.18 - Population distribution by type of dwelling (Adapted from Eurostat, 2023c)

The most important uses of energy are cooking (39.1 per cent), electrical equipment (32.6 per cent) and water heating (14.9 per cent). Space heating accounts for just 9.1 per cent of energy consumption (Figure 6.19). In 2020, Portugal recorded the second lowest percentage of heating in the EU's final energy consumption (Eurostat, 2023b), which may be partially justified by the mild climate and a significant percentage of the population in hidden energy poverty. As described by Meyer *et al.* (2018), this form of energy poverty is defined as excessively low energy expenditure, a strategy by households to avoid energy bills that are incompatible with their budget. This problem is evidenced in the work of Rodrigues *et al.* (2019) and Palma *et al.* (2019). Despite the hot climate in summer, the value recorded for cooling the environment and rates of ownership of cooling equipment are not comparable to other countries with similar climates, such as Greece, Cyprus, Spain and Malta, supporting this hypothesis of insufficient consumption.

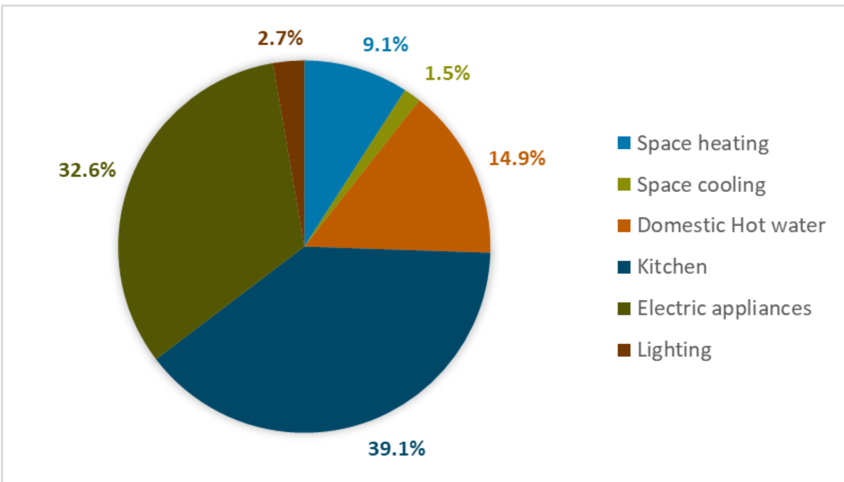

Figure 6.19 - Breakdown of final energy consumption in dwellings by type of use (INE/DGEG/ADENE, 2021)

Analysing the energy uses individually, shown in Table 6.7 and Table 6.8, it can be seen that space heating, water heating and kitchen energy use are still provided with considerable use of fossil fuels, 12%, 80%, and 27%, respectively. Biomass is also a significant energy source, especially for space heating (81%) and cooking (19%). It is, therefore, necessary to examine, individually and in-depth, the origin and form of these consumptions to draw up a strategy to suppress the former (fossil fuels) and substantially reduce the latter (biomass).

Table 6.7 - Breakdown of final energy consumption in dwellings by energy source and end use (INE/DGEG/ADENE, 2021)

Use	Space heating	Space cooling	Domestic hot water	Kitchen uses	Electrical Appliances	Lighting
Electricity	8%	100%	3%	53%	100%	100%
Natural gas	3%	-	36%	10%	-	-
Bottled LPG	3%	-	33%	15%	-	-
Piped LPG	1%	-	7%	2%	-	-
Biomass	81%	-	8%	19%	-	-
Heating gasoil	5%	-	4%	-	-	-
Solar thermal	0%	-	10%	-	-	-
Total	100%	100%	100%	100%	100%	100%

Table 6.8 - Breakdown of final energy consumption in dwellings by type of use and energy source (from INE/DGEG/ADENE, 2021)

Use	Electricity	Natural gas	Bottled LPG	Piped LPG	Biomass	Heating gasoil	Solar thermal
Space heating	4%	6%	6%	6%	69%	58%	3%
Space cooling	2%	-	-	-	-	-	-
Domestic hot water	1%	62%	52%	66%	6%	42%	97%
Kitchen uses	43%	32%	42%	29%	25%	-	-
Electrical appliances	46%	-	-	-	-	-	-
Lighting	4%	-	-	-	-	-	-
Total	100%	100%	100%	100%	100%	100%	100%

It is then necessary to look deeper into every type of energy use to understand which equipment and energy systems are used to provide the energy services and start planning their replacement. Due to data limitations, several assumptions had to be considered to estimate the amount of equipment per energy use and fuel.

Space heating

Looking at space heating, 3% of energy comes from bottled LPG (representing 6% of all bottled LPG), 1% from piped LPG (corresponding to 6% of all piped LPG consumption), 3% from natural gas (6% of total natural gas consumption); 5% from heating oil (58% of all heating oil consumption); and 81% from biomass (69% of all biomass consumption).

There is no disaggregated information directly linking these consumption portions to existing equipment to understand the real importance of each type of equipment in final energy consumption and its potential efficiency. Still, ICESD provides information on the equipment stock by type used in Portuguese homes (Table 6.9). Around 81.6 per cent used space heating equipment, and the percentages in the table correspond to the equipment found in dwellings with some type of equipment, not the total stock of dwellings.

Of all the equipment, the water-fired central heating boiler and the LPG bottle heater are the ones using fossil fuels in their operation, although the boiler could also be wood-fired, as the fuel is not specified. The data doesn't seem to align with the consumption figures, as there is an ownership rate of equipment that uses fossil fuels of approximately 23.6 per cent (given that central heating boilers mainly use this fuel). Only 12 per cent of consumption corresponds to these fuels. This could be due to different consumption habits, as consumers of fuel equipment use the equipment more sporadically, or it could also be due to the ICESD methodology itself, namely the distribution of consumption between space heating and water heating when there is mixed production equipment (*e.g.* boilers). However, the calculations used the figures provided by ICESD, as they are the best estimates available.

Table 6.9 - Number of total units and per dwelling by type of space heating equipment (INE/DGEG/ADENE, 2021)

Type of equipment	Stock		Units per dwelling
	Number of units	%	Unit/dwelling
Open fireplace	543 055	15.0	1.0
Heat recovery fire-place	874 442	24.2	1.0
Stove	339 235	9.3	1.0
Centralised heating boiler	587 305	16.6	1.0
independent electric heating	3 662 607	64.8	1.6
Bottled LPG heater	264 231	7.0	1.1
Solar thermal	5 371	0.2	1.0
Heat pump (only heating)	38 659	1.1	1.0
Air conditioning (both heating and cooling)	1 355 786	19.2	2.0

It should be noted that LPG cylinders are 100% gas, but the same cannot be said of boilers. Using the number of units installed, the efficiencies taken from Palma *et al.* (2019), and the percentages of biomass and fossil fuel consumption of the total consumption figure, a calculation was made to estimate the percentage of boilers using one or the other fuel. The result estimated approximately 38% gas boilers and 62% wood boilers.

Domestic hot water

For DHW, the energy mix is as follows: 33% of the energy comes from bottled LPG (representing 52% of all bottled LPG), 7% from piped LPG (corresponding to 66% of all piped LPG consumption); 36% from natural gas (62% of total natural gas consumption), and 8% from biomass (6% of total biomass consumption). From the ICESD, the stock of equipment by type and percentage of dwellings with some type of water heating equipment, which corresponds to 100 per cent of dwellings where at least one of these systems was found, can be seen in Table 6.10.

Table 6.10 - Number of total units and per dwelling by type of water heating equipment (adapted from INE/DGEG/ADENE, 2021)

Type of equipment	Stock	Dwellings	Units per dwelling
	Number of units	%	Unit/dwelling
Water heater	2 962 254	67.3	1.0
Electric storage water heater	756 816	16.7	1.1
Boiler	717 253	16.7	1.0
Solar thermal	342 629	8.0	1.0
Heat pump	32 884	0.8	1.0
Other	39 589	0.9	1.0

Electricity consumption, at just 3% of total energy consumption, seems to contrast with the rate of ownership of electricity-based equipment, which totals 17.5% -16.7% and 0.8% respectively for electric storage water heaters for DHW heat pumps. This is especially evident when compared to biomass consumption (8% of the total) since only the boiler, present in 16.7% of homes, uses biomass, and this equipment can also run on gas. It's possible that the greater efficiency of electricity-powered equipment partially justifies these figures. Still, it could also result from an ICESD methodological issue in the distribution of ambient and DHW consumption when mixed production equipment such as boilers is present.

Of the equipment found in Portuguese homes, the DWH systems that use fossil fuels are the water heater, the most predominant system, usually running on natural gas or LPG, and the boiler, which can use gas, electricity, heating oil or wood. As far as boilers are concerned, it is considered that they were already connected to the central heating system in 60.4% of dwellings.

Analysing the replacement of DHW equipment faces a significant barrier, just like analysing space heating equipment, which is the lack of data and subsequent lack of knowledge of the number of appliances by fuel used. Only aggregate consumption figures and the number of appliances are known, with a minimal regional breakdown (NUTS1). Electricity accounts for 3 per cent of total DHW consumption. Still, the number of heat pumps in the country that run on electricity almost exclusively represents less than 1 per cent of the total stock, and they are highly efficient devices. It is also assumed that electric storage water heaters are responsible for the remaining electricity. However, the high penetration of this equipment (16.7 per cent) suggests that the contribution of electric storage water heaters to DHW energy consumption is not being adequately considered. Part of the stock may run on natural gas or LPG, although this is a residual percentage. It was also considered that 100 per cent of water heaters without a storage run on gas.

Considering that biomass accounts for 8% of consumption and fossil fuels for 80%, and assuming an efficiency of 88% for water heaters, 75% for diesel or gas boilers, and 70% for biomass, a calculation was made to estimate the number of biomass boilers. It was estimated that 60 per cent of the boilers would run on fossil fuels and the rest on biomass. The easier and cheaper access to biomass also justifies this high percentage of biomass boilers. They are generally used in regions of the country with higher heating needs, so higher average consumption but lower efficiency is expected. Around 60.4 per cent of these boilers are integrated into a central heating system, the replacement of which was already considered in the previous step. This means that it is necessary to replace all the gas water heaters and 39.6% of the boilers, *i.e.* replace 170 419 boilers and 2 962 254 water heaters, totalling 3 132 673 DHW appliances to be replaced.

All biomass boilers are thought to be installed in houses due to the required space. Of the biomass boiler park (40 per cent of all DHW boilers), only 39.6 per cent are considered, as the rest are already mixed systems for DHW and space heating. Therefore, the total number of biomass boilers for DHW is only 113 612.

Kitchen energy uses

In the kitchen, the energy mix is as follows: 15% of the energy comes from bottled LPG (representing 42% of total bottled LPG); 2% from piped LPG (corresponding to 29% of all piped LPG consumption); 10% from natural gas (32% of total natural gas consumption), and 19% from biomass (25% of total biomass consumption). From ICESD, the stock of equipment by type of equipment and the percentage of dwellings with some type of kitchen equipment are shown in Table 6.11.

Table 6.11 - Number of total units and per dwelling per type of food preparation unit (INE/DGEG/ADENE, 2021)

Type of equipment	Stock	Dwellings	Units per dwelling
	Number of units	%	Unit/dwelling
Cooker with oven	2 353 429	52.0	1.1
Hob (cooker without oven)	2 310 450	51.6	1.0
Independent oven	2 326 200	51.6	1.1
Kitchen robot	626 423	13.9	1.1
Stove, grill, barbecue	2 044 498	45.0	1.1
Fireplace	321 373	7.2	1.0

As with other types of equipment, there is no information on the number of pieces of equipment by type and energy source jointly. There is also no information on the energy efficiency of the equipment. However, it is safe to say that kitchen robots are supplied exclusively by electricity and fireplaces by biomass. Cookers, hobs, grills and barbecues can run on electricity, gas or biomass. It is considered that stoves, grills and barbecues are used considerably more infrequently and mainly in the summer season and are therefore not considered in the calculation. The focus then turns to cookers, hobs and ovens, which comprise 6 990 079 pieces of equipment. It was considered that free-standing hobs and ovens use gas or electricity. Still, given the considerable percentage in the energy mix, it was assumed that cookers could use gas, electricity or biomass. A calculation was then made to estimate the percentage of these appliances that use one or other energy source. To do this, the percentages of total energy consumption per energy source, the number of appliances and the energy efficiency values per type of appliance were used. A higher energy efficiency value of 80 per cent was considered for electric appliances and 50 per cent for gas appliances, based on data from the RNC 2050. Wood-burning cookers were given a lower efficiency of 40 per cent. It was therefore estimated that for cookers with ovens, 50 per cent run on electricity, 25 per cent on gas and a further 25 per cent on biomass. For free-standing hobs and ovens, it was estimated that 75 per cent run on electricity and 25 per cent on gas.

Space cooling

Table 6.12 shows the range of equipment used for space cooling. Since space cooling is provided exclusively by electricity, potential interventions involve increasing the energy efficiency of the equipment rather than replacing the energy source.

Table 6.12 - Number of total units per dwelling by type of space cooling or ventilation equipment (INE/DGEG/ADENE, 2021)

Type of equipment	Stock	Dwellings	Units per dwelling
	Number of units	%	Unit/dwelling
Air conditioning (only space cooling, fixed or mobile)	141 292	7.3	1.4
Ventilator	1 083 436	58.8	1.3
Air conditioning (space heating and cooling heat pump)	1 278 618	45.4	2.0

Electrical Equipment and Lighting

Since electrical equipment and lighting are 100 per cent powered by electricity, the potential replacement of equipment is only aimed at increasing energy efficiency. The stock of electrical and lighting equipment can be seen in Table 6.13.

Table 6.13 - Number of total equipment and per dwelling by type of electrical equipment (INE/DGEG/ADENE, 2021)

Type of equipment	Stock	Dwellings	Units per dwelling
	Number of units	%	Unit/dwelling
Microwave oven	3 824 163	88.0	1.0
Exhaustor/extrator	3 039 689	69.1	1.0
Refrigerator with freezer	2 402 100	51.8	1.1
Refrigerator without freezer	360 174	7.8	1.1
Combined refrigerator	2 078 886	46.7	1.0
Chest freezer	2 494 239	54.4	1.1
Dishwasher	2 548 109	59.2	1.0
Washing machine and dryer	219 216	5.0	1.0
Washing machine	4 062 385	93.5	1.0
Dryer	1 036 090	24.2	1.0
Vacuum cleaner	3 863 288	84.5	1.1
Central vacuum	174 642	4.1	1.0
Iron	3 974 776	91.3	1.0
Ironing machine	72 512	1.7	1.0
Dehumidifier	1 233 067	26.1	1.1

No information is available on the efficiency of electrical equipment and household appliances, making it more challenging to estimate the investment needed to replace less efficient equipment. Otherwise, we could end up with estimates that are far removed from reality and promote unnecessary equipment replacement, which would be a heavy and pointless use of resources. Regarding lighting, the designation of the different solutions makes it possible to gauge if a particular solution has higher or lower energy efficiency than others.

6.3.2.2 Market inventory of measures

To meet the challenges, it is important to consider the most efficient alternatives on the market that promote electrification, the use of energy from renewable sources, and energy efficiency. An inventory of potential solutions was conducted (Annex B9), considering their most relevant characteristics and prices. The costs vary according to several factors, depending on the equipment and typical installation, such as power and efficiency, accumulation capacity, installation difficulty, and the need for building work.

The main references are speciality shops, such as air conditioning shops (*i.e.* Enerclima, Sanitop, Macolis), more general shops (*i.e.* Worten, Leroy Merlin), and the Portuguese shop aggregator 'Kuantocusta'. In terms of installation, average installation costs offered as additional services by these same shops were taken into account, and in some cases (*e.g.* DHW heat pumps), additional civil construction costs were considered. The costs relate to the application of the equipment in existing buildings and do not consider the installation of auxiliary systems, such as heat distribution systems (wall radiators, underfloor heating, associated distribution network), which are assumed to be already installed. It's important to bear in mind that this cost analysis has been carried out in line with the current economic situation, which has high inflation figures. The investments calculated are a snapshot of the current situation and do not take into account the time lag required for large-scale technological transformation and adoption, nor do they take into account discount rates or future price trends resulting from technological development and the democratisation of the technologies considered.

