A multi-criteria classification approach for assessing energy poverty in the European Union

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I declare that this document is an original work of my own authorship and that it fulfills all the requirements of the Code of Conduct and Good Practices of the Universidade de Lisboa.

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Abstract

Energy poverty is a prevalent problem in the European Union that affects people's health and affects sustainable development. In the literature, a small number of studies that attempted to measure the extent of energy poverty in the EU was found, and none of the methods from the ELECTRE family, Multi-Criteria Decision Analysis methods, had been applied in the context of measuring energy poverty. The purpose of this study was to classify energy poverty in European Union member states in the year of 2020 through a multi-criteria classification approach, by using the ELECTRE-Tri-nC method. The SRF method was also used to complement the ELECTRE-Tri-nC to assign weights to the chosen criteria. We built a model that integrated 9 criteria to classify 24 European Union member states according to their energy poverty level. The results of the carried out study showed that, generally, Eastern and Southern Europe have a high energy poverty level, the Scandinavian countries studied in this work, and Central Europe, have a low energy poverty level, and western Europe and the Baltic countries have a moderate energy poverty level.

Key words

Energy poverty, fuel poverty, European Union, Multi-criteria Decision Analysis/Aiding, ELECTRE-Tri-nC.

Resumo

A pobreza energética é um problema recorrente na União Europeia que afeta a saúde das pessoas e o desenvolvimento sustentável. Encontrámos um pequeno número de estudos com o objetivo de medir pobreza energética na UE, e os métodos de Análise de Decisão Multi Critério da família ELECTRE não foram usados em nenhum contexto de medição de pobreza energética. O propósito deste estudo é classificar a pobreza energética nos estados-membro da União Europeia no ano de 2020, através de uma abordagem de classificação multi critério, usando o método ELECTRE-Tri-nC. O método SRF também foi utilizado, como complemento ao método ELECTRE-Tri-nC, para alocar pesos aos critérios escolhidos. Construímos um modelo que integrou 9 critérios para classificar 24 estados-membro da União Europeia de acordo com o nivel de pobreza energética deles. Os resultados do estudo realizado demonstraram que, de um modo geral, a Europa de Leste e do Sul têm um nível de pobreza energética elevado, os países da Escandinávia estudados e a Europa central têm um nível de pobreza energética baixo, e os países da Europa Ocidental e os países bálticos tem um nível de pobreza energético elevado.

Palavras-chave

Pobreza energética, União Europeia, Análise de Decisão Multi critério, ELECTRE-Tri-nC.

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1 Acronyms and abbreviations

AC	Area of Concern
AHP	Analytical Hierarchy Process
CEPI	Compound Energy Poverty Indicator
EC	European Commission
ELECTRE	ELimination Et Choix Traduisant la Realité (ELimination and Choice Expressing the Reality)
EP	Energy Poverty
EPAH	Energy Poverty Advisory Hub
EPOV	Energy Poverty Observatory
EU	European Union
FPV	Fundamental Point of view
GIS	Geographic Information System
LIHC	Low Income High Costs
MCDA	Multi-Criteria Decision Analysis/Aiding
MCDA-ULaval	Multi-Criteria Decision Aiding Université Laval
NECP	National Energy and Climate Plan
OECD	Organization for Economic Cooperation and Development
SDG	Sustainable Development Goals
SILC	Statistics of Income and Living Conditions
SRF	Simos, Roy and Figueira
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution
UK	United Kingdom
WHECA	Warm Homes and Energy Conservation Act

2 Introduction

Energy poverty is a challenge that people face all over the world and the European Union is no exception. In the European Commission (2021) State of the Energy Union report, it is stated that 31 million people in the EU were affected by energy poverty in 2019. Furthermore, since Russia's invasion of Ukraine in February of 2022 and the consequent ongoing war between these two countries, the number of energy poor is expected to have increased due to the rise in energy prices (Kryk & Guzowska, 2023).

Households rely on energy, in its various forms, to guarantee adequate living conditions. As such, energy poverty has several consequences, direct and indirect, on one's health and well being. Its indirect effects on health include poor mental health, such as suffering from anxiety, stress, and depression. Its direct effects include aggravation of cardiovascular and respiratory diseases, and heat strokes, as these are linked to extreme indoor temperatures. Furthermore, cold households have been proven to exacerbate health conditions such as flu, arthritis, colds, and rheumatism. The worst health outcome related to energy poverty phenomenon is excess winter mortality, which is the surplus number of deaths occurring for four winter months compared to the average number of deaths for non-winter months. Children have also proven to be deeply affected by energy poverty, these effects may include low educational attainment, and increased absence from school (Energy Poverty Advisory Hub, 2022b; Recalde et al., 2019).

Not only does the energy poverty problem pose as a great threat to people's health, but it also affects sustainable development, as it limits the ability of citizens to benefit from and actively take part in the energy transition (Kryk & Guzowska, 2023). For this reason, mitigating energy poverty was included in one of United Nation's Sustainable Development Goals (SDG). The seventh SDG strives to "Ensure access to affordable, reliable, sustainable and modern energy for all by 2030." (United Nations, 2015). What is more, there are other two SDGs that pertain to the energy poverty issue, SDG1, which is to eradicate all forms of poverty, and SDG 3, that aims to ensure healthy lives and promote well-being for all (United Nations, 2015).

The United Kingdom (when it was still part of the EU) and Ireland were the only two member states where the existence of fuel poor was widely recognized and brought attention to in policies, research and public debates for a long time. The term "energy poverty" first appeared in the European Union legislation in 2009. Consequently, several EU measures to eradicate energy poverty are already ongoing, including EU directives and other initiatives, such as the Energy Poverty Advisory Hub (EPAH), and several EU funded projects tackling the issue. Nevertheless, an accurate energy poverty assessment is needed to help guide policy development, implementation, and follow up in the European Union.

The methods used to assess energy poverty may vary. Initially energy poverty was measured with uni-dimensional indicators. Such as Boardman (1991), who determined that energy poverty in a household has to do with the ratio between required fuel costs and income, or Hills (2012), who came up with the Low Income High costs indicator.

Despite this, most authors believe energy poverty to be a multidimensional problem and that it should be measured as such. Alkire et al. (2015) identify a number of approaches to measuring energy poverty multidimensionally, this is, to capture a spectrum of several elements that reflect the problem. The most common approaches found in the literature are the counting approach and the composite index approach. Regarding the latter approach, Multi-Criteria Decision Analysis (MCDA) models and methods are used to build these indices. In some studies, simple additive or weighted sum methods are used (Bouzarovski & Tirado-Herrero, 2017; Maxim et al., 2017). In other papers, more complex methods are adopted, such as TOPSIS (Arsenopoulos et al., 2020; Che et al., 2021), or AHP (Llera-Sastresa et al., 2017; März, 2018).

Since only eleven studies were found that assess energy poverty in the European Union, we build on the existing literature by assessing energy poverty in the European Union in the year of 2020. In this work, we contribute to the existing literature by applying a multi criteria classification approach that has not been used in this context, the ELECTRE-Tri-nC, to classify EU member states in terms of energy poverty in an attempt to answer the following research questions:

(1) How can we assess the energy poverty of EU member states in a structured framework?

(2) Can energy poverty patterns be discerned across the EU based on the varying levels of energy poverty among member states?

The present work is structured in the following way: Section 3 touches on the main European Union directives and initiatives that, among other things, contributed, or contribute, to energy poverty mitigation. Section 4 provides a literature review of the relevant studies of energy poverty, going into detail about the existing indicators and methods, the data sources used, and the energy poverty definitions adopted. Section 5 describes the methodology used in this work by introducing multi-criteria decision analysis/aiding (MCDA), the ELECTRE-Tri-nC method and the SRF method. Section 6 consists of the problem identification and structuring, in which the problem is presented and the value tree is built. Section 7 details the model building and use, this is, it describes the implementation of the model. Section 8 reports the results of the model implementation detailed in the previous section. Section 9 presents the results of the different analyses done to the model: stability, sensitivity, and scenarios analyses. Section 10 critically discusses the results by comparing them with general and particular findings in the literature. Finally, section 11 includes the main conclusions, limitations, policy implications of this work, and possible future research.

3 EU Policies and other initiatives

This section touches on the main European Union directives and initiatives that, among other things, contributed, or contribute, to energy poverty mitigation.

3.1 Electricity Directive (European Union, 2009a) and Gas directive (European Union, 2009b)

The term “energy poverty” first appeared in the European Union legislation in 2009, with the first Electricity Directive (2009/72/EC, repealed) and the Gas Directive (2009/73/EC). The directives required member states to develop action plans, nationally, and other applicable frameworks to mitigate energy poverty, protect vulnerable customers, and define them. The directives provide examples to do this, such as forbidding the disconnection of gas and electricity in tough times and improving energy efficiency.

3.2 The Regulation on the Governance of Energy Union and Climate Action (European Union, 2018)

The Regulation on the Governance of Energy Union and Climate Action (EU) 2018/1999 became effective in December 2018. In it, member states are requested to estimate the number of energy poor households and include it in their National Energy and Climate Plan (NECP), which is a 10 year long plan during the period of 2021 and 2030. If the estimation reveals a significant number of households in energy poverty, the member states in question must include in their NECP an objective to combat energy poverty, along with policies and actions to alleviate the phenomenon, with timelines, and reports on the progress.

Due their obligation to evaluate energy poverty, several EU nations have incorporated targeted measures in their national policies and creating their own definitions, measuring and monitoring techniques, and solutions to address energy poverty.

3.3 Energy Performance in Buildings Directive (European Union, 2010)

The Energy Performance in Buildings Directive demands that member states develop long-term renovation plans as part of their NECPs to help transform the nations’ building stock into a highly energy-efficient and carbon-free building stock by the year 2050. This strategy must define pertinent national initiatives that help eradicate energy poverty as well as a basic notion of the measures and policies to target the least efficient portions of the nation’s building stock.

3.4 Directive on common rules for the internal market for electricity (European Union, 2019)

According to the Directive on common rules for the internal market for electricity, EU member states are required under Article 5 to protect vulnerable consumers and the energy poor, via social policy or other measures that have an impact on the price setting of the electricity supply.

Furthermore, EU members are required by Article 27 to make sure that universal service is provided to all residential consumers and small businesses, if appropriate. Additionally, it allows consumers to name a supplier of last resort and imposes on the distribution system operators the duty to connect clients to their networks in accordance with the directive's conditions.

Article 28 of the same directive also requires member states to take measures to protect vulnerable customers, such as providing adequate safeguards, prohibiting electricity disconnection during critical times, being transparent about the terms of contracts, providing general information and providing dispute resolution procedures, providing benefits under social security systems, supporting the advancement of energy efficiency, and taking other actions to combat energy poverty. Customers in rural places should also be given extra security.

Article 29 of the directive recalls the obligation of member states to determine a set of criteria to evaluate energy poverty, as it is stated in the Regulation (EU) 2018/1999. Low income, a large percentage of discretionary income spent on energy, and ineffectiveness are only a few examples of the criteria. Moreover, it requests guidance from the European Commission on what constitutes a "substantial number of households in energy poverty".

3.5 Energy efficiency directive (European Union, 2012)

The energy efficiency directive is also relevant to the mitigation of energy poverty. According to its Article 7, member states must take into account the need to reduce energy poverty, for example by mandating a portion of energy efficiency measures or by using alternative measures, and must implement programmes with a focus on vulnerable households, including those who are experiencing energy poverty. The directive also states that the national energy and climate progress reports must include data on the results of the initiatives taken to decrease energy poverty.

Similar provisions can be found in the Commission's July 2021 proposal to recast the Energy Efficiency Directive, which defines energy poverty as "a household's lack of access to essential energy services that support a decent standard of living and health, including adequate warmth, cooling, lighting, and energy to power appliances, in the relevant national context, existing social policy, and other relevant policies." However, this legislative procedure is still ongoing. Thus, there is still no standard definition at an EU-level of energy poverty.

3.6 Commission Recommendation (European Commission, 2020a)

As mentioned above, the commission must give guidelines on the definition of "substantial number of homes in energy poverty" and on suitable indicators for evaluating energy poverty, according to the Directive on common rules for the internal market for electricity. As such, the Commission published a recommendation on energy poverty on October 14th, 2020, in which energy poverty is described as “a situation in which households are unable to access essential energy services.”. Moreover, it lists these essential services, which are “adequate warmth, cooling, lighting, and energy to power appliances are essential services that underpin a decent standard of living and health.”

Despite providing a definition, the Commission points out that there is no universally accepted definition of energy poverty, therefore, it is up to individual member states to create their own criteria by taking into account their particular national contexts.