6.3.2.3 Testing different scenarios

The vision of decarbonised energy consumption and increased energy efficiency can be achieved by replacing the current energy-consuming equipment stock with different types of equipment with varying energy sources, energy conversion efficiencies and market. The same energy service can be provided by a system that directly converts solar energy into heat and another system that uses electricity for the same purpose. The appropriate equipment selection depends on several factors, including, inter alia, the household preference, type of dwelling, location and public infrastructure available, and available budget for investment. Aiming to capture a range of possibilities for equipment replacement and accommodate competing solutions that present distinct advantages, different scenarios for each energy service are assessed to estimate a range of investment costs necessary to replace the existing stock.

Moreover, energy justice concerns should be considered when rolling out new equipment. Due to particularities and inequalities in energy access and provision, efforts to foster energy transition can increase vulnerability and inequality. This is especially true for energy-poor groups and other more vulnerable consumers. In Portugal, biomass consumption has been identified as a cultural practice to cope with EP (Stojilovska *et al.*, 2023). Therefore, different scenarios are also proposed to account for this particularity of energy consumption in the Portuguese domestic sector, with provisions for protecting vulnerable biomass consumers while assessing the required efforts to significantly decrease country-level biomass use for energy services.

6.3.3 Results

6.3.3.1 Space Heating

On the assumption that boilers are central heating systems, they should be replaced by other central heating systems. Heat pumps are highlighted in the various strategic documents as a viable alternative for providing heat more efficiently. In the particular case of houses, the multi-function heat pump, supported by a photovoltaic system, is a solution with considerable initial investment. Still, it ensures low central heating costs and can heat domestic water for bathing. Around 223 176 boilers would need to be replaced, with an average cost per home of €8 900, which would mean a total investment of around €1 986 million.

Regarding LPG heaters, since they are mobile systems that only heat one room, households sometimes have more than one unit of this type in their home, and they can be present in different housing types. An efficient replacement solution could be the multi-split air-to-air heat pump, with two units and an average cost per home of €1 800. Replacing the current 264 231 units would involve a total investment of around €476M.

Analysing the existing solutions, the same solutions considered for fossil fuels again appear advantageous for biomass reduction. One response to consider would be to end the use of biomass for space heating in all homes, and this would require replacing the entire stock of biomass equipment, which consists of 2 120 861 units. In the case of biomass boilers, these can be replaced by a multi-function heat pump, and, for the remaining equipment (fireplaces and stoves), two-unit multi-split heat pumps are indicated at the same costs as shown above. This would mean an average investment in new equipment of €3 241M and €3 162M, respectively.

On the other hand, certain segments of the population find it harder to adapt to new equipment and realities, particularly the elderly. Replacing fireplaces with heat pumps would also require investment in information and support campaigns for these groups so that this transition occurs fairly and harmoniously. As already mentioned, they will even be able to use biomass free of charge, thus helping to reduce their vulnerability. There is no data to characterise the consumption and availability of biomass or to identify the conditions of the households that consume it. It is assumed that biomass equipment is mainly used in predominantly rural and medium-urban areas, where the population over 65 is around 712 052 (INE, 2020). According to INE data for 2020, Portugal's average household occupancy rate is 2.49. Thus, this population corresponds to 285 965 dwellings, equivalent to the same number of appliances. Prioritising the replacement of open fireplaces, the least efficient equipment, with stoves installed on the same site, the investment needed to purchase the same number of stoves, in this case, wood-fired, would be around €472 M (average cost per dwelling of €1 650). On top of this, there would be the cost of investing in multi-function, air-to-air heat pumps for the remaining homes.

Another possible approach would be to identify households that depend on biomass and are in economic deprivation or energy poverty. In this way, the INE indicator 'Rate of over-burdened housing expenditure' can be used, corresponding to households whose burden of expenditure associated with housing is greater than 40 per cent. This rate is 5.1% and 4.1%, respectively, in Medium Urban Areas and Predominantly Rural Areas, totalling 32 489 people and 13 048 dwellings and equipment units to be replaced. This stock replacement results in an investment requirement of around 22 M€. In the last two options, support would not be necessary for households that would continue to use a biomass system as the system would function similarly.

To increase energy efficiency, a commitment to replacing less efficient equipment, such as freestanding electric heaters, could significantly contribute to its fulfilment in the domestic sector, especially given that these heaters are already the most widely used equipment for space heating. In some homes, there is more than one piece of equipment of this type, which is why the replacement of all this equipment was not considered, but rather the installation of an alternative piece of equipment per home, which replaces all the existing electric heaters in the house. The number of independent electric heaters per dwelling was used to calculate the number of dwellings to be replaced, and a total number of 2 289 129 was determined. The two-unit multi-split air-to-air heat pump was considered the most favourable option, resulting in a total investment of €4 120 million. This figure may be overestimated since homes can install independent electric heaters and air-to-air heat pumps. The results are summarised in Table 6.14.

Table 6.14 - Summary of equipment stock and investment needed to achieve the objectives set out in the path towards decarbonising space heating.

Space Heating	Eliminate fossil fuels 	Reduce biomass consumption 	Increase energy efficiency 

Scenario 1	New stock: • 223 thousand multi-function heat pumps • 264 thousand air-to-air heat pumps Needed Investment: 2 462 M€	New stock: • 364 thousand multi-function heat pumps • 1.76 million air-to-air heat pumps Needed Investment: 6 403 M€	New stock: • 2.2 million air-to-air heat pumps Needed Investment: 4 120 M€
Scenario 2	-	New stock: • 364 thousand multi-function heat pumps • 1.47 million air-to-air heat pumps • 286 thousand heat recovery systems Needed Investment: 6 360 M€	-
Scenario 3	-	New stock: • 364 thousand multi-function heat pumps • 1.74 million air-to-air heat pumps • 13 thousand heat recovery systems Needed Investment: 6 401 M€	-

6.3.3.2 Domestic Hot Water

Two solutions appear to be the most favourable for house typologies. The first option is solar thermal, with an electrical resistance backup system, which ensures safe and consistent DHW production based directly on renewable energy all year round. These panels are tested for standard irradiation conditions of 1 000 kWh/m^2 and, in Portugal, given that solar irradiation exceeds 1 400 kWh/m^2 (Global Solar Atlas, 2023) in all regions of the country, these panels may have an acceptable overall performance throughout the country. However, in winter, a backup system may be necessary. The high adoption of these systems is in line with the future scenarios of the RNC 2050, which estimated that 90 per cent of DHW energy would come from solar thermal, with the advantage of not needing interior space in the home, namely for thermosiphon systems. However, this system has limitations in operating regulation and maintenance difficulties, which, if not carried out, significantly reduce the system's performance.

If it is an apartment, considering the added difficulties in installing solar thermal, the hybrid electric storage water heater option (an electric storage water heater that is 50 per cent more efficient by combining resistance with a heat pump) will be the easiest solution to integrate, as it doesn't require considerable technical space. Considering that some current heat pump options require a space that may be available in part of the apartment, this option is also considered for this typology.

Since it is not possible to check which type of house has this equipment installed, the same proportion of houses per type was considered for the replacement of gas water heaters: 53.3% houses and 46.7% apartments. For the apartments, it was assumed that 40 per cent would be replaced by a DHW heat pump, with an average cost of €2 400, and the remaining 60 per cent by hybrid electric storage water heaters, costing €1 150. For the houses, the gas water heaters are replaced by solar thermal systems. It has been assumed that all the boilers are installed in houses due to the space they occupy, so they are replaced by solar thermal, costing €3 750 per unit. Thus, a total investment of €8 842 million will be needed to install 1 749 300 (170 419 + 1 578 881) solar thermal systems, 830 024 hybrid electric storage water heaters and 553 349 DHW heat pumps (Scenario 1).

Another solution to consider as an alternative to solar thermal, especially in homes with more space for a technical area, is the installation of DHW heat pumps supported by a photovoltaic system. In this case, in addition to the system's lower maintenance requirements, it is possible to make better use of the renewable potential, given the surplus 'thermal' energy from the solar thermal system, which, in the case of photovoltaics, can be injected into the grid or used for other purposes in the house. It is, however, a more expensive solution, costing around €4 600 per home. This scenario (Scenario 2) considers the installation of 1 749 301 DHW heat pumps with photovoltaic support, 830 000 hybrid electric storage water heaters and 553 349 DHW heat pumps.

A mixed option (Scenario 3) between the two already listed would be to consider installing solar thermal in 50 per cent of the houses, and DHW heat pumps with photovoltaics in the remaining 50 per cent. Ideally, a preliminary analysis would be conducted to identify which houses would have the most suitable characteristics for either solution. Under these circumstances, it would then be necessary to install 874 650 solar thermal systems and the same number of DHW heat pumps with photovoltaic support in houses, as well as 830 000 hybrid electric storage water heaters and 553 349 DHW heat pumps in apartments.

Targeting energy efficiency increase, there is a considerable stock of older electric water heaters, representing untapped potential in increasing energy efficiency and renewable energy in DHW. This potential is mainly associated with the house typology since solutions such as heat pumps and solar thermal can be installed in this type of dwelling. In apartment types, there is also some potential for improving energy efficiency by replacing them with hybrid electric storage water heaters and DHW heat pumps in a 60/40 ratio. A mixed solution is therefore proposed, in which the water heaters in houses are replaced 50 per cent by solar thermal systems and 50 per cent by heat pumps supported by photovoltaic panels. The proportion of water heaters in the typologies is considered to be identical to the proportion of dwellings per typology, as was done in previous answers.

Taking into account the potentially important role of biomass in combating EP in some areas of Portugal, and given the lack of data to characterise biomass consumers in the country, a methodology similar to that used for space heating could be applied to identify the percentage of the population that is possibly most vulnerable and enjoys free firewood, opting in these cases to replace the existing equipment with more efficient ones, without changing the energy source. As such, 13 048 units would be replaced by more efficient biomass boilers (€4 150 per unit), and the remaining 100 564 would be replaced by solar thermal systems (Scenario 1). The investment would be 431 M€ (54 M€ + 377 M€). Another possibility (Scenario 2) would be to install DHW heat pumps with solar photovoltaics, as previously tested. This option would result in a slightly higher investment of 517 M€ (54 M€ + 463 M€). As in the previous exercise for fossil fuels, a mixed solution could also be tested (Scenario 3), with 50 per cent solar thermal and 50 per cent solar photovoltaic heat pumps, reaching a total investment of 473 M€. An argument can also be made in favour of replacing all boilers with solar thermal systems, as they work independently and require no operational expertise, given the considerable solar potential in various regions of the country (investment of 426 M€). The same can be tested for heat pumps with solar photovoltaic support (523 M€), and the mixed solution (474 M€). The summary of equipment stock and investment needed for decarbonising domestic hot water is displayed in Table 6.15.

Table 6.15 - Summary of equipment stock and investment needed to achieve the objectives set out in the path towards decarbonising domestic hot water.

Domestic hot water	Eliminate fossil fuels	Reduce biomass consumption	Increase energy efficiency
Scenario 1	New stock: • 1.75 million solar thermal systems • 830 thousand hybrid electric storage water heater • 553 thousand DHW heat pumps Needed Investment: 8 842 M€	New stock: • 13 thousand new biomass boilers • 100 thousand solar thermal systems Needed Investment: 431 M€	New stock: • 202 thousand DHW heat pumps with solar photovoltaic support in houses • 202 thousand solar thermal systems in houses in houses • 212 thousand hybrid electric storage water heater in apartments • 141 thousand DHW heat pumps in apartments Needed Investment: 2 267 M€

Scenario 2	New stock: • 1.75 million DHW heat pump with solar photovoltaic support • 830 hybrid electric storage water heater • thousand multi-function heat pumps • 553 thousand DHW heat pumps Needed Investment: 10 329 M€	New stock: • 13 thousand new biomass boilers • 100 thousand DHW heat pump with solar photovoltaic support Needed Investment: 517 M€	-
Scenario 3	New stock: • 875 thousand DHW heat pump with solar photovoltaic support in houses • 875 thousand solar thermal systems in houses • 830 hybrid electric storage water heater in apartments • 553 thousand DHW heat pumps in apartments Needed Investment: 9 586 M€	New stock: • 13 thousand new biomass boilers • 50 thousand solar thermal systems • 50 thousand DHW heat pump with solar photovoltaic support • Needed Investment: 474 M€	-

6.3.3.3 Kitchen Energy Uses

According to the calculations, the stock of cookers with gas ovens (natural gas or LPG) is 588 357 units, 577 613 hobs, and 581 550 free-standing ovens. They will necessarily be replaced by equivalent equipment powered by electricity, namely an electric hob and oven set (average price per home €800), an electric induction hob (average price per home €350) and an electric oven (average cost per home €450). Betting on similar alternatives that run on electricity makes it possible to take important steps towards the electrification of consumption in the kitchen, with other benefits such as increased safety in the home due to the elimination of the risk of gas leaks. The operation of this equipment is not radically different, but consideration should still be given to supporting households with greater difficulties in terms of literacy to facilitate adaptation. In this way, consideration is given to replacing hobs with a gas oven with a combination induction hob and electric oven, gas hobs with induction hobs and freestanding gas ovens with electric ovens. Replacing this equipment with an electric solution with a higher efficiency level represents an investment of 935 M€.

Regarding biomass equipment, there is a stock of 588 357 cookers with ovens and 321 373 fireplaces. The logic applied to space heating and DHW equipment is valid for this equipment in terms of identifying vulnerable households and replacing them with more efficient biomass equipment. In this way and prioritising the replacement of fireplaces because they are the least efficient and most polluting equipment, the two figures used for vulnerable households can be considered: 285 965 dwellings for the elderly population (Scenario 1) and 13 048 dwellings for the population with a high housing cost burden (Scenario 2), for medium-sized urban and rural areas. Thus, fireplaces would be replaced by more efficient biomass cookers with better exhaust systems (average cost €1 300), in the same number as these households, and the remaining equipment would be replaced by the induction hob and electric oven combination.

Another scenario (Scenario 3), previously considered for other energy uses, would be the total replacement of all biomass equipment, cookers and fireplaces. This would mean replacing the entire stock of 909 730 elements with induction hob and electric oven units. The summary of equipment stock and investment needed for decarbonising domestic hot water is displayed in Table 6.16.

Table 6.16 - Summary of equipment stock and investment needed to achieve the objectives set out in the path towards decarbonisation for kitchen energy uses.

Domestic hot water	Eliminate fossil fuels 	Reduce biomass consumption 
Scenario 1	New stock: • 588 thousand electric hob+oven solar set • 578 thousand induction hobs • 582 thousand freestanding electric ovens Needed Investment: 935 M€	New stock: • 624 thousand electric hob+oven solar set • 286 thousand new biomass ovens Needed Investment: 871 M€
Scenario 2	-	New stock: • 897 thousand electric hob+oven solar set • 13 thousand new biomass oven Needed Investment: 734 M€

Scenario 3	-	New stock: • 910 thousand electric hob+oven solar set Needed Investment: 728 M€

6.3.3.4 Space Cooling

The previous steps consider installing a considerable number of heat pumps, which would automatically increase the penetration rate of equipment that produces cold air for cooling to at least 60 per cent, with a potential maximum value of close to 100 per cent. This is a considerable increase from the current 32.7 per cent of dwellings in which some cooling equipment is used. This means that a large proportion of homes will have efficient electrical cooling equipment. It is also arguable that some households that use fans and ventilators may not have a heat pump installed in their accommodation, which could potentially have consequences in terms of thermal comfort in the summer. These fans are less effective in terms of producing cool air and, according to the WHO, they relieve the sensation of heat. They do not prevent heat-related illnesses when temperatures rise above 35°C (WHO, 2018).

On the other hand, these devices have low power ratings, lower than heat pumps or air conditioners, so replacing them will not result in energy efficiency gains. Therefore, no efficiency improvement goal is formulated regarding this energy end-use. A potential step to be taken would be to identify these dwellings and collect data to understand whether they are, in fact, in a situation of EP or whether their dwellings, due to their construction quality and climate zone, ensure satisfactory energy performance in summer, without creating the need for active cooling equipment.

6.3.3.5 Electrical Equipment and Lighting

LED bulbs are the most efficient solution on the market, with an average cost of €3 per unit, so the goal is to replace all other types of bulbs, which implies replacing a total of 22 158 810 bulbs and an investment of approximately €67 million (Table 6.17).

Table 6.17 - Summary of equipment stock and investment needed to achieve the objectives set out in the path towards decarbonising electrical equipment and lighting.

Lighting	Increase energy efficiency 

Scenario 1	New stock: • 22 million LED bulbs Needed Investment: 67 M€

6.3.4 Discussion and conclusions

After carrying out an individual analysis of the different uses of energy in the domestic sector and the effort and investment needed to replace equipment to decarbonise final energy consumption, it is now necessary to take stock of all the information obtained and understand the overall effort that will be needed to achieve all the objectives outlined. The investment required to eradicate fossil fuels from household consumption is between 12.2 and 14.2 billion euros. Reducing biomass consumption in homes would entail an investment between 7.5 and 7.8 billion euros. Finally, to increase energy efficiency, investment stands at around 6.4 billion euros. It is important to mention that there may be some overlap between equipment and investment, leading to overestimation, especially in the case of energy efficiency, due to the quality of the data used as a basis for the study, as well as the assumptions made in the calculations due to the lack of intersection between some of the data used.

Therefore, the total estimated investment is between 26.2 and 28.5 billion euros, 11% and 12%, respectively, of the national gross domestic product in 2022 (239 billion euros). It amounts to a investment cost between approximately 6315 and 6870 euros per home. This figure illustrates the considerable financial effort needed to decarbonise final energy consumption in homes, considering the characteristics of the population and buildings and the hardships faced by the most vulnerable segments of the population. The current investment would need to increase 87-fold to match the required investment, considering the 300 million euros made available until 2025 for the residential sector. These figures represent the investment in the light of the current situation, considering the challenging economic context of high inflation and not considering discount rates and future price developments that could reduce the amount of the investment. In the estimate that comes closest to the one made in this study, the LTRS calculated a value of 45.8 billion euros for the replacement of the heating equipment in the housing stock with heat pumps, maximum photovoltaic production, the replacement of all lighting with LEDs, and a high percentage (50 per cent) of DHW energy needs supplied by solar thermal in 2050. Without photovoltaics, the figure is 26.9 billion, very similar to the estimate.

The renovation of buildings still represents a more considerable investment of 40.4 billion euros, according to LTRS's estimate, rising to 71.7 billion according to the study by Palma *et al.* (2022). This figure is more than double the investment needed for the active component of buildings relating to their equipment. It is important to note that investing in the renovation of the passive component of the building could reduce the need to invest in equipment since renovation results in better energy performance, *i.e.* lower energy needs. Both the renovation of the passive component and the decarbonisation of the active component require significant investments. Although it is important to consider both in the sector's transformation strategy, priority should be given to the renovation of buildings since it is a solution that acts on the causes of the problem, namely the reduction of energy needs with various positive externalities. It is the most sustainable and long-lasting solution, as it offers greater resilience to buildings and their occupants in terms of the impacts of potential external circumstances, be they economic, such as military conflicts and energy crises, or even climatic, in terms of extreme phenomena and the consequences of climate change.

Oğuz (2023) estimated a cost of $130B dollars heat pump rollout and $140B for renewable heating in buildings for the United States. The cost of increasing EE and decarbonising homes in the United Kingdom only considering through retrofit was estimated at between £330B and £524B according to two different analysis (Lowe, 2021). Minding the differences in housing stock sizes and regional costs, as well as currency, these values align with the estimated values in this study. The Climate Change Committee estimated a necessary investment of £250 billion to fully decarbonise a home in the UK, for a total cost of heat decarbonisation for each home of under £10 000, which is in the same order of magnitude as the decarbonisation cost for one Portuguese home (under €6 900).

Considering the current programmes and amounts available to leverage the objectives of renovating buildings, increasing energy efficiency and integrating renewable energy into homes, and their mismatch with the range of estimated investment values, a different strategy needs to be developed to achieve the desired transformation within the next few years. This strategy should focus on a diversification approach, where the necessary funds will be obtained from different forms and sources. As mentioned in the National Long-Term Strategy for Combating Energy Poverty, encouragement through non-reimbursable public funds is indispensable for leveraging this process. In particular, public programmes must play an essential role in ensuring the inclusion of the most vulnerable households, guaranteeing greater fairness in the incentive strategy.

Different levels of vulnerability result in different support needs, so an important step is the development of programmes that can identify the various profiles of households and adapt the type and magnitude of support according to need. In the current situation, the funds available are insufficient to respond to the urgent need to transform the energy system and decarbonise consumption, so a substantial increase in the availability of these funds would be significant, especially given the population's very favourable level of adherence to at least one of the programmes implemented.

The EP strategy also emphasises the need to create financial mechanisms that allow households to access private sources of finance through surcharges, interest-free loans or subsidies to carry out energy efficiency actions in their homes. Still, this type of mechanism has already been tested and implemented in the country, such as the 'Efficient Home' programme, without success. Possible reasons behind this lack of adoption were the excessively high interest rates charged by the programme, the population's lack of trust in the programme's promoters, including the banks, and financial difficulties that resulted in an unwillingness to invest.

On the other hand, innovative means of financing such as crowdfunding, cooperatives and green bonds, especially when launched by public entities, could play an important role in funding decarbonisation, as they are more supportive and inclusive mechanisms based on a more community spirit and contribute to improving the quality of life of the population, with a potential direct impact on the area or region where they live. It would be useful to survey the various types of mechanisms and programmes implemented by European countries, identify and analyse the practices that have contributed to the success or failure of these programmes, and transfer and replicate successful practices to the Portuguese context.

One point is clear. Including the population, especially the different groups of potential beneficiaries and other social actors, in designing support programmes and incentives in a collaborative and co-creation process is crucial to building more effective and inclusive programmes. Collaborations between a municipality and an energy co-operative, allowing the most vulnerable consumers to enjoy lower energy prices while simultaneously acquiring shares in the co-operative; energy communities based in public buildings for sharing energy with vulnerable consumers; and one-stop shops run by a municipality with the participation of the local energy association, to inform and help consumers to renovate their homes (Fregonese *et al.*, 2023) are examples of collaborative and inclusive public initiative models with potential for replication, not only to reduce the burden of energy bills and improve the performance and energy efficiency of homes but also to empower people in energy poverty and in general, through information and increased ownership and control over means of energy production, with a real impact on people's quality of life and a real contribution to the transformation of the sector.

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7

EXAMINING ENERGY POVERTY DIAGNOSIS IN CURRENT PUBLIC STRATEGY AND POLICY

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Comparative Analysis of Energy Poverty Definition and Measurement in Portugal and Spain

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 structured 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.

7.1 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 MSs 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 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 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 MSs (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 RQ 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.

7.2 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).

7.3 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 structured quasi-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 Figure 7.1.

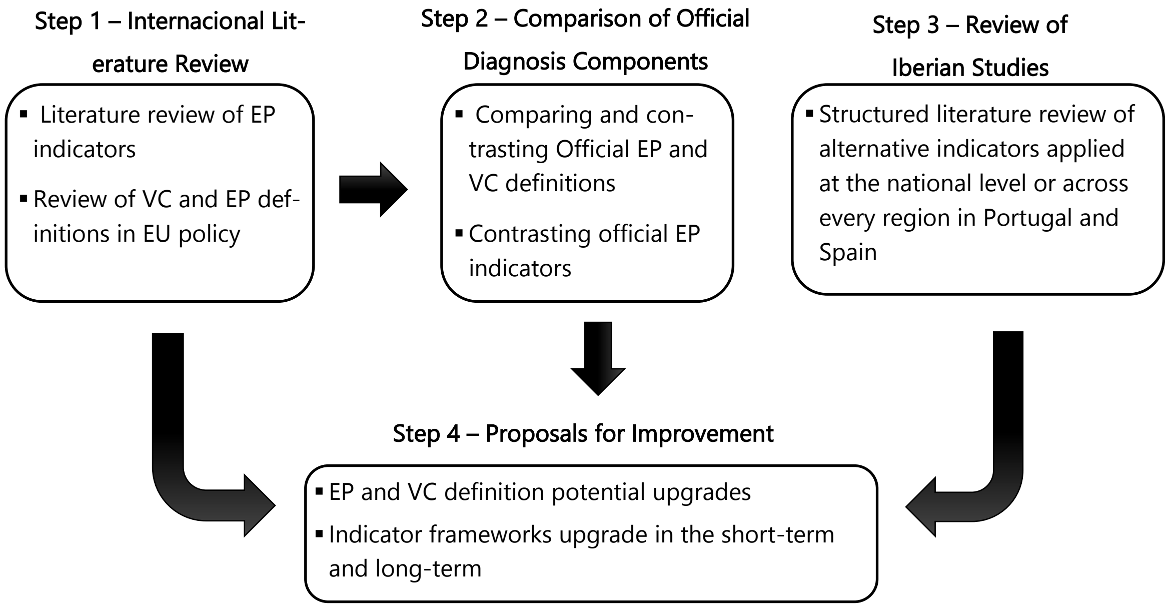

Figure 7.1 - Methodologic framework

7.3.1 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.

7.3.2 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.

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.

7.3.3 Structured review of alternative indicators

A structured 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 systematic 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 Figure 7.2. By focusing on existing data and expertise in the Iberian context, this structured review aims to contribute to drawing policy recommendations that can be adopted in the shorter term.

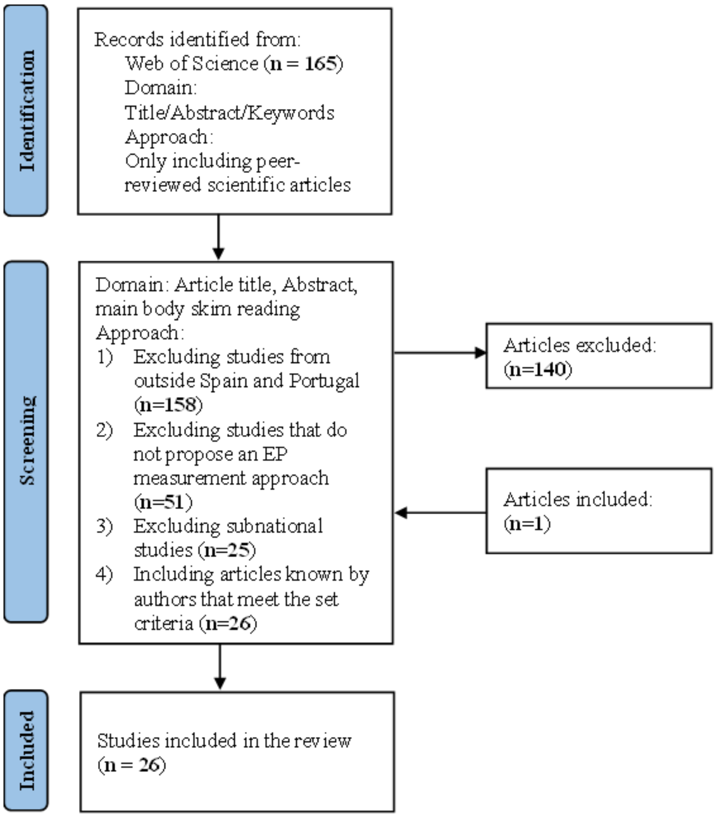

Figure 7.2 - Structured literature review framework.

7.3.4 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 structured 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.

7.4 Results and discussion

7.4.1 Literature review

7.4.1.1 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. 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 Annex C1. 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.

7.4.1.2 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.

7.4.2 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 measurement is displayed in Annex C2. 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 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 Smiech, 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.

7.4.3 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. Casta˜no-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.

7.5 National strategy diagnosis

7.5.1 Official definitions

The long-term national strategy for combating EP 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.

7.5.2 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 7.1 and 7.2 display the official indicators chosen in the two countries.

Table 7.1 - Official energy poverty indicators in Spain

Importance	Approach	Indicator	Object of measurement	Dimensions	Type of Energy Poverty	Outcome	Annual update
Primary	Quantitative	2M	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 7.2 - Official energy poverty indicators in Portugal

Importance	Approach	Indicator	Object of measurement	Dimensions	Type of Energy Poverty	Outcome	Annual update
Main	Quantitative	10% of income spend on energy	Consequences	Economic	Measured	Extent	No
		population in situation of poverty that spend 10% of 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, or rot	Consequences	Infrastructural	Perceived	Extent	Yes
		Inability to keep home comfortably cool	Consequences	Economic; Infrastructural	Perceived	Extent	No

	Mixed	Population in situation of poverty not able to maintain the house adequately warm	Consequences	Economic, infra-structural	Measured and Perceived	Extent	Yes
		Population in situation of poverty living in a home with leakage, dampness, or rot	Consequences	Economic, infra-structural	Measured and Perceived	Extent	Yes
Comple-mentary	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	Sociodemo-graphic	Vulnerability level	Magni-tude	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 Con-sequences	Economic	Measured and Perceived	Extent	Yes

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 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.

7.5.3 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. Annex C3 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 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 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.

7.6 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.

7.6.1 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 WHO. 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 7.3.

Table 7.3 - Potential improvements in EP and VC official definitions.

Potential Improvements	Portugal	Spain
Including the notion of "difficulty" in accessing energy services	x	x
Broadening the 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
Acknowledge 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

7.6.2 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 Pan˜ao (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 7.4 and Table 7.5.

Table 7.4 - 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 and energy prices and people from social vulnerable groups as contextual indicators	x	x	Census
Include regional variabilities in indicator estimation	x	-	Census, HBS, SILC, EPCs

Table 7.5 - 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 between 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 update 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 frequency of monitoring	Additional resources to collect data for HBS or new dedicated survey with intersectional indicators yearly

7.7 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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8

General Discussion and Conclusions

Energy poverty is one of the main social scourges the world population faces nowadays, affecting hundreds of millions worldwide. It negatively impacts people's daily lives and basic capabilities, preventing them from maintaining good health and general well-being. It is also detrimental to their social relations and participation in society, work, education, and overall social reproduction. This condition takes different forms and configurations due to its complex multidimensional causes, translating into diverse expressions across geographies.

In the European Union, energy poverty is primarily manifested in the difficulty in affording levels of energy services that are necessary for an adequate standard of living. It is a common affliction for millions of European people. Still, it has an asymmetrical distribution across the territory, mainly affecting populations in less affluent peripheric countries, such as southern European countries. Portugal is one of the most affected countries, with high rates of the population reporting to be unable to maintain adequate temperatures in their homes both in winter and summer, living in deteriorating low-efficient homes, and having limited economic resources to face the still high energy prices, which are identified as the leading causes determining this condition. The country also registers high rates of associated health problems, which lead to high excess mortality rates in the winter and summer periods and during extreme weather events. Public awareness of energy poverty in the EU and in Portugal has arguably risen as policymakers increasingly identify its mitigation as a political priority and integrate it into energy and climate policy strategies and legislative frameworks. Periods of crisis, such as the COVID-19 pandemic and the energy crisis triggered by Russia's invasion of Ukraine, have contributed to exacerbating households' vulnerability and energy affordability problems while also sparking the deployment of relevant funding for support and mitigation policies. Despite growing political commitment and fundraising towards mitigation action, in the aftermath of crises, energy poverty levels remain high, and 2023 saw a rise in the leading indicators used to measure it at the EU and national levels.