The recommendation includes a list of indicators produced by Eurostat (Statistical office of the European Union) and EPOV (Energy Poverty Observatory) (table 3.1). Besides the listed indicators, national indicators are recommended to be used as a complement, as they can improve the identification of energy poverty.

3.7 Other initiatives

3.7.1 Commission Energy Poverty and Vulnerable Consumers Coordination Group (European Union, 2022)

The Commission Energy Poverty and Vulnerable Consumers Coordination Group , formed by the European Union Commission formed in April of 2022, intends to give EU member states a platform to exchange best practices and improve coordination of policy measures to benefit vulnerable and households in energy poverty.

3.7.2 Energy Poverty Advisory Hub (EPAH) (European Commission, n.d.-b)

The Energy Poverty Advisory hub is the predecessor of EPOV (Energy Poverty Observatory). The hub offers a space for collaboration and exchange for regional and local authorities to mitigate energy poverty and fast forward a just energy transition for local governments in Europe.

The hub provides a variety of resources to assist stakeholders in the implementation of practical actions to eradicate energy poverty, such as publications, the EPAH ATLAS, an online interactive database that enables stakeholders to learn about national and international initiatives and measures addressing the energy poverty issue, online courses to deepen participants’ understanding of energy poverty and its mitigating measures, and calls for technical assistance to directly support local governments.

3.7.3 EU funded Projects tackling Energy Poverty (European Commission, n.d.-a)

Between 2014 and 2020, 16 projects on energy poverty were funded by the EU under Horizon 2020, a research and innovation programme, having been granted with roughly 29 million euros. One of the funded projects is

Table 3.1: List of recommended indicators

Indicators	Data source
Indicators focusing on the affordability of energy services	
Share of population at risk of poverty (below 60% of national median equivalised disposable income) not able to keep their home adequately warm, based on the question 'Can your household afford to keep its home adequately warm?'	Eurostat, SILC
Share of total population not able to keep their home adequately warm, based on the question 'Can your household afford to keep its home adequately warm?'	Eurostat, SILC
Arrears on utility bills: share of population at risk of poverty (below 60% of national median equivalised disposable income) having arrears on utility bills	Eurostat, SILC
Arrears on utility bills: share of population having arrears on utility bills	Eurostat, SILC
Expenditure on electricity, gas and other fuels as a proportion of total household expenditure	
Proportion of households whose share of energy expenditure in income is more than twice the national median share	Eurostat, Household Budget Surveys, 2015
Share of households whose absolute energy expenditure is below half the national median	Eurostat, Household Budget Surveys, 2015
Complementary indicators	
Electricity prices for household consumers – average consumption band	Eurostat
Gas prices for household consumers – average consumption band	Eurostat
Gas prices for household consumers - lowest consumption band	Eurostat
Share of population at risk of poverty (below 60% of national median equivalised disposable income) with leak, damp or rot in their dwelling	Eurostat, SILC
Share of population with leak, damp or rot in their dwelling – total population	Eurostat SILC
Final energy consumption per square metre in the residential sector, climate-corrected	Odyssee-MURE project database

ENPOR, which aims to make energy poverty visible and measurable in the private sector. Another is STEP (Solutions to Tackle Energy Poverty), which investigates behavioural change and cost-effective energy solutions to alleviate energy poverty. A third project is SocialWatt, which aims to support the creation and testing of innovative energy poverty programmes.

Over the period of 2021 to 2027, the EU has another programme, the LIFE Clean Energy Transition Programme, with a budget of around 1 billion euros to finance projects that further explore ways to reduce the energy poverty problem. The funded projects include RENOVERTY, which seeks to promote the renovation of central, eastern, and southern European buildings in a cost- and energy- efficient manner, and REVERTER, that aims to reduce households' vulnerability to energy poverty through extensive renovation roadmaps.

3.8 Conclusion of EU Policies and other initiatives

While the topic of energy poverty emerged largely in the scientific community in 1991 (Boardman, 1991). Energy poverty emerged in the policy agenda sporadically at first and more frequently during recent years. As such, the energy poverty issue has been growing its importance in the EU in recent years, as the European Commission has been taking heed of energy poverty policies, and, consequently, several measures to alleviate energy poverty are already ongoing, and this phenomenon is expected to be strengthened in the future.

This overview of policies also demonstrates that there is available data at the EU level, enabling an evaluation of energy poverty. Moreover, a list of indicators at this level exists. Nevertheless, there is still space for additional indicators beyond those recommended by the Commission.

The Commission's recommendation on energy poverty and the proposal to recast the Energy Efficiency Directive represent notable progress towards establishing an official definition of energy poverty in the EU. However, as of now, such a definition does not exist, leaving it to the member states to formulate their own definitions.

The European Union has made legislative efforts to acknowledge the energy poverty problem and provide a framework for monitorization and mitigation of the phenomenon at the member state level. Despite these efforts, there has not been an EU-wide agreed measurement, and a detailed understanding of the problem as a whole across the EU. Several authors argue that, despite the increasing significance of the energy poverty issue in the EU agenda, the policy recommendations are vague, impractical, and inadequate (Bouzarovski, 2018). The literature highlights that the primary obstacle to addressing this problem effectively is the reluctance to adopt a unified and commonly agreed definition (Bouzarovski, 2018).

4 Literature Review

It was during the oil crisis in the early 1970s that the problem of fuel poverty was first recognized. Nine years later, Isherwood and Hancock were some of the first to define "victims of fuel poverty" (Liddell et al., 2012). For the following ten years, the term appeared sporadically in the scholarly literature. It was only when Boardman (1991) published her book on fuel poverty in the United Kingdom, that the phenomenon became more known in the scientific community. Since then, energy poverty has become a broadly recognized term (Bouzarovski & Petrova, 2015). Consequently, the number of publications that include the key words fuel poverty, energy poverty, and energy vulnerability has increased. This increase has been exponential in recent years (Hassani et al., 2019). The main objective of this literature review is to provide an overview of the existent methods that assess energy poverty, as well as to present the spectrum of different energy poverty definitions adopted by the authors and the data sources used in the literature, and to discuss the existing studies that measure energy poverty in the EU, in order to identify a research gap .

4.1 Literature Review Methodology

The selection of articles for this literature was done in three steps. The first step was to select highly cited papers in *Web of science* database according to the following search terms: “Energy poverty assessment”, “Energy poverty evaluation”, “Energy poverty indicator”, “Energy vulnerability assessment”, “Energy vulnerability evaluation”, “Energy vulnerability indicator”, “Fuel poverty assessment”, “Fuel poverty evaluation”, “Fuel poverty indicator”. The second step was to select relevant articles, reports, and books that were referenced in the ones selected in the first step. The documents selected in the second step were searched in *Web of science*, *Research Gate*, and *Science Direct* databases. The third step was to search for existing papers on energy poverty measurement in the EU, this was done by adding the words "EU", "European Union", and "Europe" to the search terms mentioned above and using these new search terms in *Web of science*, *Research Gate*, and *Science Direct* databases.

4.2 Energy poverty terms

The authors refer to energy deprivation problems mainly by using 3 different terms. Some authors use the term ’energy poverty’ (Barnes et al., 2011; Betto et al., 2020; Bienvenido-Huertas et al., 2022; Che et al., 2021; Hassani et al., 2019; Jiang et al., 2020; Papada & Kaliampakos, 2018; Sadath & Acharya, 2017; Sokołowski et al., 2020; Zhao et al., 2021), others use the term ’fuel poverty’ (Boardman, 1991; Churchill et al., 2020; John, 2011; Llorca et al., 2020; März, 2018; Simões et al., 2016), and in some cases, the term ’energy vulnerability’ is used (Llera-Sastresa et al., 2017). There are authors that distinguish these terms, for instance, Bouzarovski and Petrova (2015). There are other authors that stress its similarities: "EP, also known as energy vulnerability" (Bienvenido-Huertas et al., 2022); "Energy poverty – which has also been recognised via terms such as ‘fuel poverty' and 'energy vulnerability" (Thomson et al., 2017). In this dissertation, we consider the terms energy poverty, energy vulnerability, and fuel poverty to be interchangeable.

4.3 Energy poverty measurement

Researchers have been seeking methods to evaluate energy poverty. At first, the phenomenon was assessed using uni-dimensional indicators. Nevertheless, a consensus among most authors now exists, acknowledging that energy poverty is a multidimensional issue. Uni-dimensional indicators fall short of fully capturing its comprehensive scope and impact. Hence, it should be measured at the appropriate scale. This is, there should be more than one energy-related variable or dimension considered when evaluating energy poverty. Section 4.3.1 will provide an overview of the existent uni-dimensional energy poverty indicators and section 4.3.2 will provide an overview of the existent multidimensional energy poverty measurements.

One thing that is important to note is that a measurement of poverty requires a reference population, such a country's population or European Union's population. Moreover, it is assumed that any reference population consists of at least one unit of analysis. When measuring fuel poverty, the unit of analysis is most of the time an individual or a household (Alkire et al., 2015).

4.3.1 Uni-dimensional energy poverty indicators

Uni-dimensional indicators assess energy poverty of the unit of analysis (individual or household) by a presented thresholds or energy poverty line (Alkire et al., 2015). The uni-dimensional measurements described in this section are mostly focused on one dimension of energy poverty that is expenditure based (energy costs, energy consumption, income and household costs).

The most commonly used uni-dimensional indicator is the threshold created when energy poverty (or fuel poverty) was first officially defined in the United Kingdom by Brenda Boardman's book of 1991. The book states that "a household is said to be fuel poor if it needs to spend more than 10% of its income on fuel to maintain an adequate level of warmth", as depicted in equation 1 (Boardman, 1991). This measure was adopted by the UK in the year 2000.

$$\text{Fuel poverty ratio} = \frac{\text{Required fuel costs (required consumption x price)}}{\text{Income}} > 10\% \tag{1}$$

This indicator is open to a number of criticisms. Due to the difficulty of modelling the energy consumption, the actual energy consumption is sometimes used instead of the required fuel costs to calculate the fuel poverty ratio, which underestimates the real needs of households (Papada & Kaliampakos, 2018). Hills (2012) argues that this fuel poverty ratio is overly sensitive to changes in price levels and to technicalities within its calculation. Thus, it reports misleading trends that do not reflect the underlying problems of energy poverty, and its definition can encompass households that are not poor (Hills, 2012). The fact that the rate 10% is arbitrary and that the index is adopted only to the specific conditions of the UK are also mentioned as faults in the indicator (Papada & Kaliampakos, 2018).

Papada and Kaliampakos (2018) try to address some of this criticism. To adapt the fuel poverty ratio to different countries, Papada and Kaliampakos (2018) use the Stochastic Model of Energy Poverty (SMEP) to calculate a similar index to the Boardman's that could be adjusted to the special features of energy poverty in each country. Papada and Kaliampakos (2018) use the threshold of 10% as in the definition stated by Boardman (1991); however, the authors mention that the threshold can be adjusted to any other, if it is defined differently in other countries.

Hills (2012) proposes an alternative approach to the Boardman's 10% ratio: the Low Income High Costs (LIHC) indicator. This approach is focused on individuals in households "living on a lower income in a home that cannot be kept warm at a reasonable cost." (as described by Warm Homes and Energy Conservation Act 2000 (WHECA) in the UK).

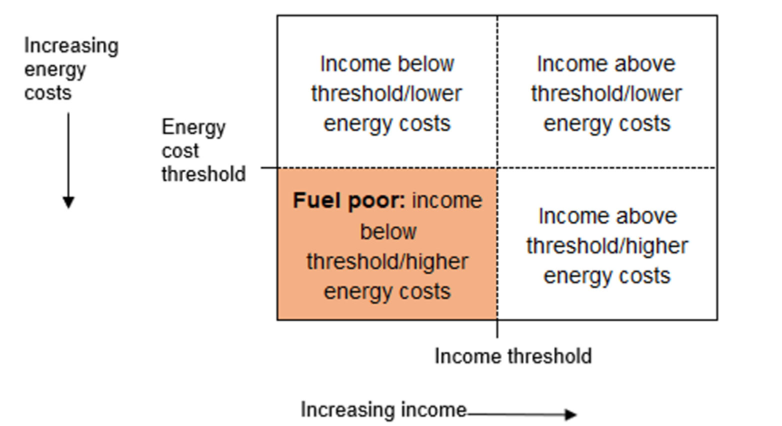


Figure 4.1: LIHC indicator. Adapted from Hills (2012)

As it can be observed in figure 4.1, the LIHC indicator has two thresholds, one for income and another for energy costs. The author proposes for the energy costs threshold the equivalised [1] median modelled bill; and for the income threshold 60% of the equivalised residual income [2]. Despite having two thresholds, we consider the LIHC indicator to be uni-dimensional because both of its thresholds are expenditure-based.