Several causes might be behind the ineffectiveness or limited success of mitigation strategies and policies. One of them is arguably diagnosis, which impacts the understanding of the nature, scope, and dimension of the problem, as well as the impact evaluation of measures designed to address it. Diagnosis is considered a cornerstone of successful energy poverty mitigation strategies or projects. It should be developed at different spatial scales for a more comprehensive and detailed approach. It is precisely in this subject that this thesis sets out to provide its contribution. Drawing on the work and methods developed by Palma *et al.* (2019) and Gouveia *et al.* (2019), this thesis took these studies as the departure point to further delve into the study of energy poverty in Portugal, aiming to increase knowledge and explore different avenues regarding energy poverty diagnosis and mitigation across different spatial scales. The specific goals were to understand and analyse the current practice of energy poverty metrology from the national to the local spatial scale, to zoom in on the energy poverty measurement spatial scale in the country, to assess the regional potential and cost of different measures to improve buildings' energy efficiency and contribute to energy poverty mitigation; and to use the acquired knowledge on energy poverty definition and measurement to analyse and propose improvements to the recently published national strategy for combating energy poverty. These goals were formulated as four different RQs. A diverse multilevel approach combining various methods was employed to address and answer the defined questions.

8.1 Answering the Research Questions

It is important to note that the answer to every question reflects the author's entry point, *i.e.*, the author's research paradigms and worldview, which translates into the approach, the choice of methods, and the underlying theories. Hence, a different approach could yield different outcomes, which would still be valid. It is relevant to examine the RQs and the contribution of this thesis to respond to each.

Aiming to delve into energy poverty measurement at multiscale and particularly to identify and analyse the data, metrics and approaches employed for this purpose, the first RQ was formulated as follows:

• RQ1: What are the most adequate indicators to describe the impact of the different causes and drivers of energy poverty from national to local scale?

The first RQ defines the foundation for this thesis, as indicators are the cornerstone of every research task developed herein. Chapter 2, Chapter 4 and part of Chapter 7 focus on different literature review processes *vis-a-vis* EP metrology; thus, they are drawn upon to address this question. Chapter 2 and Chapter 7 set the scene regarding the types of energy poverty measurement - expenditure-based, consensual-based, direct measurements, supporting indicators, and composite indicators, drawing on critical work such as the research of Rademaekers *et al.* (2016), Thomson *et al.*, (2017), Tirado-Herrero (2017). It outlines the different advantages and shortcomings of every type of indicator. While every type can be useful and provide relevant information to explain energy poverty, this does not mean that the same indicator or set of indicators should be transversally applied to every region or population. The configuration of energy poverty is diverse and dynamic, thus potentially requiring using a different set of indicators to study the specific expression of the problem across time and scales.

Chapter 7 also provides valuable inputs to answer this query, stemming from a narrative literature review of scientific articles that conducted indicator reviews or indicator analysis to identify the best practices and shortcomings. Several relevant practices regarding the selection of indicators and the measurement process were identified. Pelz *et al.* (2018) make an important statement - that the main purpose of a metric is ultimately to inform policy in assisting the population in need. Most authors agree that a multidimensional framework capturing the different causes, effects and types of energy poverty is more likely to provide a comprehensive picture of this condition despite potential difficulties in operationalisation (Pelz *et al.*, 2018) and trade-offs between simplicity and communicability, and accuracy and comprehensiveness (Culver, 2017). In their reports for the Energy Poverty Advisory Hub, Gouveia et al. (2022) and Gouveia et al. (2023) also defend that multi-indicator frameworks are more adequate for energy poverty analysis. While using thresholds, false positives and false negatives are difficult to avoid. Theories of justice prioritise the avoidance of false negatives over the identification of false positives, hence threshold should not risk excluding any energy poor households (Schuessler, 2014). The vulnerability framework is a useful tool for developing a multidimensional approach, as shown by Thomson *et al.* (2017) and Castaño-Rosa *et al.* (2019). While indicators can be combined into a single metric, analysing them independently can avoid exclusion or inclusion inaccuracies (Castaño-Rosa *et al.*, 2019). Conducting sensitivity analysis and assessing the data distribution are also seen as favourable practices (Fizaine and Kahouli, 2018). Enhanced approaches should represent severity (or depth) and dynamics of in and out, remaining effective through changes (Pelz *et al.*, 2018; Brabo-Catala *et al.*, 2024). The distinction between priority and non-priority indicators, representing internal and external factors, can provide clarity and accuracy (Thomson *et al.*, 2017). The intersection with other forms of hardship can help unveil the hidden connection between energy poverty and other vulnerability types. The restriction of other basic needs should also be considered in energy poverty analysis (Castaño-Rosa *et al.*, 2019). Data availability is highlighted as a limitation shaping indicator selection and potentially resulting in neglected population groups (Lowans *et al.*, 2021). Analysing thermal comfort, indoor air quality, and access to renewable energy should be prioritised in energy poverty measurement approaches, focusing on the connection with sustainable development (Siksnelyte-Butkiene, 2021).

Indicators are applied at different spatial scales, and the main types of indicators are mostly applied at the national level due to data availability. Considering the importance of regional and local EP diagnosis (Thomson and Bouzarovski, 2018) for supporting local governments and knowing that literature reviews have not focused specifically on subnational approaches, Chapter 4 focused on metrics applied at these scales through a structured literature review. Data availability is highlighted as a determining factor of subnational approaches, which is often bypassed by the use of support proxy indicators (März, 2018; Sanchez *et al.*, 2020). There are fewer data resources available, the more disaggregated the spatial scale is. Most studies still resort to official national statistics, such as the Census, which provides proxy indicators disaggregated by administrative units for some countries. National surveys such as the SILC, the HBS and the ECS are also common sources of data for regional approaches despite their lower level of disaggregation. They provide a set of useful socioeconomic indicators, such as the ability to maintain adequate temperatures and pay bills, energy consumption, and affordability indicators. However, direct buildings' energy efficiency indicators are mostly missing from these official sources, while for instance EPC data is not widely available and thus it is not often used. The indicators should be intersected for a more comprehensive grasp of the problem, although the intersection between indicators of different surveys is not a viable option, except in rare cases such as in Menyhért (2024). National statistics also have the downside of a low frequency of updates, as they are usually collected every five or ten years. Other proxy indicators such as income, climate variables, building stock characteristics or performance (such as the EPCs) can be accessed at higher resolution spatial scales, depending on the case study region, from official sources or entities and academia. Energy consumption from smart meters, and socio-economic indicators from NGO surveys, local government data and citizen science are still underexplored and could provide relevant input to EP analysis. Own surveys are viewed as a valuable tool for collecting EP-specific indicators at disaggregated scales. Primary data collection such as surveys and direct measurements, alone or combined with official data, can prove essential to capture specific forms of vulnerability, particularly affecting underprivileged communities, as existing statistics are often insufficient to capture the needed level of detail (Ruiz-Rivas *et al.*, 2023).

However, most studies still use secondary data from official statistics to conduct quantitative objective approaches to measure energy poverty incidence (headcount). Qualitative indicators are also frequently used for the same purpose, whereas more subjective constructivist approaches are not as common. Several authors also value the combination of quantitative and qualitative indicators, as they capture the objective and subjective nature of the problem for a more comprehensive approach. Both types of analysis are relevant to the study of energy poverty, providing depictions of different natures which can be complementary. This is partially evidence by the limited overlap between self-reported and objective expenditure-based indicators (Fahmy *et al.*, 2011; Meyer *et al.*, 2018). Regarding the quantitative approaches, various authors still apply the UK-based 10% and LIHC indicators to their contexts, a sign of path dependence (Page, 2006), which can lead to the misidentification of energy-poor households. These propose thresholds of a relative nature, which is argued to portray energy inequality rather than poverty (Romero *et al.*, 2018). Energy inequality is intertwined with EP and should be considered in the analysis, but it is not an identical phenomenon. However, new studies testing absolute indicators and considering a more comprehensive representation of household cost burden in connection to energy expenses are emerging (Barrella *et al.*, 2022b), which can be valuable alternatives. Climate variables, socioeconomic feature, and building energy performance proxy indicators are also commonly used. However, most studies only address winter vulnerability, and summer EP is increasingly more relevant (Lowans *et al.*, 2021; Torrego-Gómez *et al.*, 2023), and not only in southern Europe. Most authors develop case studies focusing on a specific region or location, while only a few develop cross-regional analyses.

Several approaches integrate different indicators, analysing them individually or in multidimensional composite metrics. The latter are mostly area-based, measuring energy poverty severity rather than a headcount, a viable option for an aggregate understanding of this condition at the regional level when only average indicators are available. However, the risk of ecological fallacies should be considered, as the use of average indicators can mask variations of energy poverty vulnerability at even smaller scales (Morrison and Shortt, 2008; Robinson *et* *al.*, 2018; Kelly *et al.*, 2020). Indicators are combined according to different methods, from direct comparisons to more complex inferential statistical analysis, which are seen as more transferable across contexts (Longa *et al.*, 2021). Walker *et al.* (2012) underline this approach as sounder than models weighted according to authors' intuition or consulted experts. However, Sareen *et al.* (2020) and Siksnelyte-Butkiene *et al.* (2021) defend a higher level of participation for a more bottom-up indicator framework, to increase legitimacy and transparency.

The outcome of the indicator is also highlighted. The focus on extent (number of affected households) and depth (magnitude) provides a better account of the reality of energy poverty, as previously mentioned. The different forms of energy poverty, measured energy poverty (excessive expenditures), and hidden energy poverty (abnormally low energy expenditures) (Meyer *et al.*, 2018) but also perceived or experienced energy poverty (based on qualitative self-reports) and its persistence through time (Hills, 2011; Fizaine and Kahouli, 2018) should also be integrated for more inclusive and comprehensive measurement approaches. The outcome can be binary or a range of values or categories. Binary indicators may simplify the problem but are too dependent on a reliable threshold. The importance of thresholds and how small changes significantly impact the identification of energy-poor households should be acknowledged (Rademaekers *et al.*, 2016). Analysing the distribution of indicators while omitting the thresholds can provide an important overall depiction of the situation (Fizaine and Kahouli, 2018) before deciding on a threshold, which should not be based on arbitrary assumptions (Lowans *et al.*, 2021). A range of values avoids the identified constraints, but each value requires a meaning for practical application.

Other underexplored indicators that can provide valuable inputs into EP measurement, addressing aspects such as environment, sustainability, type and quality of energy supply, quality of life, psychology, sociodemographic markers of disadvantage, indoor air conditions, literacy, access to information, participation, culture, territorial typologies, household resilience and ability to adapt, and direct impact of mitigation measures. Energy justice tenets and principles such as energy sovereignty, due process, cosmopolitan justice, intergenerational equity and restorative justice are also virtually absent from subnational metric development. These aspects could enable a broader framing and deeper assessments of the causes and effects of EP across territory and generations.

The outcomes of these chapters provide a comprehensive review of energy poverty indicators and measurement practices, highlighting contradictions and synergies that should be examined when developing a measurement approach regardless of scale. They also explore the particularities and challenges of energy poverty measurement at the local scale, highlighting the disparities in data availability across regions and spatial scales. It calls for more data resources at disaggregated levels, namely dedicated surveys for data collection on varied energy poverty indicators.

After taking stock of the existing measurement practices and future avenues of development, and drawing on the knowledge of energy poverty indicators, available data in the Portuguese context is mobilised to explore local-scale building stock energy performance and energy poverty. The second RQ is the following:

• RQ2: How can existing data resources be integrated to develop energy poverty measurements at the neighbourhood level?

Chapter 5 addresses this RQ2, delving into local-level EP from the building dimension. It addresses EP in a broader scope of analysis, integrating energy poverty mitigation goals within the context of the energy transition strategies, namely through the implementation of a positive energy district, an energy-sufficient area with net-zero GHG emissions (Urban Europe, 2024). Considering the literature on these two subjects, exploring a positive energy district to tackle energy poverty is a novelty. This study analyses buildings' energy performance at the local scale, which is considered one of the main determinants of energy poverty. It also targets energy supply by assessing photovoltaic electricity production potential, which is also considered a relevant energy poverty mitigation strategy (*i.e.* use of locally produced renewable energy sources).

In this work, we applied a building-typology energy model approach using sub-section (neighbourhood) Census data to compute dwellings space heating and cooling energy needs before and after simulated simple renovation intervention for each building element (windows, roof and wall). A multivariate sampling-based approach is used to estimate PV production, using different tools (PV GIS, EPCs, Google Earth, and CENSUS data), providing spatially disaggregated data on solar exposure, building orientation, and rooftop and window area. Investment costs were estimated for both types of intervention. The EPVI was used to show that energy poverty is a concern in the case-study parish, one of the most vulnerable in Lisbon. Using these local scale data resources, it was possible to estimate the potential reduction of space heating and cooling energy needs of up to 84% and 19%, from the combined set of renovation measures. These results highlight the precarious energy performance of the old building stock in these historic city neighbourhoods and the considerable potential for its improvement by implementing simple market interventions. As shown by the EPVI, this is an energy poverty hotspot within the municipality. Results also show a considerable potential of 49 GWh of generated electricity per year, with a total lifetime production of 652 GWh, with higher potential in the eastern and northern neighbourhoods. These two strategies enable a reduction of energy demand and decentralised self-electricity production to supply part of that demand, significantly contributing to structural district transformation towards a fairer energy transition.

The research carried out in this chapter highlights that there are data available in the Portuguese context to start exploring energy poverty measurements and measurement impact at the local level. It requires the combination of datasets from different sources. It highlights that relevant data and indicators are still missing for building a more comprehensive metric.

Socioeconomic data or consensual-based indicators are unavailable at the local level, precluding the enactment of the most common energy poverty metrics. Aspirational examples regarding data availability come from the UK. Robinson *et al.* (2018) manage to estimate expenditure-based indicators such as the 10% and the LIHC at the Lower Super Output Areas (areas with around 400-1200 households) in England from official data. Walker *et al.* (2013) calculated a fuel poverty risk for census output areas (125 households on average) using official datasets on income, social allowances and buildings 'quality.

It becomes clearer that more official spatially disaggregated data is necessary to further develop reliable energy poverty measurements in Portugal, which can ultimately help local policymakers identify and understand the aspects that shape the vulnerability of citizens in their jurisdictions. Local initiatives developed by NGOs, academia, or other entities can help bridge this data gap. Ponto de Transição is one example. It is a mobile energy efficiency one-stop-shop in Portugal that supports citizens while collecting relevant information to characterise the current situation in the municipality where it is located (Gouveia *et al.*, 2024). The two projects supported by EPAH's Technical Assistance in Arganil and Baixa da Banheira and Vale da Amoreira also focus on energy poverty diagnosis at the local level, respectively, in connection with building conditions and indoor monitoring and health-related indicators (EPAH, 2024a). The survey conducted by the Lisbon and Porto energy agencies are also examples of informal data collection that contributes to addressing this lack of data (AdePorto, 2024; Lisboa E-Nova, 2024). These valuable initiatives do not erase the need for updated, frequently collected official data at the local level, enabling a more comprehensive diagnosis across all regions of a country.

The explored data and metrics in the Portuguese context are then applied to investigate the potential impact of energy efficiency and decarbonisation measures rollout on dwelling stock energy performance and energy poverty levels, leading to the third RQ, formulated as follows:

• <u>RQ3: What is the potential impact and cost of different measures for future energy efficiency improvement and energy poverty mitigation?</u>

The research carried out in Chapter 6 produced the outcomes that answer RQ3. This chapter presents three different approaches for assessing the potential of energy efficiency and energy decarbonisation measures for energy poverty mitigation. Necessary costs are also estimated to provide ballpark estimates to policymakers to plan interventions. Section 6.1 presents the first research study, which conducted a cost-effective analysis of different dwellings' energy renovation scenarios, complying with the strict national regulation requirements, for space heating and cooling energy needs of the entire occupied residential building stock. This study employs an energy needs model identical to the ones used in Palma *et al.* (2019) and Gouveia *et al.* (2021) but expands and improves the building stock representation by defining a higher number of representative building typologies (264 in total). It also conducts a thorough market survey of measures, defining scenarios according to their varying thermal parameters and investment costs. The results identify roof insulation as the most cost-effective measure, as in Tadeu *et al.* (2016), although other studies focusing on the cost-effectiveness of renovation measures present different results (Kuusk *et al.*, 2014; Pahio *et al.*, 2015), depending on the type of buildings, measures evaluated, and climate conditions.