Therefore, according to the LIHC indicator, households that are below the conventional 60% of the median residual income poverty line and have fuel costs above the median level are considered fuel poor. In this way, a fuel poverty headcount is done (Hills, 2012).

Besides identifying fuel poor households, this method can also identify the extent to which household's are energy poor, this is, it identifies the fuel poverty gap, which is the extent to which people's incomes fall short of

[1] Equivalisation is to set all household sizes and types on the same basis compared to a standard. What might be a reasonable bill for a large household could be unreasonable for a small one. Both income and cost thresholds should be adjusted for household size (Hills, 2012).

[2] Residual income is the income after housing and domestic fuel costs (Legendre & Ricci, 2015).

the threshold and the extent to which costs go above the threshold (Hills, 2012).

There are many advantages to this approach when compared to the 10% threshold approach. It allows to calculate separately the extent of fuel poverty and the depth of it. Calculating the extent of fuel poverty relative to the calculated requirements of the mainstream population is more robust than Boardman (1991)'s method, both in terms of avoiding data problems and sensitivities to technical choices. This indicator is more stable in terms of who is identified as fuel poor, therefore, it is more stable in assessing the effectiveness of interventions and how well they are targeted on those at risk of fuel poverty. The fuel poverty gap allows the impact of some interventions to be seen even if they do not put someone out of fuel poverty (Hills, 2012).

Despite its advantages over Boardman (1991) ratio, the LIHC has also been criticised because it can mask the impact of increasing energy prices and complicates the monitoring of the effect of political interventions (März, 2018).

The LIHC indicator was adopted in 2015 in the UK. Furthermore, this indicator has been applied in other countries, for example, Legendre and Ricci (2015) successfully used the indicator to assess energy vulnerability in France.

Tirado-Herrero and Ürge-Vorsatz (2012) apply 3 different expenditure based thresholds to assess energy poverty in Hungary: (1) energy costs are equal or above the median relative energy expenditure of the three lowest income deciles. (2) energy costs are equal or above twice the median relative energy expenditure. (3) household's energy costs are larger than its food and non-alcoholic beverages costs. The first two are the underlying criteria employed by Boardman (1991) to define in the 10% threshold, however total household expenditure was used instead of income because the authors consider it to be a more accurate estimate of purchasing power.

Like Boardman (1991)'s approach, Barnes et al. (2011) use energy consumption and income to define an indicator to determine energy poverty in rural Bangladesh. The indicator is set by defining an energy poverty threshold based on the basic minimum level of energy consumption that a household must maintain to subsist. This is, the minimum quantity for lighting, cooking and heating. This threshold is defined by looking at the energy demand function (by looking at how household energy demand varies with changes in household income and other major welfare indicators). At lower income levels, household energy demand is fairly constant and is not related to income. It is assumed that those households consume the minimum amount of energy (or less) at basic sustenance levels. But at higher income levels, there is a significant positive relationship between income and energy demand. The threshold point is the point at which energy consumption begins to increase with increases in households income. At or below the threshold point, the households consume a bare minimum level of energy and should be considered energy poor.

Jiang et al. (2020) extended the Barnes et al. (2011) method to assess energy vulnerability in rural Qinghai, China, by considering the affordability of modern energy rather than focusing on the minimum energy requirement of life. This is done because Jiang et al. (2020) want to distinguish those who are income poor from those who are energy poor. The authors argue that measuring energy poverty by focusing on the minimum energy requirement for life, like Barnes et al. (2011) did, does not fit in some contexts, because, for example, energy poor households could be consuming more energy that non-energy poor households, since energy poor households could be using less efficient and less clean energy sources (such as coal instead of biogas and solar energy). To do this, Jiang et al. (2020) examine the relationship between energy share and household income, by using regressions and define an energy poverty threshold based on this relationship.

4.3.2 Multidimensional energy poverty measurements

As mentioned earlier, a prevailing viewpoint among authors is that energy poverty exhibits a multidimensional nature. Consequently, the most common approach found in the literature for analyzing the phenomenon is through a multidimensional lens. As such, there is a necessity to capture a spectrum of several elements to reflect this complex phenomenon.

There are several approaches to measuring fuel poverty multidimensionally (Alkire et al., 2015). The most common ones found in the literature are the counting approach (Aristondo & Onaindia, 2018; Betto et al., 2020; Sokołowski et al., 2020) and the composite index approach (Arsenopoulos et al., 2020; Bouzarovski & Petrova, 2015; Che et al., 2021; Llera-Sastresa et al., 2017; März, 2018; Maxim et al., 2017).

The counting approach identifies the energy poor according to the number (count) of dimensions they are deprived in. This is done through the dual cut-off. Firstly, by determining if the individuals are deprived or not in each dimension and secondly by determining if they are energy poor or not, considering the number of dimensions in which they are deprived. After the dual cut-off, a deprivation value is assigned to each individual or household, which depends on their deprivation values in all dimensions (Alkire et al., 2015). Once the energy poor have been identified, some authors, such as Aristondo and Onaindia (2018) and Sokołowski et al. (2020) use a composite index approach to aggregate individual poverty.

The counting approach allows for an individual or household to be identified as energy poor in at least one dimension, at least two dimensions, at least in one specific dimension, etc. Aristondo and Onaindia (2018) take into account 3 dimensions to measure fuel poverty and considered energy poor individuals in 3 different situations: individuals deprived in 1 dimension, 2 dimensions or 3 dimensions to reach conclusions on fuel poverty in Spain. Betto et al. (2020) identify hidden energy poverty in Italy if households are deprived in all of the considered dimensions: if the energy expenditure is below a fixed threshold, their total expenditure is below the relative threshold, they are in absolute poverty and their dwellings are not well insulated. Sokołowski et al. (2020) define households as energy poor in Poland if at least two out of the five following forms of deprivation are present: low income high costs, high actual cost, not warm enough home, housing faults, and bills difficulties.

It must be noted that, in the counting approach, choosing different cut-offs to identify energy poor, or choosing different dimensions, criteria or variables to evaluate energy vulnerability adds arbitrariness, since different choices can lead to different or contradictory results (Aristondo & Onaindia, 2018).

A composite index is a function that assigns relative weights to indicators and transforms deprivation indices into a real number (Alkire et al., 2015). On the one hand, composite indices satisfy the need to aggregate information to a level that makes analysis convenient. Thus, it is extremely useful for policy analysis and public communication and allows comparisons across countries. On the other hand, this process includes some sort of reduction to a single measure, which can lead to simplifying too much the analyses of the results. This can be misleading in terms of policy (Nussbaumer et al., 2012). Nevertheless, the composite index approach stands out as a widely employed methodology in measuring energy poverty. Upon reviewing the literature, it becomes evident that this method has gained significant prominence and has been the most frequently utilized approach in recent years.

Composite indices may be naturally regarded as a multi-criteria issue. As such, there are simpler multi-criteria decision analysis (MCDA) methods applied to build a composite index, such as the simple additive method, or weighted sum. Maxim et al. (2017) and Bouzarovski and Tirado-Herrero (2017) built composite fuel poverty indices, the Compound Energy Poverty Indicator(CEPI) and the Energy Poverty Index, through a weighted sum of the variables chosen to assess the phenomenon in the European Union, as depicted in equations 2 and 3, respectively. The variables depicted in these equations are further detailed in table 4.2.

$$\text{CEPI} = (0,3\text{x not warm} + 0,2\text{x Not cool} + 0,1\text{x Dark} + 0,2\text{x Arrears} + 0,2\text{x Leaks})\text{x}100 \quad (2)$$

$$\text{Energy Poverty Index} = (0,5\text{x \% Inability} + 0,25\text{x \%Arrears} + 0,25\text{ x \%Housing faults})x100 \quad (3)$$

Other more advanced approaches to build composite indices deriving from multi-criteria decision analysis are used in this context. Arsenopoulos et al. (2020) take the TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) approach to rank eleven EU countries regarding their resilience against energy poverty. Che et al. (2021) resort to an improved TOPSIS approach to evaluate energy vulnerability in 125 countries. The AHP approach (Analytical Hierarchy Process) is another approach that has been used by some authors (Llera-Sastresa et al., 2017; März, 2018). März (2018) uses the AHP technique for a GIS-MCDA (Geographic Information System Multi-Criteria Decision Analysis) to compare fuel poverty vulnerability of urban neighbourhoods in Oberhausen, Germany. Llera-Sastresa et al. (2017) use AHP as well to measure energy vulnerability in Spain.

As far as this literature review goes, the ELECTRE methods have not been applied in this context, despite being amongst the most widely used methods in MCDA (Amor et al., 2022).

4.3.3 Dimensions and criteria

Multidimensional fuel poverty assessment authors select both quantitative and qualitative dimensions and criteria in their methods, as depicted in table 4.2. The several dimensions and criteria selected reflect the different ways of approaching this phenomenon and the different views on it. Their selection, often made by stakeholders or experts on the matter, is largely dependent on their knowledge, implying the subjectivity of the methods

(Arsenopoulos et al., 2020). Thus, the results' validity can be limited by the subjectivity of these people (März, 2018).

Besides Arsenopoulos et al. (2020), who take a different approach when it comes to the chosen dimensions and criteria, the other authors chose dimensions and criteria that are in similar realms. Dimensions that reflect the expenditure or consumption of the unit of analysis and the building's condition of the unit of analysis are among the most commonly found.

It is important to highlight the fact that, as pointed out by Bienvenido-Huertas et al. (2022), the lack of available data may limit in some cases the extent of the dimensions used.

The chosen dimensions and criteria in this work are further detailed in chapter 6.

Table 4.2: Multidimensional measurement

Study	Method	Dimensions	Criteria
Aristondo and Onaindia (2018)	Counting and composite index approach		Ability to keep the home adequately warm Arrears on utility bills (electricity, water, and gas) Presence of a leaking roof, damp walls or rotten windows
Betto et al. (2020)	Counting approach	Energy expenditure Absolute poverty Energy efficiency of building	
Sokołowski et al. (2020)	Counting and composite index approach		Low income, high costs High share of energy expenditure in income Inability to keep the home adequately warm Presence of leaks, damp, or rot Inability to pay utility bills
Che et al. (2021)	Rough set theory and improved TOPSIS	Energy availability	Household energy consumption Household electricity consumption Access to electricity
		Energy affordability	Gross domestic product Household final consumption expenditure Cellphone ownership
		Energy cleanliness	Access to clean fuels and technologies for cooking Household biomass and waste consumption Household carbon dioxide emissions Household non-solid commercial energy Non-thermal power generation

März (2018)	GIS-MCDA, using an AHP	Heating Burden	Location
			Energy infrastructure
		Socio-economic vulnerability	Elderly people
			Household with children
			Single person househols
			Single parent family
			Poverty in old age
			Unemployment
		Building vulnerability	Heating demand
			Ownership
			Building age
			Building type
Llera-Sastresa et al. (2017)	AHP	Dwelling characteristics of the home	Geographical area of building location
			Environment surrounding the building
			Year of construction of the building
			Ownership
			Type of residence
			Size
			Number of rooms
		Performance of the energy installations	Is the home equipped with heating equipment?
			Main type of heating in use
			Is the home equipped with air conditioning?
		Cost of energy	Voltage supplied
			Is the voltage supplied known by household members?
			Electric tariff applied
			Is the electric tariff applied known by household members?
			Energy expense
			Expense of other energy sources
		Characteristics and habits of household members	Social service aid
			Household income
			Number of household members
			Number of minors in the household
Arsenopoulos et al. (2020)	TOPSIS	Climate	Average temperatures (winter-summer)
		Demographics	Population growth
		Economy	Unemployment
			Purchasing power
		Policy	Political will
		Residential building stock	Average building age
			Persons per room
			Number of tenants
		Energy market	Electricity price
		Obligation schemes	Adoption of article 7
		Legislation	Official definition
Maxim et al. (2017)	Composite index (weighted sum)		Inability to keep home adequately warm

		Dwelling not comfortably cool during summer Dwelling too dark Arrears Leaks
Bouzarovski and Tirado-Herrero (2017)	Composite index (weighted sum)	Inability to keep home adequately warm Having arrears in utility bills Home with a leaking roof, or the presence of damp and rot

4.4 Energy poverty definitions

One prominent challenge in devising indexes, approaches, and evaluation methods for energy poverty is the absence of a standardized definition. Consequently, various approaches to defining energy poverty can be found in the literature.

The dimensions, criteria and indicators mentioned in the previous section to build each model depend on the way the concept of fuel poverty is defined or approached by the authors. Moreover, the way the concept is defined may also have to do with the case study being applied.

Legendre and Ricci (2015), Sokołowski et al. (2020) and Aristondo and Onaindia (2018) state that there is a difference in defining energy poverty in developing and developed countries. In developing countries, energy poverty is usually understood as the lack of availability of energy services. Whereas in developed countries, energy poverty is usually understood as not being able to afford energy services, usually by mentioning energy expenditures, incomes and high energy costs. However, while analysing the literature, this dichotomy in defining fuel poverty is not always evident, as it can be observed in table 4.3.

Sokołowski et al. (2020), Betto et al. (2020), Papada and Kaliampakos (2018), Simões et al. (2016) and Maxim et al. (2017) clearly adopt energy poverty definitions typically associated with developed countries. While Sadath and Acharya (2017) and Jiang et al. (2020) adopt definitions that are associated with developing countries. Other authors, such as Che et al. (2021) and Bienvenido-Huertas et al. (2022), use fuel poverty definitions that mention energy vulnerability concepts associated with both developed and developing countries.

In some cases, it is not evident if the authors are defining energy poverty as it is understood in developed countries or in developing countries. This is the case of Barnes et al. (2011), Aristondo and Onaindia (2018), and Recalde et al. (2019). However, in these cases, it is clarified in the dimensions, criteria or indicators chosen to assess the phenomenon which definition of energy poverty is being adopted.

It is also important to note that some authors only refer to heating, despite energy poverty being more than that.

In the recommendation of the European Commission (2020a), as mentioned in the document review section, the concept is described as "a situation in which households are unable to access essential energy services". It is later clarified by the listed recommended indicators that the main concern is the affordability of these energy services, as the EU member states are developed countries.

Thus, in this work, we adapt the definition stated by the Commission, by clarifying it, and define fuel poverty as a situation in which households are unable to afford essential energy services, this is, energy services that reflect a decent standard of living and health.

Table 4.3: Energy Poverty Definitions

Study	Case Study's Country	EP definition
Che et al. (2021)	125 countries (developed and developing)	Lack of access to sufficient, affordable and high quality energy to meet survival and development, characterized by high energy cost in developed countries and a lack of access to modern energy in developing countries.
Sokołowski et al. (2020)	Poland	Being unable to afford the energy needed to provide its members with adequate warmth, cooling, lighting, and appliance use.
Betto et al. (2020)	Italy	Hidden energy poverty: having low energy bills because they decide to restrain energy consumption due to not being able to afford it.
Papada and Kaliampakos (2018)	Greece	Spending over 10% of its income on all domestic energy use (heating, domestic hot water, cooking, lighting and electrical appliances), in order to achieve a satisfactory level of warmth (21 ℃ in the living room and 18 ℃ in the rest of the house).
Simões et al. (2016)	Portugal	Not affording to heat households adequately (20ºC during the heating season and of 25ºC during the cooling season).
Sadath and Acharya (2017)	India	Inability to realize the essential capabilities as a result of insufficient access to affordable, reliable and safe energy services, and taking into account the alternative means of realizing these capabilities in a reasonable manner.
Jiang et al. (2020)	China	Difficulty in obtaining electricity, clean fuels, and energy facilities, and a high dependence on traditional fuel, such as biomass and firewood, and inadequate cooking devices that have high pollution characteristics, such as biomass and firewood.
Barnes et al. (2011)	Bangladesh	The point at which people use the bare minimum energy (derived from all sources) needed to sustain life.
Bienvenido-Huertas et al. (2022)	Spain	Not being capable of keeping acceptable thermal comfort conditions or having energy services at an acceptable price, and also not being capable of doing essential activities because of the difficulty to access energy.
Aristondo and Onaindia (2018)	Spain	The lack of essential, affordable, reliable and safe energy services.
Maxim et al. (2017)	EU-28[3]	The inability of households to afford adequate access to energy services.
Recalde et al. (2019)	EU-27_2007 [4]	The inability of a household to secure a socially and materially required level of energy services in the home.

[3] EU member states from July 1st 2013 to February 1st 2020 (European Commission, 2020b).
[4] EU member states from January 1st 2007 to June 30th 2013 (European Commission, 2020b).

4.5 Available data

Table 4.4 depicts the data sources used in papers that assess energy vulnerability. National surveys data (Barnes et al., 2011; Betto et al., 2020; Jiang et al., 2020; Sadath & Acharya, 2017; Sokołowski et al., 2020), census data (März, 2018; Simões et al., 2016) and national statistical entities (Betto et al., 2020; Papada & Kaliampakos, 2018; Simões et al., 2016; Sokołowski et al., 2020; Tirado-Herrero & Ürge-Vorsatz, 2012) are used to obtain data at a local or national level. Eurostat data (Arsenopoulos et al., 2020; Bárcena-Martín et al., 2020; Kryk & Guzowska, 2023; Papada & Kaliampakos, 2018; Tirado-Herrero & Ürge-Vorsatz, 2012) are employed to gather information at both the European and national levels. At a global level, data from the World energy balances, The Energy balances of OECD and Non-OECD countries and the data from the World Bank are used (Che et al., 2021). In this work, we utilized the Eurostat data source (EU-SILC, 2020).

Numerous papers highlight the shortage of available data, which frequently constrains the choice of criteria and indicators utilized to construct the model (Papada & Kaliampakos, 2018; Zhao et al., 2021). The scope of this study is also affected by the lack of available data. Zhao et al. (2021) excluded some Chinese provinces of the study and Betto et al. (2020) did not increase the number of countries in their study due to data availability limitations. This data scarcity on energy poverty, or energy poverty indicators, is felt both at an European level (Hassani et al., 2019; Thomson & Snell, 2013) and at a global level (Hassani et al., 2019).

Table 4.4: Data sources

Study	Case Study	Data Sources
Papada and Kaliampakos (2018)	Greece	Hellenic Statistical Authority
		Eurostat
		Ministry of Development, Competitiveness, Infrastructure, Transport and Networks
Tirado-Herrero and Ürge-Vorsatz (2012)	Hungary	Household Budget Survey (HBS), Eurostat
		Hungarian Central Statistical Office (KSH)
Barnes et al. (2011)	Rural Bangladesh	Household survey representative of rural Bangladesh
Jiang et al. (2020)	Rural Qinghai, China	Household survey in rural Qinghai
Aristondo and Onaindia (2018)	Spain	Surveys on Living Conditions.
Betto et al. (2020)	Italy	Household Budget Survey, by the Italian National Institute of Statistics
Sokołowski et al. (2020)	Poland	Polish Household Budget Survey (HBS) , by the Polish statistical office
Che et al. (2021)	125 countries	The World energy balances
		The Energy balances of OECD countries
		The Energy balances of Non-OECD countries
		The World Bank
Zhao et al. (2021)	China	China Emission Accounts and Datasets (CEAD)
		Various statistical year books of China
Sadath and Acharya (2017)	India	India Human Development Survey-II (IHDS-II)
März (2018)	Oberhausen, Germany	Census
		German Meteorological Service (DWD)
Simões et al. (2016)	Portugal	National Statistics Intitute
		National Energy Directorat (DGEG)
		Census
Arsenopoulos et al. (2020)	11 EU countries	Eurostat and others
Bárcena-Martín et al. (2020)	28 EU countries	EU-SILC, Eurostat
Kryk and Guzowska (2023)	24 EU countries	Eurostat

4.6 Measurement of energy poverty in the EU

As far as this study goes, we found eleven studies that measure energy poverty in the EU, by doing a per-country analysis. The studies found are depicted in table 4.5. Healy and Clinch (2002) conducted the pioneering study of the phenomenon in the EU. that evaluated the problem through an EU-wide comparative analysis encompassing 14 European countries during the years from 1994 to 1997. It was not until 2013, with the works of Bouzarovski (2013) and Thomson and Snell (2013) that other works pertaining to fuel poverty in the European Union were published. Given that the previous analyses of fuel poverty had been conducted before the EU enlargement, the publication of such works was long overdue.

It was only after energy poverty became a part of the European Union's policy agenda, starting in 2009 with the Electricity and Gas directives (European Union, 2009a, 2009b), that EU-wide studies of the phenomenon become more frequent. Bouzarovski (2013) states that the study was needed due to policy on the subject being formulated in the absence of systematic and detailed scholarly research.

After that, three studies on the matter were published in 2017 (Bollino & Botti, 2017; Bouzarovski & Tirado-Herrero, 2017; Maxim et al., 2017). Since then, the works of Recalde et al. (2019), Arsenopoulos et al. (2020), and Bárcena-Martín et al. (2020), all concerning the measurement of fuel poverty at an EU-wide level, were published, by using the Eurostat database. In 2021, Che et al. (2021) attempted not only to assess European countries in regards to energy poverty, but also other parts of the world, such as North, Central, and South America, Middle East, North Africa, and Sub-Saharan Africa. Despite this, we found it relevant to include this study in this sub section because it does a per-country analysis of the fuel poverty of countries in the European Union.

The most recent study that evaluates energy poverty at the European Union level was conducted by Kryk and Guzowska (2023). Their work assesses fuel poverty between the years 2010 and 2020, inclusive.

This study attempts to build upon the existing literature on energy poverty measurement within the EU, considering the limited research on this topic. Notably, only one published work studies the European Union in the most recent years (2020).

Table 4.5: Measurement of energy poverty in the EU

Study	Title	Geographical scope	Temporal scope
Healy and Clinch (2002)	Fuel poverty in Europe: a cross-country analysis using a new composite measure	EU-15[5] except Sweden	1994-1997
Thomson and Snell (2013)	Quantifying the prevalence of fuel poverty across the European Union	EU-27_2007	2007
Bouzarovski (2013)	Energy poverty in the European Union: landscapes of vulnerability	EU-27_2007	2003-2010
Bollino and Botti (2017)	Energy Poverty in Europe: A Multidimensional Approach	EU-28 plus Iceland, Norway, and Switzerland	2012-2014
Bouzarovski and Tirado-Herrero (2017)	The energy divide: Integrating energy transitions, regional inequalities and poverty trends in the European Union	EU-28	2003-2013
Maxim et al. (2017)	Energy Poverty in Southern and Eastern Europe: Peculiar Regional Issues	EU-28	2012
Recalde et al. (2019)	Structural energy poverty vulnerability and excess winter mortality in the European Union: Exploring the association between structural determinants and health	EU-27	2010-2017
Arsenopoulos et al. (2020)	Assessing Resilience to Energy Poverty in Europe through a Multi-Criteria Analysis Framework	11 EU countries	2017
Bárcena-Martín et al. (2020)	Rethinking multidimensional poverty through a multi-criteria analysis	EU-28	2016
Che et al. (2021)	Assessing global energy poverty: An integrated approach	125 countries	2001-2016
Kryk and Guzowska (2023)	Assessing the Level of Energy Poverty Using a Synthetic Multidimensional Energy Poverty Index in EU Countries	EU-28 except Cyprus Finland Luxembourg, and Malta	2010-2020

In each of the works depicted in table 4.5, the research on fuel poverty was approached in a slightly different manner. Different research methodologies, sets of data, and temporal scopes were used to assess this problem. Despite these differences, there are common findings amongst these papers.

The worst performing countries in regards to their energy poverty are Southern European and Eastern European (Arsenopoulos et al., 2020; Bouzarovski, 2013; Bouzarovski & Tirado-Herrero, 2017; Kryk & Guzowska, 2023; Maxim et al., 2017; Recalde et al., 2019). However, their performances are bad for different regional particularities. The authors point out that Southern European countries have mild winters, therefore, most of their energy poverty problems are because of their building traditions, since houses were built without adequate heating systems and basic energy efficiency features, such as floor and roof insulation. Moreover, the high levels of energy

[5]EU member states from January 1st of 1995 until April 30th 2004(European Commission, 2020b).

poverty in Southern Europe are related to the economic situation of the population (Kryk & Guzowska, 2023; Maxim et al., 2017). In Eastern European countries, winters are generally cold and summers are characterised by having high temperatures (Maxim et al., 2017). Thus, their high levels of energy poverty are mostly a consequence of legacies of the centrally planned economy, such as the predominance of an unsustainable supply mix. The issue is exacerbated by the dependence of Eastern European member states on Russian energy imports, making the supply unpredictable, since Russian energy imports are often used as a political instrument (Bouzarovski & Tirado-Herrero, 2017).

The best performing countries in regards to their fuel poverty levels are from Western Europe, and Northern Europe. In these countries, when there are households with high levels of energy poverty, this is usually related to particular types of housing and demographic groups (Arsenopoulos et al., 2020; Bouzarovski & Tirado-Herrero, 2017; Recalde et al., 2019).

A common theme amongst these studies is the link between world events, such as the 2008 economic crisis (Arsenopoulos et al., 2020; Bouzarovski & Tirado-Herrero, 2017; Recalde et al., 2019) and the COVID-19 pandemic (Kryk & Guzowska, 2023) and the energy poverty situation in the European Union. Hence, these have to be taken into account when measuring fuel poverty in a particular time scope.