The novelty of this study lies in the regional analysis of the whole dwelling stock renovation, providing a complete picture of the potential and cost of a full renovation strategy. Authors have analysed the renovation of one building or parts of building stock, but not the whole country's building stock, and with a regional focus. Results show that renovating all building components results in the highest estimated total energy needs reduction, supporting full-scale interventions for achieving the full potential. Due to its regional basis, the study pinpoints the regions whose building stock has a higher need for energy performance enhancement and potential energy need reduction, as well as the specific building typologies that should be prioritised. These results enable a regionally nuanced renovation strategy, allocating funding through the implementation of programs addressing priority building types in hotspot regions through the most impact and viable measures.

The estimated cost of fully renovating the building stock ranges between €71.7 to €99.6 billion. However, these values represent the necessary investment to renovate the whole housing occupied stock, which does not consider the different socioeconomic conditions of households and social vulnerabilities such as energy poverty. This study explores the building aspect of the condition, which is a structural cause of energy poverty. Still, it does not specifically target this population segment, as the intersection of building and socioeconomic data is not possible as they stem from different sources. However, it is possible to shed light on the necessary investment to renovate the dwelling stock of energy-poor households by crossing the total investment with energy poverty indicators.

The "inability to keep the home adequately warm" and the 2M and M/2 (abnormally high and low energy expenditures) provide respectively a subjective and objective account of this condition while being considered by EPAH as key indicators (EPAH, 2024b). In 2023, 20.8% of Portuguese people reported to be unable to keep their homes warm (Eurostat, 2024), the highest share in the EU. In 2022, 12.8% of the low-income population recorded an abnormally high or low energy expenditure (INE, 2024), signs of measures and hidden energy poverty. Renovating the homes of these population groups would require an estimated investment between €9.1-€14.9 billion. between 3.7% and 6.1% of the country's gross domestic product in 2022 (Pordata, 2024), Illustrating the magnitude of the necessary investment.

Aiming to draw a straighter link with energy poverty while assessing a different kind of intervention, Section 6.2 draws upon Gouveia *et al.* (2019) work, namely the energy poverty vulnerability index, to evaluate the impact of space heating and cooling equipment large-scale replacement on regional energy poverty vulnerability levels. Results show significant reductions in municipal average energy poverty levels from increasing the energy efficiency of the current equipment stock by replacing older equipment with newer more efficient systems of identical type. Higher reductions are associated with deep changes of the existing stock, with the extensive roll out of heat pumps in the carbon neutrality scenario. The research also pinpoints the country's hotspot regions of vulnerability and the regions with the highest potential for vulnerability reduction (*i.e.* priority go to areas). The connection between energy efficiency measures and GHG emissions reduction is not straightforward due to the historical problem of hidden energy poverty in the country, where people restrict their energy consumption due to hardship and adaptation/coping strategies. Thus, interventions may not necessarily decrease energy consumption, as these households may need to spend the same energy level to guarantee their basic needs, potentially even causing the so-called rebound effect (Galvin, 2014). This also creates a potential bottleneck between the country's need for energy consumption reduction aligning with decarbonisation strategies and a reduction of energy poverty through increased energy consumption for better living conditions and higher indoor thermal comfort (Gouveia, 2017).

Section 6.3 presents another complementary analysis, estimating the cost of replacing all the domestic energy equipment - the space heating and cooling systems, domestic hot water equipment, kitchen appliances, electrical appliances and lighting. This replacement is framed as the technical solution to phase out fossil fuels, reduce biomass consumption, and increase energy efficiency in the domestic sector. It focuses on the whole equipment stock but includes special provisions for population segments who rely on available local energy resources and their current equipment, such as biomass and fireplaces, to mitigate their socioeconomic vulnerability. The same calculation conducted for the results of Section 4.1 can be applied to the calculated cost of total equipment replacement to estimate the specific cost of conducting this transformation in energy-poor households. Taking the lowest estimate of €26.2 billion, a value ranging from €3.4 to €5.4 billion would be necessary to decarbonise the energy consumption of energy-poor households, minding that space heating and domestic hot water are the more challenging energy services to address due to the high penetration of fossil fuel and biomass systems, as well as lower efficiency electric ones (*i.e.*, radiators and ventilators), in the country.

The outcomes of these three approaches are complementary. They can be combined to design more accurate and regionally specific intervention strategies that are informed and tailored according to potential costs, impact, and feasibility estimations. These *ex-ante* analyses, mostly missing in policy strategies, can render it more sustainable, resource-efficient, and effective in achieving the aimed goals of energy decarbonisation and energy poverty mitigation. Nevertheless, energy poverty mitigation and decarbonisation efforts are not always synergetic, as shown by Dong *et al.* (2021) and Mahoney (2024). Abbasi *et al.* (2022) warn that social dimension and behaviour choices are often left out of energy efficiency interventions. Implementing low-carbon energy technologies without considering energy poverty, literacy difficulties (*i.e.* digital, energy, financial) and other forms of hardship, can deepen the risk of energy deprivation and exclusion. Technical solutions on their own cannot ensure that existing or new forms of inequality and injustice are not produced. The fashion in which these solutions are planned and deployed is paramount to guarantee the rights of the less privileged population and a citizen-centric inclusive energy transition tailored to overcome the complex weave of energy injustice manifestations. These works explore concrete examples of how to conduct planning and *ex-ante* assessment of interventions that integrate and target energy-poor households.

The outcomes of the analyses conducted to answer the previous RQs were then summoned to build a critical analysis of the recently adopted national energy poverty strategy for combating energy poverty in Portugal, also supported by a broad review of practices regarding energy poverty definition and measurement and a direct comparison with the current Spanish policy strategy. The fourth RQ was the following:

• RQ4: How can energy poverty diagnosis in public policy be improved?

It is fundamental to design strategies and policies that not only target the energy poor but also understand the sources and nature of their vulnerability and are tailored according to the characteristics and needs of these vulnerable groups. An effective mitigation strategy should be built on a comprehensive and accurate diagnosis of the condition to implement measures that directly address the causes and relevant determinants of the problem. Chapter 7 takes in the outcomes and learnings of the previous chapters and undertakes a critical analysis of the energy poverty diagnosis presented in the recent National Strategy for Combating Energy Poverty 2050 in Portugal (January 2024). It analyses the Portuguese strategy in light of a diverse pool of practices and knowledge from scientific literature and policy on energy poverty diagnosis, particularly the definition of the condition and the indicators to measure or analyse it. It is also compared and contrasted with the Spanish strategy, aiming to identify potentially transferable practices from two similar contexts and energy poverty reproductions. This study directly addresses the RQ by identifying several potential improvements that can inform the strategy's future update or even the upcoming action plans to be proposed by the National Energy Agency ADENE (Resolução do Conselho de Ministros nº11/2024). Either supported by empirical evidence or stemming from the author’s logical reasoning, the proposed improvements target the expansion of the definition to integrate a wider range of causes and expressions; the clearer distinction and interconnection between energy-poor and vulnerable consumers; the increase in vulnerable groups representativeness; indicators replacement and refinement their use; inclusion of new dimensions and indicators in the measurement framework; introduction of regionally disaggregated assessments; and measurement broadening to aspects of depth and persistence. This study also defends the need for increased intersectionality between indicators, as it enables a more robust and complete understanding of the interconnectedness of factors and causes, as well as compound vulnerabilities. Using unique joint SILC-HBS microdata Menyhért (2024) shows that the existing consensual and expenditure-based indicators identify different population segments, while about one-third of the analysed households suffer from more than one form of energy deprivation. It also confirms the significant diversity of backgrounds and conditions underpinning EP. The call for new indicators is also supported by Menyhért (2024) findings, which point out that a considerable part of EP remains hidden using current data and measurements.

This exercise involves a degree of subjectivity, as it is directly connected to the authors' perceptions, background knowledge and perspectives on this issue. Nevertheless, proposals are thoroughly consensual in literature, such as the inclusion of hidden energy poverty (Eisfeld *et al.*, 2022; Barella *et al.*, 2022) as a form of energy poverty or discontinuing the use of the 10% indicator (Thomson *et al.*, 2017, Palma and Gouveia, 2022), something that is missing in the Portuguese strategy. Policy analysis is a thoroughly explored subject in literature but as energy poverty-dedicated strategies are still scarce and relatively recent, this study finds its novelty in its aim. It contributes to a deeper characterisation of energy poverty in dedicated policy, bridging research and practice and building on scattered attempts to define and evaluate it in national energy and climate plans. It lays out a replicable methodology that can be applied to critically analyse and enhance energy poverty strategies at different scales across the European Union.

8.2 General Considerations

As previously discussed, energy poverty is at the crossroads of several complex factors that create and shape it into different forms. This condition of deprivation translates into a range of negative effects on the lives of millions of people. These factors are determined by underlying systems that are rigid, long-lasting, and difficult to change. Whether it is the past construction of large inefficient building stocks, the historically high energy prices linked to the use of fossil fuels and market design, or wealth distribution inequalities that result in low wages for families, all these systems are in place mostly due to political decision-making, current or past. This reality is evidenced in the words of Stefan Bouzarosvki at the Public Hearing "The responsibilities of fossil fuel companies in the cost-of-living crisis", organised by the Committee on Petitions. He stated that "*energy poverty eradication is ultimately a political choice*", contesting the idea that scarcity is the chief determinant. In fact, historical political decision-making regarding resource distribution within societies has shaped the systems that create this problem, while the current one continues to perpetuate them throughout the years, preventing its eradication.

Energy poverty is a reality in countries where energy use exceeds the required levels for a decent standard of living (Millward-Hopkins *et al.*, 2020), because energy and economic capacity are used for forms of production that promote corporate profit accumulation with little Impact on well-being (Hickel and Slamersak, 2022). This level of energy use is largely sustained by a colonial policy of unequal trade, exploitation and appropriation of energy resources of less affluent countries of the Global South, contributing to deep energy poverty issues in these countries (Hickel and Slamersak, 2022). Since the inception of the EU, the historical priority in energy matters has been arguably to create a common internal market based on free competition to facilitate trade and provide energy access and low energy prices to citizens. The capitalist political economy and economic liberalisation have so far proven ineffective, as energy poverty continues to loom large in the old continent.

Energy poverty mitigation has gained ground in energy policy and legislation in the EU, taking a more prominent position over the years, as evidenced in the "Clean Energy for All Europeans" legislative package, the recent political strategies such as the European Green Deal and the Renovation Wave, and the European Social Climate Fund. However, as efforts are rolled out to drive the energy transition, vulnerable consumers are still not at the centre of strategy-making and policy design. Energy vulnerabilities are regarded as an inevitable consequence of existing policy developments and decisions, and measures mostly aim to reduce their effects rather than change the underlying systems that create them. This political stance has had consequences across the board *vis-a-vis* energy poverty, from diagnosis efforts to strategic planning and concrete eradication policy and action.

On the diagnosis front, while mandating Member states to address this issue, the European Commission still relies on proxy indicators not tailored to assess energy poverty, basing their support to MSs (EC, 2020) on these arguably insufficient metrics and resources. This thesis identified and discussed some of the shortcomings of the EU reference indicators (EPAH, 2024) while pointing out existing problems in national energy poverty strategies that can be traced back to the EU-based indicators, as strategies are mostly tailored according to EU recommendations (EC, 2020; EC, 2024; EPAH, 2024)). The limited availability of adequate energy poverty data at the national level and path dependency issues pertaining to the use of historically relevant but obsolete metrics also hinder diagnosis in MSs. Researchers have defended the development of a dedicated annual energy poverty survey (Thomson *et al.*, 2017; Eisfeld, 2023), but the European Commission have shown resistance to a broader and more targeted data collection to study this condition, or even changes or additions to the current income and living conditions survey. The limited data resources at the national level are also a potential sign of a lack of awareness regarding the importance of energy poverty and diagnosis in particular, or even the lack of political will and commitment to address this condition, choosing not to spend public funding on its study. This limited commitment is also manifested in the lack of data at more disaggregated scales, as resources are even more scarce at the regional and local levels. The research presented herein shows that subnational energy poverty measurement approaches are deeply shaped by the lack of data, prompting researchers to develop different approaches. Some authors use indirect averaged indicators for area-based vulnerability estimations to overcome the identified data gaps. In contrast, others conduct their own surveys for applying mixed-method approaches, aiming to increase knowledge on energy poverty in their small-scale case studies.

Considering the importance of multilevel diagnosis in analysing a phenomenon such as energy poverty, which is characterised by varying configurations and hidden manifestations that require local observations to extricate them, multidimensional data at the local level is paramount. This thesis demonstrates a method to explore neighbourhood-level energy poverty measurement in Portugal while highlighting further data needs that would help enhance diagnosis. It also shows that local scale measurements are crucial to inform and support tailored technical energy transition solutions such as positive energy districts. They help validate these solutions as potentially effective in transforming how energy demand and supply consider the needs of vulnerable populations, contributing to a more accurate targeting of the most vulnerable regions. However, how energy transitions are deployed on the ground determines their ability to address all the dimensions and goals of a fair and inclusive energy transition. For instance, home renovations can increase tenants' cost burdens (Platten *et al.*, 2022) or even lead to eviction (Webber and Zingman, 2023). Moreover, not every household has the financial capacity to invest in energy renovations or renewable energy technologies, which leads to an unequal energy transition that is only accessible to the ones who can afford it. The "ownership" of the energy transition is a sensitive but relevant issue that needs to be addressed. Fighting energy poverty is not simply a technical endeavour; it involves empowering citizens towards more active energy citizenship, involving them in decision-making, and promoting inclusion and participation (DellaVale and Czako, 2022). Only this way will it be possible to address energy poverty in the broader concept of energy justice, targeting not just distributional injustices but also the procedural and recognition aspects that undermine the legitimacy of these transformations.

Focusing on the Portuguese context, this thesis enriches the discussion over energy poverty definitions, proposing a more comprehensive and inclusive definition of energy poverty, encompassing a wider range of energy services, quality of energy provision, causes, vulnerability manifestations, and vulnerable groups. However, in connection with the concept of energy citizenship, there is still room for further definitional developments. Progress can arise from exploring links with energy justice frameworks (*e.g.* Sovacool *et al.*, 2016, Heffron and McCauley, 2017) which uncover underexplored aspects that may deepen the understanding of energy poverty, such as generational hardship and equity, restorative justice and energy independence and sovereignty. Only energy poverty mitigation solutions that are cognisant and tailored to address the relevant dimensions- causes, driving factors and recognised injustices, can foster the systemic change that produces long-lasting effects.

As the private sector assumes a prominent role in the rollout of energy transition solutions, with profit gains as the primary desideratum, community-led democratic models are essential to promote new models of ownership and governance that can foster this deeper transformation. Integrating the concept of commons into energy can contribute to constructing more sustainable, democratic and sufficiency-focused alternatives to the current profit-driven socioeconomic models (Giotitsas *et al.*, 2022). Decentralised renewable energy production at the local scale in the form of citizen-led energy communities is regarded as a solution with considerable potential to drive the energy transition while contributing to energy poverty mitigation and increase energy sovereignty. However, there are relevant challenges to be addressed. Since it requires an initial investment, funding constraints may prevent the energy poor from participating (Koukoufikis *et al.*, 2023). Public incentives from national and local governments can play an important role in promoting these different energy models and helping to overcome this challenge, ensuring the participation of underprivileged groups of the population. The energy community of Telheiras (Viver Telheiras, 2024) in Portugal is an example of a public-common partnership (Heron, 2021), an alternative democratic model to the binary of market and state, shaped to include vulnerable consumers from its inception.