4.7 Literature review conclusion

Energy poverty is a challenging concept to grasp, and researchers have been striving to evaluate this phenomenon since 1991. However, despite extensive efforts, a globally accepted definition and metric are yet to materialize. Furthermore, the process of analyzing energy poverty is unavoidably influenced by available data, chosen dimensions and criteria, as well as contextual factors.

A noteworthy research gap was found in this literature review: none of the methods from the ELECTRE family, despite being widely used in Multi-Criteria Decision Analysis (MCDA), have been applied in the context of measuring energy poverty. To address this gap, this dissertation implements the ELECTRE-Tri-nC method to assess fuel poverty.

Moreover, in our investigation, we found only eleven studies attempting to measure the extent of energy poverty in the European Union. As a result, our study complements the existing literature on the measurement of fuel poverty in the EU, given the limited number of published studies on this matter.

As discussed in the conclusion of section 3.8, the lack of a universally adopted EU-wide fuel poverty definition stands as the primary reason for the vagueness, impracticality, and inadequacy of EU policy recommendations, as observed by some authors (Bouzarovski, 2018). To bridge this gap, this study adopts a definition of energy poverty that allows us to establish a common EU-wide framework for the assessment of energy poverty.

5 Methodology

5.1 Multicriteria Decision Analysis/Aiding (MCDA)

Multicriteria Decision Analysis/Aiding (MCDA) is a field of study of Management Science and Operational Research that deals with decision-making/aiding problems involving the assessment of multiple alternatives subject to a set of several (conflicting) criteria, goals, attributes, objectives and points of view. As such, MCDA offers strong analytical tools to solve complex real world problems by providing more flexible techniques when compared to uni-criterion ones (Doumpos et al., 2019).

MCDA includes a wide variety of methodologies, each having its own features that are based on significantly different approaches. MCDA handles three types of problems: (1) sorting, in which the objective is to assign a set of alternatives described by several criteria to a predetermined range of categories, usually, the categories are ordered from worst to best; (2) ranking, which involves ranking the alternatives from best to worst, with the possibility of ties and incomparabilities, according to each alternative's performance in relation to the predetermined criteria; and (3) choosing, in which the goal is to select the smallest possible subset of alternatives considered to be the most interesting ones (Figueira et al., 2012).

One relevant remark to make is that in sorting problems the outcome depends entirely on absolute evaluation of alternatives, this is, when an action is assigned to a category, only its intrinsic assessment on all the criteria is taken into account; it neither depends nor affects the category that is chosen for the assignment of another alternative. Whereas in ranking and choosing problems, the results depend on relative evaluation, this is, the alternatives are assessed in relation to one another (Figueira et al., 2012).

Multi-criteria decision analysis can also be used in a wide range of applications and problem domains (Doumpos et al., 2019), including assessment of investments in technology (Boucher & McStravic, 1991), management of water and agriculture (Nikas et al., 2018; Özelkan & Duckstein, 1996), energy planning (Afgan & Carvalho, 2000), finance (Doumpos & Figueira, 2019), and various areas of policy making (Martins et al., 2023).

Belton and Stewart (2002) identify 3 key phases of the MCDA process: (1) problem identification and structuring; (2) model building and use; and (3) development of action plans. Since phase 3 is outside the scope of this work, only phases 1 and 2 will be implemented.

(1) Problem identification and structuring: this is the phase where all parties involved, including the facilitators and technical analysts, need to come to an agreement on the problem, this is, the decisions that must be made and the type of problem that is being dealt with, as well as the alternatives and the criteria the alternatives are to be judged by. The problem at hands in this study is a multi-criteria sorting (classification) problem, which we will elaborate more on in section 6.

(2) Model building and use phase: Phase in which a formal model is created so that the alternatives being considered may be assessed in a comparative and systematic manner. In this work, the model is built according to

the ELECTRE-Tri-nC framework.

Belton and Stewart (2002) identify the key elements of the model framework: the alternatives to be evaluated; the criteria against which the alternatives will be evaluated; key stakeholders to the process; and key uncertainties.

There are numerous key participants in the MCDA process, including decision makers, clients, sponsors, other stakeholders, and facilitators or analysts (Belton & Stewart, 2002). In this study, there is participation of one facilitator/analyst and stakeholders with different types of expertise regarding the energy poverty problem (energy poverty experts), since Nikas et al. (2018) brings attention to the importance of having the participation from stakeholders with various types and degrees of expertise of the problem domain.

5.2 The ELECTRE-Tri-nC method

5.2.1 Introduction to the method

The ELECTRE-Tri-nC method is a part of the ELECTRE (ELimination Et Choix Traduisant la Realité - ELimination and Choice Expressing the Reality) family of MCDA methods. The ELECTRE methods have been successfully applied to real-world cases since their creation in the 1960s in a variety of fields, in particular finance, military, forest management and agriculture, medicine, transportation, and nanotechnologies (Figueira et al., 2012).

The method, introduced by Almeida-Dias et al. (2012), is a generalization of the ELECTRE Tri-C method (Almeida-Dias et al., 2010). Each category is defined by a single reference characteristic aleternative in the ELECTRE Tri-C method, whereas in the ELECTRE-Tri-nC method, each category is defined by a set of various reference characteristic alternatives, which improves the definition of the categories (Figueira et al., 2012).

ELECTRE-Tri-nC is used to help solve sorting problems (see definition of sorting problems in section 5.1). In this type of problem, there are three assumptions made: (1) total ordering: the alternatives must be allocated to completely ordered categories; (2) equally processed: prior to the method's execution, each category is designed to receive alternatives that will be processed in the same manner; and (3) categories' characterization: each category is characterized by a subset of reference alternatives. In this work, this subset is chosen by the analyst (Figueira et al., 2012).

5.2.2 Definitions, Concepts and notation

By taking into account the performance of a set of alternatives, denoted by $A = \{a_1, a_2, ..., a_i, ..., \}$, which are evaluated by a set of n criteria, denoted $F = \{g_1, g_2, ..., g_j, ..., g_n\}$, with $n \geq 3$, the goal of ELECTRE-Tri-nC is to allocate the set of alternatives to the set of completely ordered categories (from worst to best), denoted by $C = \{C_1, C_2, ..., C_h, ..., C_q\}$. Furthermore, $g_i(a_i)$ is the performance of alternative a_i on criterion g_j.

In this framework, each category is defined by a set of reference characteristic alternatives, denoted by $B = \{B_1, B_2, ..., B_h, ..., B_q\}$. $B_h = \{b_h^r, r = 1, ..., m_h\}$ denotes a subset of reference alternatives that characterize category C_h, such that $m_h \geq 1$ and $h = 1, ..., q$.

It is crucial to draw attention to the arbitrariness that affects how the criteria are defined as well as the inherent imperfect knowledge associated with the data from computing the performances $g_j(a)$ for every a in A. For that reason, the following presented concepts of pseudo-criterion and discriminating thresholds model this arbitrariness and imperfect knowledge (definitions 1, 2, and 3).

Definition 1(Pseudo-criterion). Each criterion g_j is said to be a pseudo-criterion when two thresholds are associated with it (a preference threshold, (p_j),and an indifference threshold ,(q_j)), such that $p_j \geq q_j \geq 0$. We consider only constant thresholds in this study.

Definition 2(Preference threshold, p_j). Refers to the smallest performance difference between two alternatives so that the alternative with the best performance is strictly preferred when the difference in performance between two alternatives is greater than the preference threshold.

Definition 3(Indifference threshold, q_j). Refers to the biggest performance difference between two alternatives that are considered compatible with an indifference situation between two alternatives with different performances.

The indifference and preference thresholds allow us to discriminate relations of indifference, strict preference, and weak preference when comparing two alternatives a and a', where the performance of a is at least as good as the performance of a', this is, $g_j(a) \geq g_j(a')$ for all $g_j \in F$. These relations are explained in definitions 4, 5, and 6.

Definition 4(per-criterion indifference relation). $|g_j(a)–g_j(a')| \leq q_j$ represents a non-significant advantage of one of the two alternatives over the other, indicating that a is indifferent to a' according to g_j, represented by aI_ja'.

Definition 5(per criterion strict preference relation). $g_j(a)–g_j(a') > p_j$ represents a significant advantage of a over a', indicating that a is strictly preferred to a' according to g_j, represented by aP_ja'

Definition 6(per-criterion weak preference relation). $q_j < g_j(a)–g_j(a') \leq p_j$ represents an ambiguity zone. The advantage of a over a' is a bit larger to conclude about an indifference between a and a', but this advantage is insufficient to draw the conclusion that a is strictly preferred. In this scenario, a is weakly preferred to a', represented by aQ_ja'.

From the definitions presented thus far, the following definition of per-criterion outranking relation is given as follows.

Definition 7(per-criterion outranking relation). Alternative "a outranks alternative a'" ($aSja'$) if "a is at least as good as a'" according to criterion g_j. This means that $g_j(a)$-$g_j(a) \geq$ -q_j.

After the introduction of the main definitions, concepts and notation needed to understand the ELECTRE-Tri-nC framework done in this section, the two following section (5.2.3 and 5.2.4) explore main phases of the method, namely the construction of outranking relations and the assignment procedure.

5.2.3 The construction of an outranking relation

All outranking-based methods, such as the ELECTRE-Tri-nC method, rely on the concepts of concordance and non-discordance for building outranking relations. These notions represent the reasons in favour of and against a situation where one alternative ranks higher than the other (e.g., "alternative a outranks alternative a'") (Figueira et al., 2012). A comprehensive concordance index and per-criterion discordance indices are used to model these ideas of discordance and non-discordance, respectively. They are then combined to get a credibility degree for the relation "a outranks a'". In the process of construction of an outranking relation, a categorical credibility index for the statement "a outranks the set B_h" is also defined. This section goes on to describe each of these concepts.

Concordance with the statement "a outranks a'

Being in concordance with the statement "a outranks a'" denotes the existence of a powerful enough concordant group of criteria that support the proposition. The importance (power) of a criterion g_j is given by its weight w_j. A way of allocating the weights to the criteria is by using the deck of cards procedure proposed by Figueira and Roy (2002). The criteria that support the assertion "a outranks a" plus a fraction of the power of those criteria for which "a is weakly preferred to a" determine the strength of the concordant set of criteria. This idea is modelled by the concordance index, $c(a, a)$, which has the following definition.

$$c(a,a') = \sum_{j \in C(aPa')} W_j + \sum_{j \in C(aQa')} W_j + \sum_{j \in C(aIa')} W_j + \sum_{j \in C(a'Qa)} W_j \varphi_j, \tag{4}$$

where

$$\varphi_j = \frac{g_j(a) - g_j(a') + p_j}{p_j - q_j} \in [0,1[\tag{5}$$

Non-discordance with the statement "a outranks a'

The concept of non-discordance lies in the fact that the statement "a outranks a'" cannot be refuted by a powerful minority group or criteria. The veto threshold v_j is a preference parameter used in the opposing power of criterion g_j, this is, the veto threshold is used to identify situations in which the difference between two alternatives with regard to one particular criterion precludes any potential outranking relationship indicated by other criteria. A criterion's veto threshold, together with its intrinsic weight, define the role a criterion plays. The following definition of per-criteria discordance indices models the opposing power of a criterion.

$$d_j(a,a') = \begin{cases} 1 & \text{if} g_j(a) - g_j(a') < -v_j, \\ \frac{g_j(a) - g_j(b) + p_j}{p_j - v_j} & \text{if} - v_j \leq g_j(a) - g_j(b) < -p_j, \\ 0 & \text{if} g_j(a) - g_j(b) \geq -p_j. \end{cases} \tag{6}$$

We must bring attention to the fact that the indifference, preference, and veto thresholds are presented in equations 4 and 6 as being constant.

Credibility of the assertion "a outranks a'"

The strength of the statement (credibility of the statement) “a outranks a'” is measured by $\sigma(a, a')$. The credibility index, $\sigma(a, a')$, is defined as follows:

$$\sigma(a, a') = c(a, a') \prod_{j=1}^{n} T_j(a, a'), \tag{7}$$

where

$$T_j(a, a') = \begin{cases} \frac{1-d_j(a,a')}{a-c(a,a')} & \text{if} d_j(a, a') > c(a, a') \\ 1 & \text{otherwise} \end{cases} \tag{8}$$

Categorical credibility indexes

We need to define categorical credibility indexes for the statement "a outranks the set B_h". To get a credibility index for each alternative a regarding each subset of reference alternatives $B_h, h = 1, ..., q$, the max operator is a natural choice for an operator. As such, the categorical credibility indices can be defined by the following.

- $\sigma(a, B_h) = max_{l=1,...,|B_h|}\{\sigma(a, b_{hl}\}$.
- $\sigma(B_h, a) = max_{l=1,...,|B_h|}\{\sigma(b_{hl}, a)\}$.

The above formulas for $\sigma(a, B_h)$ and $\sigma(B_h, a)$ take into account certain principles. To explain these definitions we will explain the two axioms taken into account to define $\sigma(a, B_h)$, as the justification of the definition of $\sigma(B_h, a)$ is alike. The axioms are:

- (1) when B_h contains a single reference alternative ($l = 1$) and thus $B_h = \{b_{h1}\}$, then $\sigma(a, B_h) = \sigma(a.b_{h1})$;
- (2) when B_h contains more than one reference alternative, i.e., $l \geq 2$, and there is a $b_{hr} \in B_h$ such that $\sigma(a, b_{hr}) \leq \sigma(a, B_h)$, then, for any a, $\sigma(a, B_h\ b_{hr}) = \sigma(a, B_h)$.

Comprehensive binary relations

A cut-off level is necessary to validate or not an outranking statement. This is, a preference parameter denoted by λ. The parameter is named credibility level, which is the minimum degree of credibility which is considered by the decision maker, or in the case of this work, the analyst, for the validation, or invalidation, of an outranking statement, taking into account all criteria from F.

This minimal degree of credibility accepts values between 0,5 and 1, inclusive. The λ value, enables the definition of four λ-binary relations, when an alternative a is compared to a subset of reference alternatives B_h, as it is stated in definition 8.

Definition 8(Comprehensive binary relations).

- λ-outranking: $aS^{\lambda}a' \Leftrightarrow \sigma(a, a') \geq \lambda$
- λ-preference: $aP^{\lambda}a' \Leftrightarrow \sigma(a, a') \geq \lambda \wedge \sigma(a', a) < \lambda$
- λ-indifference: $aI^{\lambda}a' \Leftrightarrow \sigma(a, a') \geq \lambda \wedge \sigma(a', a) \geq \lambda$
- λ-incomparability: $aR^{\lambda}a' \Leftrightarrow \sigma(a, a') < \lambda \wedge \sigma(a', a) < \lambda$

5.2.4 The assignment procedure

This framework uses two joint assignment rules, the ascending and descending rules, with the result being the assignment of a range of alternatives to a set of categories. Both joint rules firstly choose between two categories, Secondly, they choose a suitable category by using a selective function, denoted $\rho(\{a\}, B_h)$, depicted in equation 9, which allows to choose between two consecutive categories where an alternative a can possibly be assigned to.

$$\rho(\{a\}, B_h) = min\sigma(\{a\}, B_h), \sigma(B_h, \{a\}) \tag{9}$$

The descending and ascending assignment procedures can be presented as follows.

Definition 9(Descending assignment procedure): Choose a credibility level $\lambda(0,5 \leq \lambda \leq 1,0)$. Decrease h from $(q+1)$ until the first value, t, such that $\sigma(\{a\}, B_t) \geq \lambda$. Then, proceed as follows:

- For $t = q$, select C_q as a possible category to assign alternative a.
- For $0 < t < q$, if $\rho(\{a\}, B_{t+1}$, then select C_t as a possible category to assign a; otherwise, select C_{t+1}.
- For $t = 0$, select C_1 as a possible category to assign a.

Definition 10(Ascending assignment procedure). Choose a credibility level $\lambda(0,5 \leq \lambda \leq 1)$. Increase h from zero until the first value, k, such that $\sigma(B_k, \{a\}) \geq \lambda$. Then, proceed as follows:

- For $k = 1$, select C_1 as a possible category to assign alternative a.
- For $1 < k < (q+1)$, if $\rho(\{a\}, B_k) > \rho(\{a\}, B_{k-1})$ then select C_k as a possible category to assign a; otherwise, select C_{k-1}.
- For $k = (q+1)$, select C_q as a possible category to assign a.

The joint application of the ascending and descending rules results in the selection of a lowest and a highest possible categories to which an alternative a can be allocated to. Hence, the outcome could take one of the three forms:

- A single category, when the joint rules select the two same categories.

- One of the two selected categories, when the joint rules select two consecutive categories.
- One of the two selected categories or one of the intermediate categories, when the joint rules select two categories that are not consecutive.

Additional notes: Reference alternatives

Two specific subsets of reference alternatives ($B_0 = \{b_0^1\}$ contains the reference alternative for which $g_j(b_0^1)$ is the worst possible performance on criterion g_j, and $B_{q+1}^1 = \{b_{q+1}^1\}$ contains the reference alternative for which $g_j(b_{q+1}^1)$ is the best possible performance on the same criterion g_j) must be selected based on their performance on criterion g_j, such that for any alternative a one has:

- $g_j(b_0^1) < g_j(a) < g_j(b_{q+1}^1)$, for all $g_j \in F$
- $g_j(b_1^r) - g_j(b_0^r), r = 1, ..., m_1$, for all $g_j \in F$
- $g_j(b_{q+1}^1) - g_j(b_q^s) > 0, s = 1, ..., m_q$

The reference alternatives must satisfy the dominance condition in order to characterise two successive distinct categories: It is required that the reference alternatives belonging to B_{h+1} and the ones belonging to B_h define two consecutive distinct categories. This calls for the requirement that every characteristic reference alternative from B_{h+1} dominates every characteristic reference alternative from B_h.

5.2.5 MCDA-ULaval

In this study, the MCDA-ULaval programme ("Multicriteria Decision Aiding software MCDA-ULaval", n.d.) is used to implement the ELECTRE-Tri-nC method.

The MCDA-ULaval is a multi-criteria decision analysis/aiding software tool created at Université Laval in JAVA specifically for the implementation of ELECTRE family methods. Not only does the software tool contain methods for sorting problems, such as, the ELECTRE Tri B, ELECTRE TRI-C, ELECTRE-Tri-nC, and ELECTRE TRI-rC, but it also contains methods for ranking problems, such as the ELECTRE II and the ELECTE III.

This tool has a number of helpful features including the ability to display multiple windows at the same time, since the interface is multi-document, which also allows for multiple projects to be worked on at once. Additionally, it is possible to use both ordinal an cardinal criteria. Also, the ordinal criteria's number of levels ant the cardinal criteria's numerical precision can both be defined by the user. Another useful feature of the software is that it carries out stability and scenario analysis, which strengthens the analysis of the results.

5.2.6 Strengths and weaknesses of ELECTRE-Tri-nC

The ELECTRE-Tri-nC has several strong features. The method is able to deal with both qualitative and quantitative scales of criteria and with heterogeneous scales, it takes into account the imperfect knowledge of data and some arbitrariness associated with the construction of the criteria, by defining the indifference and preference thresholds. Moreover, it does not allow for compensation of performance among criteria, this is, bad performances on certain criteria cannot be compensated by good performances on other criteria. Finally, the ELECTRE-Tri-nC method takes into account the reasons for and the reasons against an outranking (Figueira et al., 2012).

Despite its strengths, the method also has some weaknesses. The ELECTRE-Tri-nC method does not assign a score to each alternative and in some contexts it could be relevant or required to do it. Furthermore, if all the criteria scales are quantitative, it is recommended to use other methods, unless the user wants to use a non-compensatory method, in the case, the method is recommended(Figueira et al., 2012).

5.3 The SRF method

The ELECTRE-Tri-nC method allows for there to be different weights assigned to the criteria, which are established a priori to the method's implementation. The weight of a criterion in the ELECTRE method family can be thought of as its voting power. Hence, the more significant the criteria, the larger the weight allocated to that criteria (Figueira et al., 2012).

In this study, the weights' allocation is done according to Simos, Roy and Figueira (SRF) Deck of Cards approach (Figueira & Roy, 2002), which attributes weights to the criteria based on the stakeholders' perception of the importance of the criteria. This model was initially created by Simos (1990a, 1990b) as a technique to allow any stakeholder to think through and express how they wish to organise the various criteria, as well as to give analysts the information they need to assign a numerical value to each criterion's weight when an ELECTRE type method is being used. In 2002, Roy and Figueira revised Simos' procedure (Figueira & Roy, 2002). The revised Simos' procedure (also known as SRF) has been used in different real-world problems, such as environmental, water resources, and public transportation ones.

5.3.1 Collecting information

To gather information from the energy poverty experts, an interactive activity between the facilitator and the expert takes place. The energy poverty expert receives a deck of cards with the same number of cards as the given criteria, n, in which a playing card serves as the physical representation of each criterion. The set of cards is then ranked by the expert from least to most important criteria, this is, in ascending order. If the expert determines that some criteria are equally important, the cards representing those criteria should be held together. As a result, a pre-order on the n criteria is obtained with a certain number of ranks, the first rank is $Rank\ 1$, the second rank is $Rank\ 2$, and so on.

After ranking the criteria cards according to their importance, the facilitator instructs the expert to consider the fact that the relevance of two successive criteria (or two subsets of *ex aequo*) criteria may be closer or less close. It is necessary to take into account this smaller or larger difference in importance between successive criteria when determining their weights. Hence, the white cards, a new set of cards, are introduced. The energy poverty expert is required to place a white card between the ascending ordered criteria, according to their relative importance. The more significant the difference in importance between two criteria (or two subsets of *aequo criteria*), the more white cards are placed between them. As such:

- Criteria that are equally relevant will be held together.
- Two criteria (or two subsets of *ex aequo*) criteria with a small difference in importance between them will have no white cards placed between them.
- Two criteria (or two subsets of *ex aequo*) criteria with medium or large importance difference will have one or more white cards placed between them.

u is the weight difference between two consecutive cards, this is, two criteria with no white cards between them. Thus, one card placed between two criteria (or two subsets of *ex aequo* criteria), means a difference in weight of two times u, two cards placed between two criteria (or two subsets of *ex aequo* criteria) mean a difference in weight of three times u, and so on.

Once the white cards have been placed, the facilitator asks the expert to specify how many times the last criterion in the ranking (or the last set of *ex aequo* criteria in the ranking) more important than the first one, z reflects the value of this ratio (equation 10).

$$z = \frac{w(\text{most relevant criterion})}{w(\text{least relevant criterion})} \tag{10}$$

5.3.2 The algorithm

The algorithm must assign a numerical value to each criterion's weight, g_i, for i=1,...,n. Therefore, it needs to establish the non-normalized weights and the normalized weights.

Determining non-normalized weights $k(r)$:

The non-normalized weights $k(1), \ldots, k(r), \ldots, k(\overline{n})$ for each subset are determined in the following way:

e'_r denotes the number of white cards between the ranks r and $r+1$.

$$\begin{cases} e_r = e'_r + 1 \qquad \forall r = 1, \ldots, \overline{n}-1, \\ e = \sum_{r=1}^{\overline{n}-1} e_r, \\ u = \frac{z-1}{e} \end{cases} \tag{11}$$

We obtain

$$k(r) = 1 + u(e_0 + \ldots + e_{r-1}), \text{with } e_0 = 0 \tag{12}$$

One important thing to note is that if several criteria *ex aequo* exist in the rank r, then each of those criterion's weight must be equal $k(r)$.

Determining the normalized weights k_i:

The normalized weights have to be allocated in such a way that the condition $\sum_{i_1}^{n} k_i = 100$ is met. k_i denotes the normalized weight of each criterion g_i, for $i = 1, \ldots, n$. The normalized weights are determined in the following way:

g_i denotes a criterion of rank r and k'_i denotes the weight of this criterion in its non-normalized expression $k'_i = k(r)$.

$$\begin{cases} K' = \sum_{i=1}^{n} k'_i \\ k^*_i = \frac{100}{K'} k'_i \end{cases} \tag{13}$$

There is a distortion associated with the rounding process, which is necessary to obtain the final weights k_i, such that $\sum_{i=1}^{n} k_i = 100$, otherwise, the weights sum would never be exactly 100%. As such, k''_i is calculated from $k*_i$ by deleting some of its decimal figures. For this, a rounding off technique that considers three options characterized by w is used as follows:

$$\begin{cases} w = 0: & \text{takes into account no figures after the decimal point} \\ w = 1: & \text{take into account only one figure after the decimal point} \\ w = 2: & \text{take into account only two figures after the decimal point} \end{cases}$$

By using this rounding off technique, we obtain the following result:

$$\begin{cases} K'' = \sum_{i=1}^{n} k''_i \leq 100, \\ \epsilon = 100\check{\ } K'' \leq 10^{-w} \text{x} n. \end{cases} \tag{14}$$

After the rounding off, if we set $k_i = k''_i + 10^{-w}$ for v criteria ($v = 10^w$xϵ) suitably selected and k''_i for the other $n - v$ criteria, we have $\sum_{i=1}^{n} k_i = 100$ with the normalized weights k_i showing the required number of decimal places.