In fact, the state's pivotal role as a main driver of the energy transition is not limited to the public sector. It is a crucial catalyser of the energy transition in the private sector. The structure of public funding to address the 2022's energy crisis is evidence of an energy strategy that is not designed with the primary goal of tackling inequalities and deprivation, as the chief part was committed to untargeted income support and price mitigation measures (Galgóczi, 2023). Moreover, the recent Social Climate Fund is another mechanism created to tackle the predicted consequences of an uneven and asymmetric energy transition strategy, and funding is considered to be too short to tackle these consequences significantly.

In Portugal, the current conjecture is problematic due to deeply rooted systems that perpetuate energy poverty in the country, and political commitment has been manifestly insufficient in addressing them. Periods of austerity since the 1970s, together with the EU integration and the push for a liberalised market, have led to the privatisation of energy production and transportation in the country without the expected effects of reduced energy prices for citizens. Housing is mostly energy inefficient due to inexistent energy performance regulation until 1990 and waves of extensive cheap housing and self-construction in the later decades of the XX century. Vulnerable consumers and energy poverty have become topics of relevance in recent national energy policy due to the influence of the EU on energy-related legislative packages. However, despite growing efforts from later governments, energy vulnerability is still a harsh reality for a large part of the population. As in the EU, public funding and support to drive the energy transition through renewable energy integration and building renovation has been mostly allocated to untargeted programs. These do not include specific provisions for the most vulnerable consumers. Their design and eligibility criteria (such as being only eligible to homeowners) often render them less accessible to less affluent households. For the first time, there was an energy poverty dedicated program to promote energy efficiency (*i.e.* Energy Efficiency Voucher or Vale Eficiência), but it has had low adoption rates in its first phase, as the second is currently ongoing. This thesis makes another relevant contribution to this subject, as it estimates the needed investment to deeply enhance energy efficiency, both the passive and active components, of energy-poor homes and the whole dwelling stock. This transformation could significantly reduce energy poverty and considerably boost efforts to decarbonise the Portuguese economy. The estimated necessary funding (minimum €12.5 billion) for energy-poor households is vastly superior to the funding allocated to the energy poverty program (€100 million from 2021 to 2024), stressing the urgent need for further mobilisation of public funding to address this condition. Upcoming funding stemming from European Social Climate Funding will likely fall significantly short of the estimated values. While households struggle to pay their energy bills, private energy companies such as Energias de Portugal register considerably high net revenues (Nunes, 2024) and see their social responsibilities, such as funding the social energy tariff (the only bill support scheme implemented) being softened after favourable evaluation from the European Commission (Silva, 2024), and will possibly have direct public funding, as proposed by the new government (Ribeiro, 2024). The current context calls for a shift in public policy, towards holding the private sector accountable and responsible for participating in energy poverty eradication through mechanisms such as windfall taxes, which help collect precious public funding to drive the transition. It is important also to mention the valuable efforts at the regional level, by academia, energy agencies, and local governments and other associations to promote energy literacy and tackle the deep lack of access to relevant information regarding energy bills, public support measures, and energy efficiency measures through direct contact and advice in one-stop shops across different municipalities. In-person support contributes to ameliorating energy poverty but its impacts are limited, as the transformation of structural and institutional factors that determine energy poverty requires political action. Thus, they should be seen as a complement rather than a replacement for more structural action (Simcock and Bouzarovski, 2023).

The thesis sheds light on the efforts to transform structural factors across the territory, as it provides a regional analysis of building renovation measures´ cost-effectiveness. It also demonstrates a method to link the assessment of energy efficiency measures to energy poverty measurement, which can help policymakers plan a more targeted, efficient, and impactful use of available funding towards a fair energy transition. Despite the contributions of research, such as the ones of this work, only with a considerable increase in political commitment can the eradication of energy poverty become a reality, including a shift in how energy poverty is perceived and integrated into public policy. This shift needs to be connected to the framing of energy as a basic human right for a healthy standard of living and as a public service and a common. This transformation calls for a more comprehensive understanding of energy poverty at different scales. It will require a more frequent and thorough data collection process at different scales, considering a more comprehensive and inclusive definition, namely of its causes, drivers, and effects in the different population groups across the territory. Subsequently, deep changes in the type and volume of public support measures are also needed. Considering the socioeconomic condition of energy poor population, public policy should focus on energy efficiency for a consumption that provides energy sufficiency, the necessary level of energy services for a good standard of living within lifestyles that respect planetary boundaries, against the logic of industrial capitalism. This can mean the deployment of effective and targeted direct public subsidies for building renovation, energy equipment replacement, and renewable energy integration; promotion of energy literacy amongst the population; market regulation ensuring that large renewable energy generation projects effectively reduce prices for final consumers; and a strong promotion and support of community-based democratic renewable energy and building renovation models that challenge the existing profit-driven models of energy generation, transportation, and provision. Concurrently, it is also vital to expand consumers' basic rights, such as disconnection prohibition and granting a universal minimum energy services level, to guarantee that no one is left behind in the energy transition rollout and everyone has access to sustainable, safe, and sufficient energy in their lives.

8.3 Limitations and Future Work

Every research endeavour is based on paradigms and theories encompassing different perspectives, ideas and assumptions to explain complex multidimensional phenomena. This paradigm determines the methodology chosen or developed to increase understanding of a phenomenon, which has inherent limitations. This thesis enacts a post-positivist methodological approach to studying a subject that has a deep social nature. It rejects the rigidity of absolute objectivity and integrates subjectivity in its analysis using quantitative and qualitative methods (as described by Dawadi *et al.*, 2021). However, it is still based on the identical principles to the positivist approach, developing a scientific method that arguably analyses a social-based phenomenon such as energy poverty as a law-governed natural science, one of the main criticisms of positivism. The post-positivist nature is reflected in the recognition that it is not possible to observe and objectively perceive or predict all the processes and factors that determine it nor control the conditions of its reproduction (Maksimovic and Evtimov, 2023). This recognition leads to a critical interpretation of results, acknowledging that these constitute the outcome of one research endeavour and not the absolute objective truth of the matter. The thesis selects a set of factors associated with energy poverty according to the existing literature of positivism and non-positivist nature to employ deterministic methods that analyse cause-and-effect relationships. This is a limitation in itself, as, considering the recognised complexity of this phenomenon, it is bound to leave out factors that play a relevant role due to lack of data, involuntary omission, lack of dedicated literature, or even the author's perspective on the problem, stemming from his worldview. Several examples can be underlined. One is excluding energy behaviour variability in the estimation of space heating and cooling energy needs. Occupant behaviour and needs are determining factors of buildings' energy performance and can impact energy poverty assessments (DellaValle, 2019). However, due to a lack of data on the different behaviour profiles and the fact that this thesis deals with macro assessments (country-level) to assess the energy needs that guarantee thermal comfort to all citizens, the regulation default conditions were assumed (homes at a comfortable temperature 100 percent of the time and for the whole indoor space), which are arguably not realistic. The method applied to estimate the energy needs is based on the quasi-steady state method of the EN ISO 13790, which was the official method established in the buildings' energy performance regulation of the country. This method has been replaced by a new standard, the ISO 52016-1, which no longer recommends the use of seasonal quasi-steady state, recommending a more dynamic method for higher accuracy of estimates. Besides temporal and behavioural transient effects, the applied method also excludes energy services other than space heating and cooling in the energy performance assessment, which can underestimate total energy needs and wider vulnerability settings. On the building characterisation, physical parameters are taken from a sample of EPCs. This might lead to a mischaracterisation of the stock's energy performance, as certificates are often more representative of dwellings that have been previously renovated since they are only mandatory when they are new, for sale or on the rental market. Cost-effectiveness and economic analyses yield valuable results but do not consider the complexity of citizens' choices and preferences, creating more simplistic macro scenarios based on top-down assumptions. It also relies on the cost of measures that can rapidly become outdated due to extraneous economic factors, potentially impacting estimated investment cost to some degree.

The energy poverty measurement applied is also limited in its scope and range, as it is an area-based model using averaged indicators that may hide important nuances and variability at more disaggregated scales. Due to its regional-based nature, it does not provide estimates of incidence but rather a vulnerability range to compare regions based on the proportions of the different indicators across regions. Thus, its application for policy is limited. It also resorts to several assumptions and interpolations, increasing uncertainty probability. The level of uncertainty is one of the main limitations of the applied methods, also due to the combination of indicators from different data sources and collected at different scales. It is shaped by data availability; thus, it is not able to include relevant indicators such as those that have been analysed and discussed throughout this thesis. Indicators such as affordability and self-reports of financial hardship, energy use and restriction, and thermal comfort would enable a more comprehensive approach to strengthening the subjective component of the analysis. Higher availability of qualitative data through interviews or surveys could enable a different research design and methodology, leaning toward a more constructivist or the more transformative advocacy/participatory worldview. It should be noted that this research makes a point of integrating and discussing the results against the current political context, which is one of the tenets of the advocacy/participatory paradigm. It addresses an important social issue and holds a view and agenda for changing the lives of the subjects of the analysis, the energy poor (Creswell, 2018).

The nature of the models used in this thesis can also be critiqued. They are static white-box deterministic models grounded in fundamental physics, providing a detailed depiction of buildings' energy performance, and capturing the interaction between the various building components. However, they are restricted to the degree of understanding of fundamental principles; they require simplifications; do not vary with time; are prone to uncertainties; are not capable of including uncertainties in the model; and pose scalability problems while not having such strong predictive accuracy as black-box models (Estrada-Flores *et al.*, 2006; Shahcheraghian, A., 2024).

The next steps in this research path can take several directions and spawn from the identified limitations. Despite the different sources of data and its compatibility problems, future research could proceed with the study of future energy poverty vulnerability, applying the Gouveia *et al.* (2019) model to test more comprehensive scenarios and assess the joint effect of the projections for every indicator. It would also be useful to define energy transition scenarios to test implementing several energy efficiency measures in conjunction. There is also potential to improve the energy poverty vulnerability index by testing out the inclusion of new datasets, new indicators, different methods of combination, or even conducting a new stakeholder consultation to validate and compare the weights of each indicator - not only to update the index but to also study the difference in stakeholders' perceptions. The integration of regionally specific energy behaviour indicators and scenarios could also yield valuable results, diversifying the results of the metric and deepening the analysis. It would also be interesting to explore neighbourhood-scale measurements, continuing the process of fully transferring the energy poverty vulnerability index at this scale, which would potentially require dedicated on-the-ground surveys with the local citizens or the use of proxy indicators. In the latter case, the results would have to undergo a validation process to check if the different model versions would produce sound results. Energy poverty research can also be further pursued using national surveys on income and living conditions, domestic energy consumption, and household budget surveys. These data can also be used to explore measurement at a high-resolution spatial scale, namely through testing statistical models such as small area estimation models (as in Fahmy *et al.*, 2011), often used in income poverty studies. The results of the two models could be crosschecked to analyse their validity or potential complementarity.

The connection between a range of energy poverty indicators and several socioeconomic and energy use aspects can be further explored using this microdata, aiming to continue to deepen the understanding of this condition in the Portuguese context. The intersection with other forms of hardship and the potential overlap of different energy poverty manifestations (represented by several previously discussed indicators) could also provide extra insight into this condition at the household scale. It is something that has been conducted in other contexts with interesting results (*e.g.* Bardazzi *et al.*, 2021). This deeper analysis could follow the path of the energy justice frameworks, aiming to investigate the connection between energy poverty and the different principles, tenets and types of injustices. The same procedure could be conducted from the capabilities approach (Day *et al.*, 2016), aiming to draw a connection with all the capabilities identified. These are only a few avenues of possible future steps derived from this work in energy poverty research, a subject that is as diverse and complex as it is relevant for our societies.

Research plays a relevant role in boosting the deep transformation that is required to eradicate energy poverty. However, only with the right political direction and commitment, and the close collaboration of all sectors of society will it be possible to achieve the desired outcome and provide a better quality of life to the people in need.

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Annexes

Annex Contents

This thesis includes three annexes, providing supplementary information for Chapters 4, 6, and 7, as detailed in the corresponding chapters. The annexes are the following:

- Annex A - List of countries per European region and subnational energy poverty assessment articles reviewed (Chapter 4)
- Annex B - Roof, wall and window renovation measures and equipment market options (Chapter 6)
- Annex C - Energy Poverty Definitions across Europe, literature reviews or critical analysis articles on EP indicators, alternative indicators (Chapter 7)

Annex A

Annex A1 - Subnational energy poverty assessment articles reviewed

Regional Pool	Country	Articles
Southern Europe	Croatia	Grdenic *et al.* (2020)
	Greece	Katsoulakos (2011); Paravantis and Santamouris (2014); Papada *et al.* (2016); Paravantis and Santamouris (2016); Papada and Kaliampakos (2017); Pignatta *et al.* (2017); Papada and Kaliampakos (2019);Boemi and Papadopoulos (2019a); Boemi and Papadopoulos (2019b); Ntaintasis *et al.* (2019); Antepara *et al.* (2020); Spiliotis *et al.* (2020); Boemi *et al.* (2020); Papada and Kaliampakos (2020);Papada *et al.* (2021); Balaskas *et al.* (2021); Karani *et al.* (2021); Lyra *et al.* (2022)
	Italy	Fabbri (2015); Besagni and Borgarello (2019); Bardazzi *et al* (2021); Camboni *et al* (2021); Fabbri and Gaspari (2021)
	Portugal	Simões *et al.* (2016); Gouveia *et al* (2018); Gouveia *et al.* (2019); Horta *et al.* (2019); Antepara *et al.* (2020); Panão (2021); Avanzini *et al.* (2022); Desvallées *et al.* (2022)
	Spain	Scarpellini *et al.* (2015); Llera-Sastresa *et al* (2017); Aristondo and Onaindia (2018); Sánchez *et al.* (2018); Aranda *et al.* (2018); Romero *et al.* (2018); Aguilar *et al.* (2019); Sanchez Guevara *et al.* (2019); Antepara *et al.* (2020); Uche-Soria and Rodríguez-Monroy (2020); Murias *et al.* (2020); Sanchez *et al.* (2020a); Perez-Bezos *et al.* (2020); Castaño-Rosa *et al* (2020); Bienvenido-Huertas *et al.* (2020); Oliveras *et al.* (2020); Sánchez *et al.* (2020b); Martín-Consuegra *et al.* (2020); Bienvenido-Huertas *et al.* (2021a); Bienvenido-Huertas *et al.* (2021b); Bienvenido-Huertas *et al.* (2021c); Cuerdo-Vilches *et al.* (2021);Gómez-Navarro *et al.* (2021); Alba-Rodríguez *et al.* (2021); Ortiz *et al.* (2021); Clavijo-Núñez *et al.* (2022); Oliveras *et al.* (2021); Carrere *et al.* (2021); Lepetit *et al.* (2022); Taltavull de La Paz *et al.* (2022); Carrere *et al.* (2022); Heredia *et al.* (2022); Bienvenido-Huertas *et al.* (2022); Carrere *et al* (2022); Barrella *et al.* (2022a); Barrella *et al.* (2022b); Marí-Dell'Olmo *et al.* (2022); Sánchez-Torija and Nieto (2022); Clavijo-Núñez *et al.* (2022); Stevens *et al.* (2022); Terés-Zubiaga *et al.* (2023)
Western Europe	Austria	Brunner *et al.* (2012); Stojilovska *et al* (2021); Eisfeld and Seebauer (2022)
	Belgium	Meyer *et al.* (2018); Bartiaux *et al.* (2018); Bartiaux *et al.* (2021)
	France	Mayer *et al.* (2014); Martellozzo (2017); Stojilovska *et al* (2021); Kahouli and Okushima (2021)
	Germany	März (2018)