The v criteria ($v = 10^w$xϵ) is carried out according to an algorithm that minimizes the distortion of the weights. To know more about this algorithm, please read Figueira and Roy (2002).

5.3.3 The DecSpace web platform

The DecSpace [6] is a web-based platform used in this work to implement the SRF method. By providing an input of the criteria, and the energy poverty's expert opinion on the criteria, we are able to obtain an output of the normalized weights of the set of criteria, by using the DecSpace platform. This platform uses MCDA techniques in an intuitive and visual way, in order to facilitate the decision-making process.

[6] http://app.decspacedev.sysresearch.org/

6 Problem identification and structuring

Typically, the energy poverty issue has been studied on a country-specific basis. Furthermore, the established EU policy encourages member states to address fuel poverty at a national level, rather than implementing a standardized approach to assess energy poverty level across all EU countries. The absence of an EU-wide adopted definition and methodology for measuring energy poverty creates challenges in comparing energy poverty levels among member states, as each country employs its own monitoring system, and is pointed out by some authors as the reason for the vagueness, impracticality and poorness of EU policy recommendations for fuel poverty issues (Bouzarovski, 2018).

Keeney (1992) emphasizes the significance of generating alternatives by either combining existing ones or creating new ones through the MCDA process. However, this is applied when the objective of the MCDA process is to develop an action plan. In our study, the aim is not to devise an action plan, but rather to classify a defined set of alternatives, the EU member states, based on their energy poverty levels. In effect, this study sorts (classifies) EU member states based on their energy poverty levels in 2020, as it is the most recent year for which sufficient data is available for the majority of European Union countries.

Owing to limitations in data availability, this study does not encompass all 27 EU member states. Specifically, Cyprus, Finland, and Malta are excluded from the analysis. The set of alternatives for this work consists of the following: a_1 Austria; a_2 Belgium; a_3 Bulgaria; a_4 Croatia; a_5 Czechia; a_6 Denmark; a_7 Estonia; a_8 France; a_9 Germany; a_{10} Greece; a_{11} Hungary; a_{12} Ireland; a_{13} Italy; a_{14} Latvia; a_{15} Lithuania; a_{16} Luxembourg; a_{17} Netherlands; a_{18} Poland; a_{19} Portugal; a_{20} Romania; a_{21} Slovakia; a_{22} Slovenia; a_{23} Spain; a_{24} Sweden. These alternatives will be assigned to one of the categories outlined in table 6.6.

Table 6.6: Set of categories

C_1	Very high energy poverty level
C_2	High energy poverty level
C_3	Moderate energy poverty level
C_4	Low energy poverty level

6.1 Value tree

Nussbaumer et al. (2012) states that the selection and organisation of the criteria should take into account the multidimensional nature of energy poverty. The criteria should be carefully chosen based on their applicability to the fuel poverty problem and measurability (including the availability of adequate and reliable data). Thus, a value tree was constructed

A value tree serves the purpose of selecting, and organizing the set of criteria used to evaluate the set of alternatives (Belton & Stewart, 2002), while capturing the problem's core values. The construction of the value tree involved the collaboration with four energy poverty experts and took into consideration two preceding sections of this work: section 3, which covers EU policies and other initiatives, and section 4, which encompasses the literature review.

When constructing the value tree, three key attributes were sought to ensure the appropriate selection of criteria that align with the values or the problem. These attributes are as follows:

- (1) Each criterion supports the definition of energy poverty adopted in this work.
- (2) Each criterion is recognized and rightfully justified in the literature as an energy poverty indicator.
- (3) There is data available on each criterion for the year of 2020 across the 24 member states evaluated in this sorting problem.

Regarding characteristic (1), as outlined in the literature review section (section 4.4), this work defines fuel poverty as a situation in which households are unable to afford essential energy services, this is, energy services that reflect a decent standard of living and health.

While some authors, such as Simões et al. (2016), argue that energy poverty solely pertains to heating services, the literature review conducted in this study demonstrates that energy poverty encompasses a broader range of energy services within the household. This includes not only heating but also space cooling, cooking, lighting, entertainment, communication, and more. However, it is important to note that transportation services are not included in the adopted definition of energy poverty.

To build a value tree, three components are defined: the areas of concern (AC), the fundamental points of view (FPV), and the criteria (g_n), all of which are detailed below and depicted in table 6.7.

6.1.1 Areas of concern

The areas of concern are the overarching subjects that encompass the broad concerns of the problem. These reflect the comprehensive dimensions in which the fundamental points of view are included. Three areas of concern are defined and described below.

AC_1 Facilities/Housing: Refers to the conditions of the household. According to Rademaekers et al. (2016) physical infrastructure is a crucial factor that has an impact on the state of energy poverty.

AC_2 Socio-economic factors: Reflects the socio-economic aspects of the population. Rademaekers et al. (2016) identified these factors as drivers of fuel poverty. Furthermore, Preston et al. (2014) highlight that energy vulnerable households often exhibit specific socio-economic characteristics.

AC_3 Cost of energy: Reflects the household cost of energy, since high energy prices are identified as one of the main causes of energy poverty (Energy Poverty Advisory Hub, 2022b).

6.1.2 Fundamental points of view:

The fundamental points of view outlined align with the adopted definition of energy poverty. They reflect potential drivers or causes that prevent households to afford vital energy services. Five FPVs are detailed next in this document.

FPV_1 Household energy efficiency: Energy efficiency of the buildings in which people live. The energy efficiency of residential buildings plays a crucial role in determining the level of energy poverty experienced by individuals. Homes that are energy efficient consume less energy to meet basic energy services' needs compared to energy inefficient homes. The inefficient use of energy in households can contribute to the inability to afford adequate energy services (Rademaekers et al., 2016). Recognizing the significance of energy efficiency in adressing energy poverty, the Energy Poverty Advisory Hub (2022b) report identifies low household energy efficiency to be one of the main causes of energy poverty. Several authors emphasize the importance of considering energy efficiency when the energy poverty issue is addressed, such as Betto et al. (2020) who demonstrate how energy poverty in Italian households is impacted by low energy efficiency. Moreover, the EU establishes a clear connection between improving energy efficiency in buildings and reducing energy poverty in its 2010 energy performance in buildings directive (European Union, 2010) and its 2012 energy efficiency directive (European Union, 2012).

FPV_2 Household energy services: Refers to the availability of energy services in households. This study, along with other scholarly definitions (see e.g., Sadath and Acharya (2017) and Aristondo and Onaindia (2018)), recognizes the pivotal role of energy services in evaluating and defining energy poverty. Therefore, this FPV is considered in the study.

FPV_3 Vulnerable groups: Groups of people that have a predisposition to be vulnerable to energy poverty. Simões et al. (2016), and März (2018) underline the relevance of identifying groups of people who are especially susceptible to energy vulnerability. Moreover, Rademaekers et al. (2016) state that it is crucial to identify population groups who cannot afford basic energy services.

FPV_4 Income: The money that a household receives in exchange for their labour. Authors have been relating energy poverty to income since its first official definition (Boardman, 1991). Hills (2012) also makes this link with its LIHC indicator. Hence, income is a relevant factor in measuring the affordability of energy services of a household.

FPV_5 Energy prices: Prices related to energy consumption to obtain household energy services. The Energy Poverty Advisory Hub (2022a, 2022b), and Rademaekers et al. (2016) highlight the importance of domestic energy prices in assessing energy poverty as it is one of the main causes of energy poverty. Bouzarovski and Tirado-Herrero (2017) establish a clear correlation between the escalating rates of energy poverty and the growing energy costs across different regions in the EU.

6.1.3 Criteria

The criteria operationalise the selected areas of concern and fundamental points of view. In this work, we select nine criteria, described as follows.

g_1 Presence of leak, damp, rot: Share of the country's population living in a dwelling with a leaking roof, damp walls, floors or foundation, or rot in window frames or floor. Rademaekers et al. (2016) state that this criterion measures energy efficiency, as indicated in the value tree. This is because it gives information about the home's state of conservation, which is connected to the home's energy efficiency (Energy Poverty Advisory Hub, 2022a). Moreover, Aristondo and Onaindia (2018), Bouzarovski and Tirado-Herrero (2017), and Sokołowski et al. (2020) use this criterion in their approaches for evaluating the energy vulnerability problem.

g_2 Inability to keep home adequately warm: Share of the population not able to keep their home adequately warm. Rademaekers et al. (2016) specify that this particular criterion pertains to the provision of heating energy services. Moreover, Aristondo and Onaindia (2018), Bouzarovski and Tirado-Herrero (2017), Maxim et al. (2017), and Sokołowski et al. (2020) use this criterion for measuring fuel poverty. Therefore, it is a widely recognized and employed as a significant indicator within the field.

g_3 Low education level: Share of adults with a low education level (i.e., at most a lower secondary qualification, ISCED 2 or below [7]). Simões et al. (2016) and Healy and Clinch (2002) highlight the need to assess the level of formal education of the household population. This is because, according to these authors, there is a linear relationship between educational levels and energy poverty.

g_4 Unemployment: Percentage of the people in the labour force that are unemployed. Simões et al. (2016) use this criterion, stating that, people who are unemployed typically face more financial challenges. Moreover, Hills (2012) shows that unemployment is a key driver of fuel poverty. At last, Arsenopoulos et al. (2020) highlight that fuel poverty is more pronounced in nations with higher unemployment rates.

g_5 Arrears on utility bills: Share of population with arrears on utility bills, i.e., unable to pay utility bills (heating, electricity, gas, water, etc.) on time. Numerous authors, including Aristondo and Onaindia (2018), Maxim et al. (2017), and Sokołowski et al. (2020), and Bouzarovski and Tirado-Herrero (2017) employ this criterion. The reason behind its widespread usage lies in the underlying assumption that individuals facing challenges paying their utility expenses are likely to encounter difficulties in affording essential energy services.

g_6 Disposable income: Mean equivalised disposable income per inhabitant per year (€). The equivalised disposable income is the total income of a household, after tax and other deductions, that is available for spending or saving, divided by the number of household members converted into equivalised adults. The Energy Poverty Advisory Hub (2022b) identifies low income to be one of the key drivers of energy vulnerability. Moreover, income has been related to fuel poverty for as long as the problem was first defined (Boardman, 1991), as it can be observed in the literature review of our study.

g_7 Risk of poverty: Percentage of the population at risk of poverty and social exclusion. People who have an equivalised disposable income below the risk-of-poverty threshold, which is set at 60% of the national median equivalised disposable income (after social transfers), are considered to be at risk of poverty or social exclusion. Maxim et al. (2017) have shown that this criterion is positively correlated with energy poverty levels.

g_8 Household electricity prices: Electricity prices for household consumers (€/kWh). Consumption that is within the band 2500-5000 kWh/yr is considered. All taxes, and levies are included in this criterion because prices

[7] To know more aboud ISCED levels please see Eurostat (2023).

should be considered with taxes when comparing the cost of energy in various nations, as taxation might vary greatly between member states. Electricity prices, which are directly related to one of the three primary causes of energy poverty, rising energy prices, is a significant indicator for the assessment of energy poverty. The reason for its significance is that energy services such as, lighting, space cooling, space heating, among others, are often provided by electricity (Energy Poverty Advisory Hub, 2022a). Authors frequently makes use of this criterion (Arsenopoulos et al., 2020).

g_9 Household gas prices: Natural gas prices for household consumers (€/kWh). Consumption that is within the band 20-200GJ/yr. All taxes, and levies are included for the same reason given in the description of criterion g_9. Natural gas is used directly in households for a number of energy services, such as, heating, providing hot water, and some gas powered appliances. Therefore, it is an indicator recommended in the report of the Energy Poverty Advisory Hub (2022a) and it is relevant for this work.

Table 6.7: Value tree

Areas of concern	**Fundamental points of view**	**Criteria**
AC_1 Facilities/Housing	FPV_1 Household energy efficiency	g_1 Presence of leak, damp, rot
	FPV_2 Household energy services	g_2 Inability to keep home adequately warm
AC_2 Socio-economic factors	FPV_3 Vulnerable groups	g_3 Low education level
		g_4 Unemployment
		g_5 Arrears on utility bills
	FPV_4 Income	g_6 Disposable income
		g_7 Risk of poverty
AC_3 Cost of energy	FPV_5 Energy prices	g_8 Household electricity prices
		g_9 Household gas prices

It must be noted that certain criteria deemed crucial to the areas of concern and fundamental points of view are not included in the value tree. This omission is due to the absence of the third attribute mentioned in the beginning of section 6.1, which pertains to data availability issues. Noteworthy, among the missing criteria are those that describe other household energy services (FPV_2), specifically, the inability to maintain an adequately cool home and the household being considered too dark. Another set of missing criteria pertains to energy prices (FPV_5) beyond electricity and gas, namely, biomass, district heating, and coal household prices. Lastly, criteria relating to household energy efficiency (FPV_1) should be employed to complement criteria g_1, for instance, by utilizing energy performance certificates of households.