	Ireland	Kelly *et al* (2020)
	Nether-lands	Mashhoodi *et al* (2019); Longa *et al* (2021); Stevens *et al.* (2022); Mulder *et al.* (2023)
	United Kingdom	Fahmy *et al* (2011); Walker *et al.* (2012); De Haro and Koslowski (2013); De Vries and Blane (2013); Walker *et al.* (2013); Walker *et al.* (2014); Sharpe *et al.* (2015); Mould and Baker (2017a); Mould and Baker (2017b);Butler and Sherriff (2017); Forster *et al.* (2017); Curl and Kearns (2017); Petrova (2017); Murage *et al.* (2018); Robinson *et al.* (2018a); Robinson *et al.* (2018b); Robinson (2019);Castano-Rosa *et al.* (2019); Robin-son *et al.* (2019); Marchand *et al.* (2019); Ramsden (2020); Castaño-Rosa *et al.* (2020); Gupta and Gregg (2020); Robinson and Mattioli (2020); Shirani *et al.* (2021); Stevens *et al.* (2022)
Central and Eastern Europe	Czechia	Bouzarovski and Tirado (2017); Bouzarovski and Thomson (2018); Thomson *et al.* (2019);
	Poland	Lis *et al* (2016); Bouzarovski and Tirado (2017); Bouzarovski and Thomson (2018); Thomson *et al.* (2019); Sokolowski *et al* (2020a); Sokolowski *et al* (2020b); Karpinska and Smiech (2020); Nowalska-Kapuścik (2021); Karpinska *et al.* (2021); Karpinska and Śmiech (2021); Mamica *et al.* (2021)
	Hungary	Bouzarovski and Thomson (2018); Bouzarovski and Tirado (2017); Thomson *et al.* (2019); Stevens *et al.* (2022)
	Latvia	Stevens *et al.* (2022)
	North Macedo-nia	Bouzarovski and Thomson (2018); Thomson *et al.* (2019)
	Ukraine	Petrova *et al.* (2013); Pysar *et al.* (2018)
	Serbia	Bajić *et al.* (2016)
	Romania	Bîrsănuc (2022)
North-ern Eu-rope	Norway	Bredvold and Inderberg (2022)
	Sweden	von Platten (2022)

Annex A2 - Countries per European region

Central and Eastern Europe	Albania, Azerbaijan, Armenia, Belarus, Bosnia and Herzegovina, Bulgaria, Croatia, Czechia, Estonia, Georgia, Hungary, Kosovo, Latvia, Lithuania, Moldova, Monte-negro, North Macedonia, Poland, Romania, Russia, Serbia, Slovakia, Slovenia, Ukraine
Northern Eu-rope	Denmark, Estonia, Finland, Iceland, Latvia, Lithuania, Norway, Sweden
Southern Eu-rope	Cyprus, Greece, Italy, Malta, Portugal, San Marino, Spain
Western Europe	Andorra, Austria, Belgium, France, Germany, Ireland, Liechtenstein, Luxembourg, Monaco, Netherlands, Switzerland, United Kingdom

Annex B

Annex B1 - Roof and wall renovation measures

Building element	RM	Thickness (cm)	Thermal resistance (m²·K/W)	Investment cost (€/m²)
Roof	Thermal insulation in expanded polystyrene	12.0	3.6	25.5
	Thermal insulation in mineral wool felt	14.0	3.3	8.9
	Thermal insulation in mineral wool felt	12.0	2.9	8.1
	Thermal insulation in expanded polystyrene	9.0	2.7	19.5
	Thermal insulation in mineral wool felt	10.0	2.4	7.2
	Polyurethane foam	10.0	2.4	29.3
	Polyurethane foam	8.0	1.9	26.0
	Thermal insulation in expanded polystyrene	6.0	1.8	14.2
	Polyurethane foam	6.0	1.4	21.2
Exterior Wall - Inside	Inside insulation with expanded polystyrene	15.0	4.8	52.0
	Inside insulation with mineral wool	12.0	3.8	45.2
	Inside insulation with cork agglomerate	12.0	3.3	62.5
	Inside insulation with expanded polystyrene	9.0	2.9	37.6
	Inside insulation with mineral wool	9.0	2.8	41.1
	Inside insulation with cork agglomerate	9.0	2.5	57.1
	Inside insulation with expanded polystyrene	6.0	1.9	35.2
	Inside insulation with mineral wool	6.0	1.9	38.0
	Inside insulation with cork agglomerate	6.0	1.7	52.0
Exterior Wall - Outside	Ventilated façade with expanded polystyrene insulation	15.0	4.8	105.8
	ETIC with PVC insulation	14.0	3.7	80.0
	Ventilated façade with volcanic rock wool panel insulation	12.0	3.4	110.1
	Ventilated façade with cork agglomerate insulation	12.0	3.3	126.3
	ETIC with PVC insulation	12.0	3.2	76.0
	ETIC with volcanic rock wool panel insulation	12.0	3.2	106.2

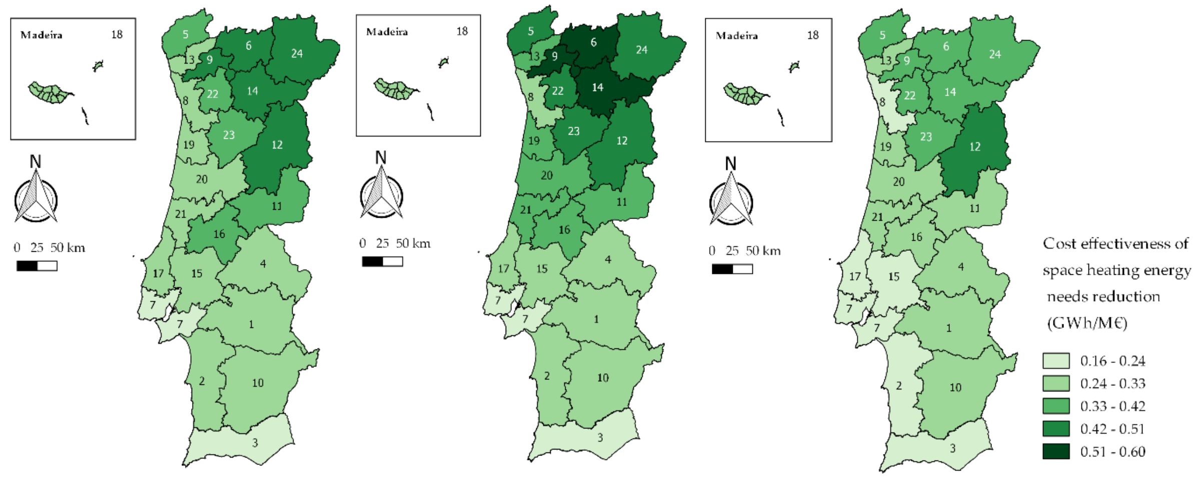
	ETIC with cork agglomerate insulation	12.0	3.0	134.1
	Ventilated façade with expanded polystyrene insulation	8.0	2.6	102.4
	Ventilated façade with volcanic rock wool panel insulation	8.0	2.3	105.2
	Ventilated façade with cork agglomerate insulation	8.0	2.2	118.2
	ETIC with PVC insulation	8.0	2.1	65.1
	ETIC with volcanic rock wool panel insulation	8.0	2.1	85.5
	ETIC with cork agglomerate insulation	8.0	2.0	103.7
	Ventilated façade with expanded polystyrene insulation	4.0	1.3	99.1
	Ventilated façade with volcanic rock wool panel insulation	4.0	1.1	101.5
	Ventilated façade with cork agglomerate insulation	4.0	1.1	110.0
	ETIC with PVC insulation	4.0	1.1	55.5
	ETIC with volcanic rock wool panel insulation	4.0	1.1	65.6
	ETIC with cork agglomerate insulation	4.0	1.0	76.3

Annex B2 - Window and glazing replacement measures

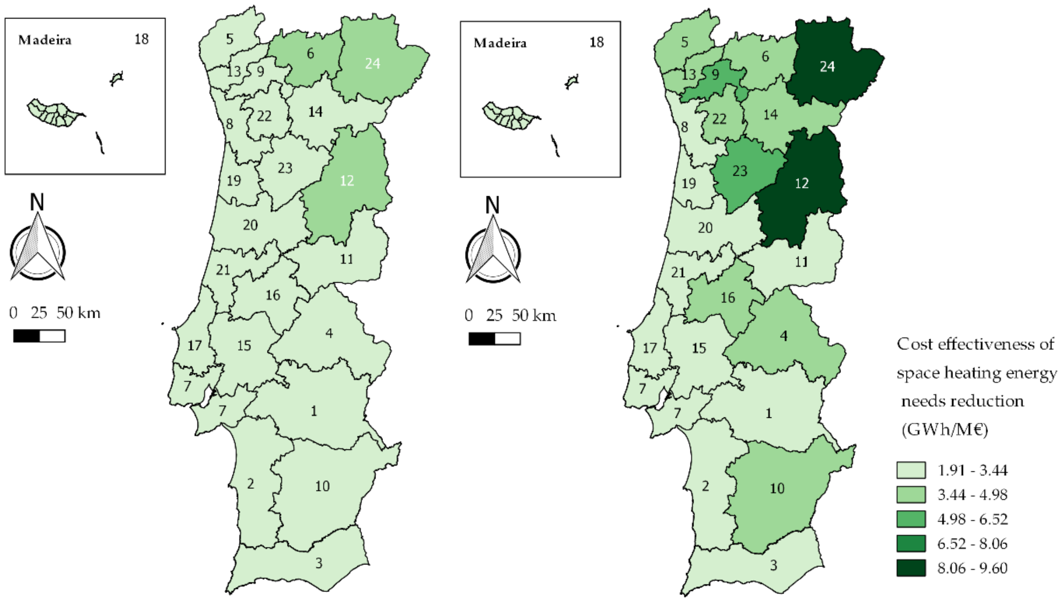
Building element	**RM**	**Solar Factor**	**Thermal resistance ($m^2 \cdot K/W$)**	**Investment cost (€/m^2)**
Window	Aluminium window frame with thermal break and low emissivity glazing	0.4	0.8	905.0
	Aluminium window frame with thermal break and standard glazing	0.8	0.7	800.6

	PVC window frame and low emissivity glazing	0.4	0.6	455.0
	PVC window frame and standard glazing	0.8	0.5	350.6
	Aluminium window frame and low emissivity glazing	0.4	0.5	605.0
	Aluminium window frame and standard glazing	0.8	0.4	500.6

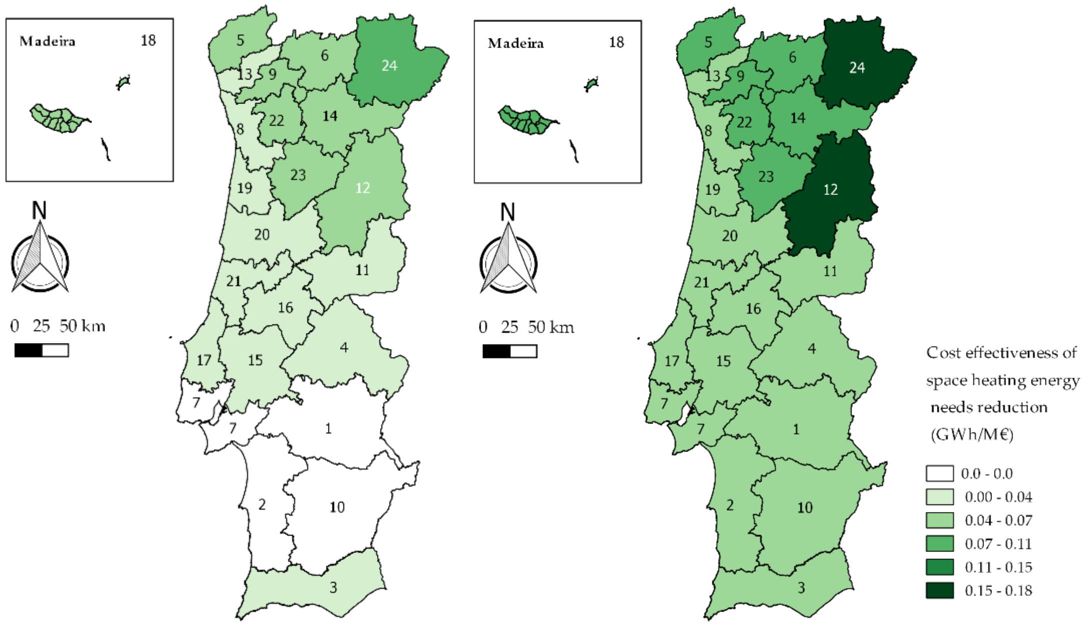
Annex B3 - Cost-effectiveness of wall renovation in space heating energy need reduction, per NUTS3 regions of Portugal, for Scenario A (left), Scenario B (centre) and Scenario C (right)



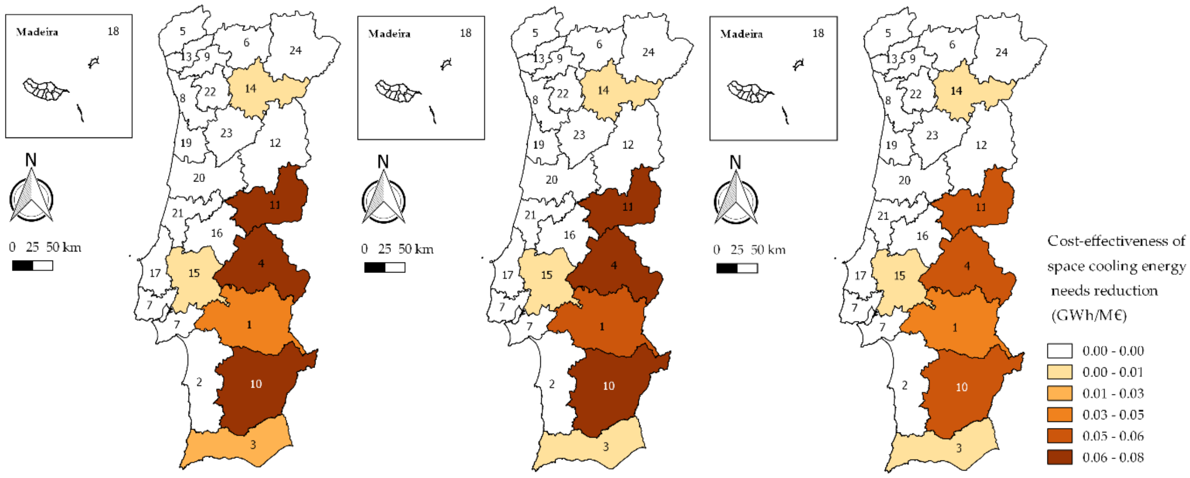
Annex B4 - Cost-effectiveness of roof renovation in space heating energy need reduction, per NUTS3 regions of Portugal, for Scenario A (left) and Scenario B and C (right)



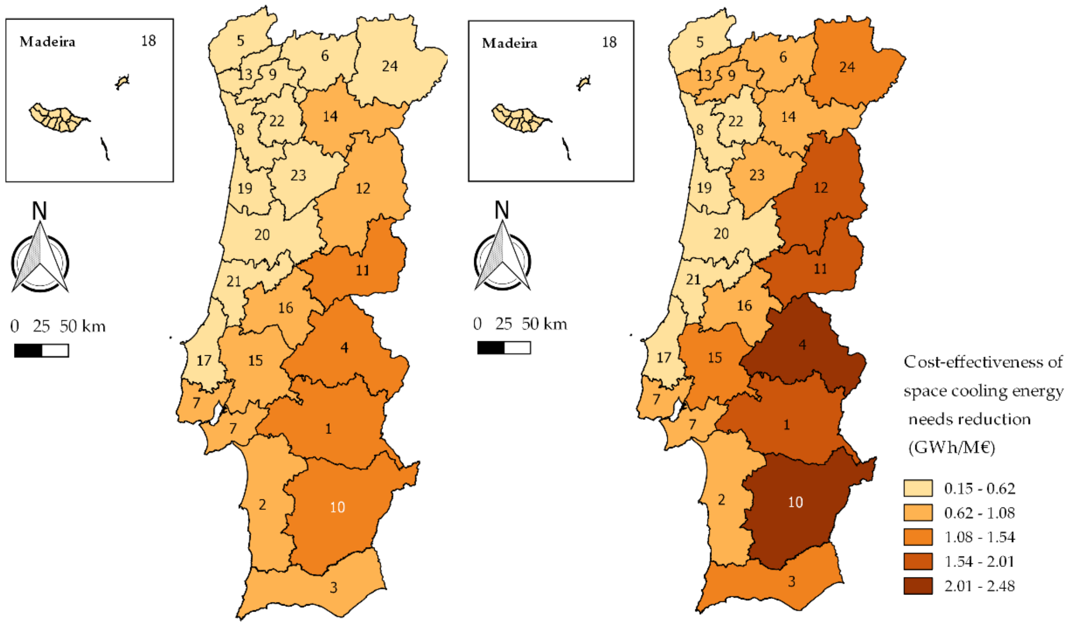
Annex B5 - Cost-effectiveness of windows' renovation in space heating energy need reduction, per NUTS3 regions of Portugal, for Scenario A (left) and Scenario B and C (right)



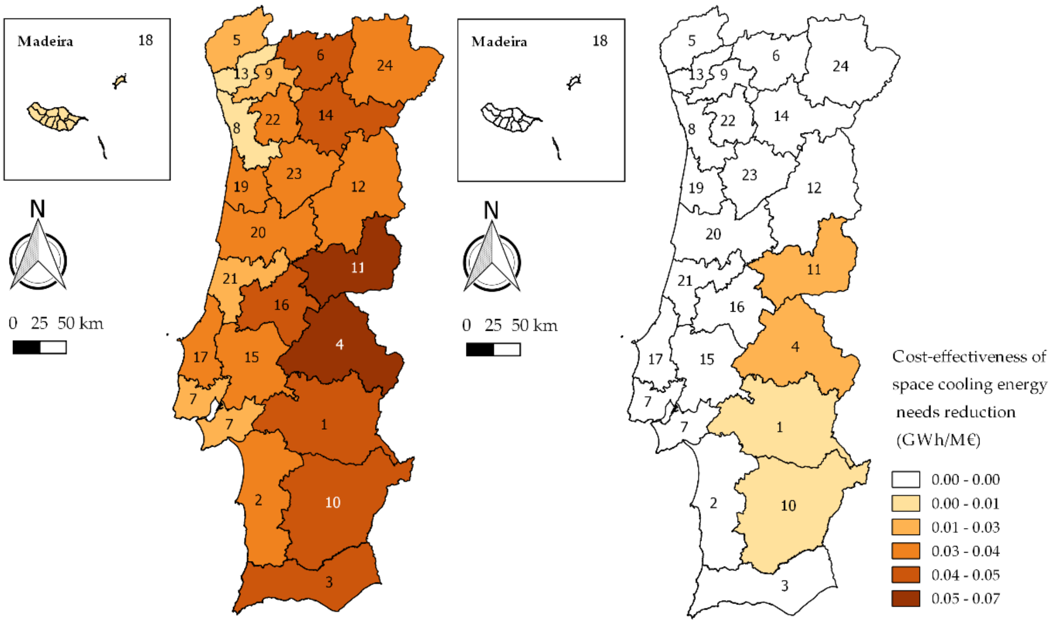
Annex B6 - Cost-effectiveness of wall renovation in space cooling energy need reduction, per NUTS3 regions of Portugal, for Scenario A (left), Scenario B (centre) and Scenario C (right)



Annex B7 - Cost-effectiveness of roof renovation in space cooling energy need reduction, per NUTS3 regions of Portugal, for Scenario A (left) and Scenario B and C (right)



Annex B8 - Cost-effectiveness of windows' renovation in space cooling energy need reduction, per NUTS3 regions of Portugal, for Scenario A (left) and Scenario B and C (right)



Annex B9 - Identification of the best equipment options for energy transition in homes (representative photos taken from the Leroy Merlin and Baxi websites)

Equipment	Characteristics	Energy Use	Aplicability	Cost with equipment and installation
Electric radiators and electric fan heaters 	Low purchase/installation cost. Easy to install and move between rooms. Possibility of more punctual heating compared to centralised systems. Low efficiency (Joule effect), for example when compared to heat pumps, leading to high energy consumption.	Space heating	They can be considered in the case of low-consumption apartments/buildings (NZEB, ZEB) located in mild climate zones where, given the low energy needs, investment in more efficient central heating equipment is not justified. Possibly also for occasional use.	50€ - 150€ per unit 150€ to 450€ average fraction
Biomass heat recovery fireplace 	More efficient burning of biomass when compared to the 'fireplace' option - from 75% to 90% when the theoretical efficiency of fireplaces is around 15%. Generally used for space heating and domestic hot water production, when associated with a water tank. Using biomass as pellets facilitates semi-automatic or automatic fuelling and increases efficiency. Fuel certified as being of sustainable origin should always be used. Uncertainty is associated with the selling price of fuel, which has risen significantly on the European market recently. Also associated with indoor/outdoor air quality problems, as already mentioned.	Space heating	A natural substitute for fireplaces, as it is often possible to integrate it into the existing space for the purposes of air intake and gas exhaust. Even with automatic fuelling, it always requires effort to clean up the ash produced and greater maintenance of the equipment. Not so suitable for apartments due to the associated logistics.	800€ to 3000€
Biomass boiler	Typically, more efficient than stoves and inserts, and more controlled. Most commonly fuelled with pellets and a semi-automatic or automatic feeding system. It uses wall-mounted radiator systems to distribute the heat. Efficiencies from 85 per cent upwards, but they can also be of the 'condensing' type with efficiencies above 100 per cent. They can also be used to produce domestic hot water when	Space heating; domestic hot water	They can be used to replace existing fossil fuel boilers (gas, diesel), providing the same energy service. As with stoves and recuperators, the issue of supply can jeopardise applicability to certain types.	3 000€ to 5 000€

	combined with a water tank.			
Air-conditioning (Air-to-air heat pump) 	Heat pump operating principle, typically with ‘Air-to-Air’ systems and direct expansion installations - mono-split or multi-split. High efficiency, with SCOP and SEER close to 6 or 7 under ideal conditions. At extreme temperatures, efficiency drops significantly. Ease of installation (split and mono-split) when compared to radiator heat pumps or underfloor heating, especially in existing buildings without heat distribution infrastructure. Associated with some air quality/allergy problems due to lack of maintenance and cleaning of air filters.	Space heating and cooling	A more affordable and easy-to-install solution for existing buildings, requiring only façade space (and sometimes condominium authorisation) to install the outdoor unit. Suitable for more occasional occupancies (end of day), such as those of many families, and quicker to reach comfort levels due to the convection effect than radiant systems. However, the quality of comfort is inferior to that of radiant systems..	600€ - 1 000€ split unit (9 000 to 12 000BTU, 20 to 35 m^2) 2 000€ - 4 000€ medium fraction (*e.g.* 27 000 to 36 000BTU, 60 to 100 m^2)
Domestic hot wat heat pump  	As an alternative to a water heater, it represents an investment around 5 times greater. More common than other heat pumps and less expensive, they typically work up to temperatures of 63ºC and have electrical resistance for higher temperatures. Efficiencies (COP) between 3 and 4. They can be compact systems, with all the equipment integrated in the same unit, or with two pieces of equipment inside and outside, the exchanges being carried out through refrigerants between the two. They sometimes require adaptation work, given the need for indoor/outdoor space (technical area) for installation or at	Domestic hot water	In existing buildings, to replace water heaters or thermo-accumulators. Given the need for space, they are easier to integrate into houses than apartments, which require more adaptation work. However, there are already compact solutions, such as hybrid solutions or solutions with outdoor units, which save space inside the home. The current market has a certain distribution between use in apartments and houses, given the diversity of equipment.	Conventional DHW heat pumps: 1 500 to 3 000€

	least the possibility of connection to the outside.			
Hybrid electric storage water heater 	Hybrid solution, smaller in size (80 to 100 litres), with less power than a heat pump (about half that of a conventional one) and which work part of the time as a water heater. Known as hybrid electric storage water heaters, they are around 50 percent less efficient than conventional heat pumps, but they are cheaper, take up less space and do not have to be connected to the outside.	Domestic hot water	For places that have no available space and difficulty connecting to the outside. They can use indoor air to exchange heat without causing discomfort.	1 000 to 1 300€
Heat pump  	High investment, both in the equipment and sometimes in the installation. If low temperature (50-60ºC) they supply underfloor heating and are more efficient with COPs close to 5. If high temperature (70-80ºC), they feed wall-mounted radiators and are less efficient. They can also produce domestic hot water in parallel with a DHW tank. Efficiencies (COP) between 3 and 4. Unlike typical air-to-air systems for homes, known as ‘air conditioning’, they allow for some energy storage (inertia tanks), for example, to take greater advantage of photovoltaic energy. Typically used exclusively for heating. If reversible, they can be used for low cooling needs (underfloor heating). Need indoor/outdoor space (technical area) for installation or at least the possibility of connecting to the outside.	Centralised space heating and Domestic hot water	In existing buildings, to replace fossil fuel or biomass boilers. Given the need for space, they are easier to integrate into houses than apartments, which require more adaptation work. The current market is mainly associated with housing. In new buildings, as long as there is planning (technical area and ventilation ducts), adaptable to the spaces (by fraction or collective). The current high price of construction (€/m^2) is a constraint. However, there are already compact solutions, designed for apartments, in which the indoor unit occupies the same space as a boiler, with the large volume occupied by the outdoor unit.	Exclusive space heating (low or high temperature): €5 000 to €8 000 Space heating and DHW (high or low temperature): €7 000 to €11 000 Exclusive space heating (low or high temperature): €5 000 to €8 000 Space heating and DHW (high or low temperature): €7 000 to €11 000

Solar thermal  	It makes it possible to use the heat from the sun to heat water, typically for DHW, but also sometimes for space heating. Two types of system can be considered in terms of the positioning of the storage tank: ● Thermosiphon Forced circulation. They typically work with electrical resistance support in the storage tank, but can also be associated with heat pumps.	Domestic hot water	It requires the availability of space on the roof and the orientation of the roof, preferably in the south quadrant. Thermosiphon system, although typically less efficient and less durable as the tank is outside, saves space inside the house. Forced circulation system, requires pumping to circulate the heat transfer fluid. Lifespan of around 15 to 20 years, but maintenance needs can be critical to achieving this.	3 000 to 4 500€ (200 to 300 litres)
Solar photovoltaic (support to heat pump) 	Production of electrical energy from solar radiation. Considered here as support for space heating or DHW systems, specifically heat pumps. In order to make the best use of the solar resource, a certain capacity for accumulating energy in DHW and/or inertia tanks must be dimensioned according to use.	Space heating and cooling; domestic hot water; other	Relatively easy to install and low maintenance requirements compared to solar thermal energy. Advantage over solar thermal energy in that surplus energy can be used for other purposes in the home or injected into the grid. Average lifespan of around 25 years, with production falling to 80 per cent of the initial level.	2 200 to 3 400€ (1.5 to 3kW)
Induction hob 	Electric Induction hob Maximum power approx. 7000W	Kitchen	As placas de indução transferem diretamente a energia para o fundo magnético dos tachos e panelas, o que resulta no aquecimento mais rápido e eficiente. De fácil instalação, pode ser efetuada pelo utilizador. Eventual necessidade de reforço de potência da instalação elétrica na zona da cozinha.	111€ to 699€

Electric oven 	Electric oven with maximum power between 1450-3000W.	Kitchen	A more efficient and safer solution than a gas oven. Similar use to a gas oven. Easy installation, can be carried out by the user.	212€ to 1 349€
Wooden stove 	Wood stove with an average power of 8000W	Kitchen	Versão mais moderna e eficiente, com saída de fumos.	1 000€ to 1 500€
LED bulbs 	LED bulbs turn around 70 per cent of electricity into light, making them more efficient than traditional bulbs. They do not use environmentally harmful elements such as lead, mercury and cadmium.	Lighting	Easy installation by the user.	1,2€ to 14€

Annex C

Annex C1 - 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)	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 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."	Scottish Government (2021)
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 an apartment 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)

Annex C2 - Literature review articles 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 utility 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 impact of determinants

Siksnelyte-Butkiene (2021)	Worldwide	Composite EP indicators	Analyse EP indicators to propose a selection of indicators to measure the most important dimensions and to 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.* (2022)	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

Annex C3 - 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, buildings characteristics, equipment, and conservation state, dwelling ownership, 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 10 parishes	Selected sample of households	Area-based composite index (same as Gouveia *et al.*, 2019) + 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 + projections of space heating and cooling equipment stock)	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	Estimating vulnerability in future scenarios

					National Roadmap for Carbon Neutrality 2050					
Panão *et al.* (2021)	Portugal	NUTS3 regions	Whole population	Expenditure-based indicators (LIHC, MIS, 2M)	HBS	Quantitative	Consequences	Economic	Measured	Estimating number of EP households
Matos *et al.* (2022)	Portugal	national level	Whole population	Qualitative (inability to heat; presence of leak, damp 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, (2018)	Spain	Country level	Whole population and selected samples of household	Qualitative indicators (inadequate temperature – winter, arrears on bills, and presence of leak, damp and rot)	SILC	Qualitative	Causes, drivers, and consequences	Climatic, Infrastructural	Perceived	Estimating 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 number of EP people (individuals)
Aristondio & Onaindia, (2018)	Spain	Country level	Whole population and selected samples	Qualitative indicators (inadequate temperature – winter, arrears on bills, and presence of leak, damp and rot)	SILC	Qualitative	Drivers, and consequences	Sociodemographic	Perceived	Estimating number of EP people (individuals) and EP inequality among groups

			of household							
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 number of EP households
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 number of EP households and the significance of each EP drivers
Barrella *et al.*, (2021)	Spain	Country and provincial (NUTS3) level	Vulnerable consumers	Quantitative disproportionate expenditure indicators (Absolute threshold 2M)	Social tariff beneficiaries' database	Quantitative	Consequences	Economic, Infrastructural, Sociodemographic, climatic	Measured	Estimating 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 leak, damp and rot)	SILC	Qualitative	Consequences	Economic, Sociodemographic	Perceived	Estimating number of EP households before and after social electricity tariff, and Difference-in-differences assessment

Bagnoli *et al.*, (2022)	Spain	Country and regional (NUTS2) level	Whole population and selected samples of household	Quantitative disproportionate expenditure indicators (2M)	HBS	Quantitative	Drivers and Consequences	Economic, Sociodemographic	Measured	Estimating 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 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	Qualitative (inadequate temperature – winter, arrears on bills, and presence of leak,	SILC	Mixed	Consequences	Economic, Sociodemographic	Measured and Perceived	Estimating number of EP

			selected samples of household	damp and rot) and quantitative (10% and income poverty) indicators						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 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
Arce (2019)	Spain	country level	whole population	ration of electricity expenditure and family income over 80% 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 effectiveness of subsidy in reducing EP
Aguilar *et al.* (2019)	Spain	country level and one region	whole population	10% Indicator; 2M; LIHC; ADCP; MIS;	Household Budget Survey	quantitative	consequences	economic	measured	measure and compare EP in Spain and Canary Islands
Sánchez-Torija *et al.* (2022)	Spain	country level	whole population	Maximum square metres of housing eligible without being in EP (calculated with 2M)	Household Budget Survey; Living Conditions Survey	quantitative	consequences	economic	measured	proposing 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 to EP

EXPLORING ENERGY POVERTY MEASUREMENT ACROSS SPATIAL AND TEMPORAL SCALES: INSIGHTS FOR MULTILEVEL FUTURE POLICY-MAKING IN PORTUGAL

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2024