7 Model Building and Use

After the problem identification and structuring of section 6, the model building and use phase can take place. This section entails the building of the model, and its implementation. This is, the performance table, the criteria weighting, the definition of the criterion (w_j, q_j, and p_j) and method parameters (λ), and the definition of the reference alternatives (b_h^r), while taking into account the previously defined set of criteria and set of categories.

7.1 Data

The starting point of the analysis performed with the ELECTRE-Tri-nC algorithm is the performance table depicted in table 7.8.

The data in the performance table was collected from Eurostat database (Eurostat, 2020), which is the statistical office of the European Union. Most of the indicators of the criteria (g_1, g_2, g_5, g_6, and g_7) were gathered from EU-SILC (European Union Statistics on Income and Living Conditions) (EU-SILC, 2020), which includes cross-sectional and longitudinal data on income, poverty, social exclusion, and living conditions in a timely and comparable manner. EU-SILC provides two different types of data: longitudinal data on individual-level changes over time, observed periodically over a four year period, and cross sectional data over a specific period or a given time. The rest of the indicators of the criteria (g_3, g_4, g_8, and g_9) were taken from Eurostat, however they were not taken from EU-SILC.

It is also relevant to note that some of the indicators of the criteria, namely g_1 (Presence of leak, damp, rot), g_2 (Inability to keep home adequately warm), and g_5 (Arrears on utility bills) are self reported indicators, this is, indicators that rely on the individual's own perception, hence, these are subjective indicators. Bouzarovski and Tirado-Herrero (2017) highlight the importance of combining self-reporting indicators with indicators that are not self-reported, which we did in this work.

For the implementation of the algorithm, all criteria are to be minimized except for criterion g_6, disposable income, which is to be maximized, as depicted in table 7.8.

Table 7.8: Performance table and minimization/maximization

EU member states	Criteria								
	g_1 (%)	g_2 (%)	g_3 (%)	g_4 (%)	g_5 (%)	g_6 (€/capita)	g_7 (%)	g_8 (€/kWh)	g_9 (€/kWh)
a_1 Austria	9.1	1.5	14.3	6.0	3.1	29 503	16.7	0.0732	0.0307
a_2 Belgium	15.7	4.1	20.2	5.8	3.8	27 641	20.3	0.0786	0.0250
a_3 Bulgaria	11.0	27.5	16.9	6.1	22.2	5 927	33.6	0.0560	0.0175
a_4 Croatia	9.4	5.7	13.4	7.5	13.6	8 643	20.5	0.0580	0.0233
a_5 Czechia	6.8	2.2	5.9	2.6	1.9	11 885	11.5	0.0749	0.0414
a_6 Denmark	16.8	3.0	18.5	5.6	4.2	34 346	16.8	0.0409	0.0160
a_7 Estonia	10.2	2.7	10.7	6.9	5.0	13 705	22.8	0.0444	0.0232
a_8 France	18.0	6.7	18.5	8.0	5.5	25 382	19.3	0.0701	0.0296
a_9 Germany	12.0	7.0	14.3	3.7	3.3	29 896	20.4	0.0574	0.0294
a_{10} Greece	12.5	17.1	21.2	17.6	28.2	10 041	27.4	0.1021	0.0254
a_{11} Hungary	20.4	4.2	14.4	4.1	10.4	7 278	19.4	0.0352	0.0156
a_{12} Ireland	16.6	3.3	14.5	5.9	7.9	30 709	20.1	0.1097	0.0321
a_{13} Italy	19.6	8.3	37.1	9.3	6.0	20 449	24.9	0.0925	0.0309
a_{14} Latvia	17.5	6.0	8.3	8.1	8.3	10 413	25.1	0.0567	0.0120
a_{15} Lithuania	10.9	23.1	4.6	8.5	6.3	10 491	24.5	0.0484	0.0170
a_{16} Luxembourg	15.4	3.6	21.5	6.8	2.9	43 687	19.9	0.0668	0.0210
a_{17} Netherlands	14.8	2.4	19.0	4.9	1.5	29 297	16.0	0.0779	0.0313
a_{18} Poland	6.0	3.2	6.8	3.2	4.7	8 907	17.0	0.0469	0.0231
a_{19} Portugal	25.2	17.5	44.6	7.0	3.5	12 696	20.0	0.0702	0.0292
a_{20} Romania	10.0	10.0	19.6	6.1	13.9	4 846	35.6	0.0612	0.0192
a_{21} Slovakia	4.9	5.7	7.3	6.7	5.2	9 003	13.8	0.0663	0.0235
a_{22} Slovenia	20.8	2.8	9.8	5.0	9.4	15 836	14.3	0.0645	0.0254
a_{23} Spain	19.7	10.9	37.1	15.5	9.6	18 116	27.0	0.0541	0.0275
a_{24} Sweden	7.1	2.7	13.5	8.5	2.4	26 646	17.7	0.0425	0.0476
Maximize/ Minimize	Min	Min	Min	Min	Min	Max	Min	Min	Min

7.2 Criteria weighting

The weights were obtained by using the SRF method in the DecSpace web platform, as described in section 5.3, through an interactive process between the energy poverty expert and the analyst. Taking into account the opinion of one energy poverty expert, the ranks of the set of cards were determined, as illustrated in table 7.9, and a z ratio of 4 was determined. The outcome of the SRF method, this is, the weights of the criteria, are depicted in table 7.10.

Table 7.9: Rank of the set of cards

Rank	Grouping	Number of cards
1	g_1, g_6	2
2	White card	1
3	g_2, g_7	2
4	White cards	3
5	g_3, g_4, g_8, g_9	4
6	g_5	1

Table 7.10: Normalized weights of the criteria

	Criteria	w_j
g_1	Presence of leak, damp, rot	19.05
g_2	Inability to keep home adequately warm	14.95
g_3	Low education level	6.81
g_4	Unemployment	6.81
g_5	Arrears on utility bills	4.76
g_6	Disposable income	19.05
g_7	Risk of poverty	14.95
g_8	Household electricity prices	6.81
g_9	Household gas prices	6.81

7.3 Setting preference and indifference thresholds

We found it relevant to define preference and indifference thresholds for all criteria in the model developed. However, we did not find it pertinent to define veto thresholds for the criteria. This is because, within the context of the problem, despite the possibility of existing a big difference between the performance of two alternatives with regard to one particular criterion, it did not make sense to preclude any potential outranking relationship indicated by other criteria. Since energy poverty is a multidimensional problem, all criteria have to be taken into account to define the outranking relationship, thus, one criterion only cannot dictate the outranking relationship of two EU-countries.

For criteria g_1, g_2, g_4, g_5, and g_7, the indifference threshold is 2 and the preference threshold is 4. For criterion g_3 the indifference threshold is 3 and the preference threshold is 5. For criterion g_6 the indifference threshold is 250 and the preference threshold is 500. For criterion g_8 the indifference threshold is 0.02 and the preference threshold is 0.03. Finally, for criterion g_9 the indifference threshold is 0.005 and the preference threshold is 0.01. The values of the thresholds are depicted in table 7.11.

Table 7.11: Thresholds of the criteria

	Criteria								
Thresholds	g_1	g_2	g_3	g_4	g_5	g_6	g_7	g_8	g_9
q_j	2	2	3	2	2	250	2	0.02	0.005
p_j	4	4	5	4	4	500	4	0.03	0.01

7.4 Setting reference alternatives

It is required that the reference alternatives that define each category are determined to successfully implement the ELECTRE-Tri-nC method. In the current work, the reference alternatives assigned to each category are depicted in table 7.12. Two reference alternatives were assigned to each category. Reference alternatives b_1^1 and b_1^2 were assigned to category C_1 (very high energy poverty level), reference alternatives b_2^1 and b_2^2 were assigned to category C_2 (high energy poverty level), reference alternatives b_3^1 and b_3^2 were assigned to category C_3 (moderate energy poverty level), lastly, reference alternatives b_4^1 and b_4^2 were assigned to category C_4 (low energy poverty level).

Table 7.12: Reference alternatives

Reference alternatives	Criteria								
	g_1 (%)	g_2 (%)	g_3 (%)	g_4 (%)	g_5 (%)	g_6 (€/capita)	g_7 (%)	g_8 (€/kWh)	g_9 (€/kWh)
b_1^1	30	30	45	20	30	4500	42	0.150	0.050
b_1^2	23	21	33	17	22	7500	31	0.100	0.040
b_2^1	22	20	32	16	20	9000	30	0.090	0.035
b_2^2	19	15	25	14	15	10000	25	0.080	0.031
b_3^1	15	9	22	12	10	15000	22	0.070	0.030
b_3^2	12	6.5	20	7	5	25000	18	0.060	0.025
b_4^1	10	5	10	5	4	30000	17	0.050	0.020
b_4^2	5	2	5	3	1	40000	12	0.030	0.010

7.5 Implementation of the model in MCDA-ULaval

Once all the parameters needed for the implementation of the model were determined, the application of the model on the MCDA-ULaval programme was done. The input of the parameters and other information needed for the model was done as illustrated in figures 7.1 to 7.8.

Firstly, the set of EU member states analysed in this study was provided as an input for the set of alternatives (figure 7.1). The set of criteria, their description, and measure was also provided, as represented in figure 7.2. Then, the performance table data was inserted, as presented in the performance table 7.8 (figure 7.3). After that, the method to be used was selected (ELECTRE-Tri-nC method), as portrayed in figure 7.4. The criterion parameters were also provided as an input (figure 7.5), this is, the weights, the preference thresholds, the indifference thresholds, and the direction of each criterion, represented in figure 7.5 as k, q_β, p_β and direction, respectively. Figure 7.6 depicts the insertion of the λ parameter, λ=0.7 was the chosen value for this parameter. Lastly, the set of reference alternatives (figure 7.8) and the allocation of those alternatives to the categories (figure 7.7) was inserted.

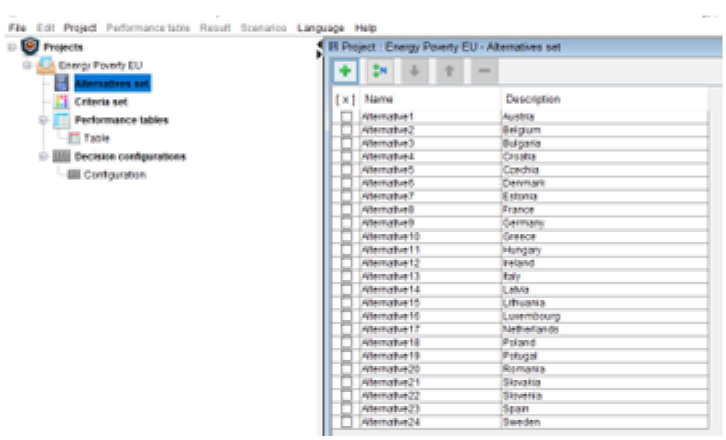
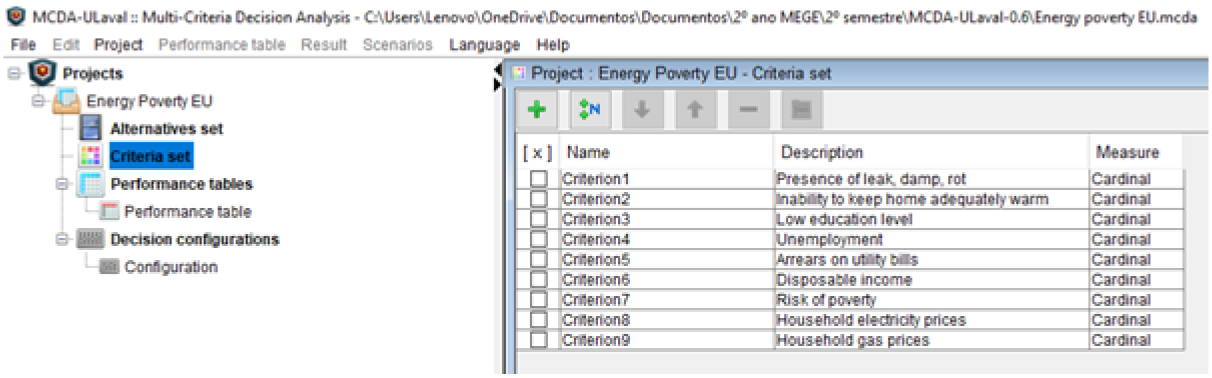
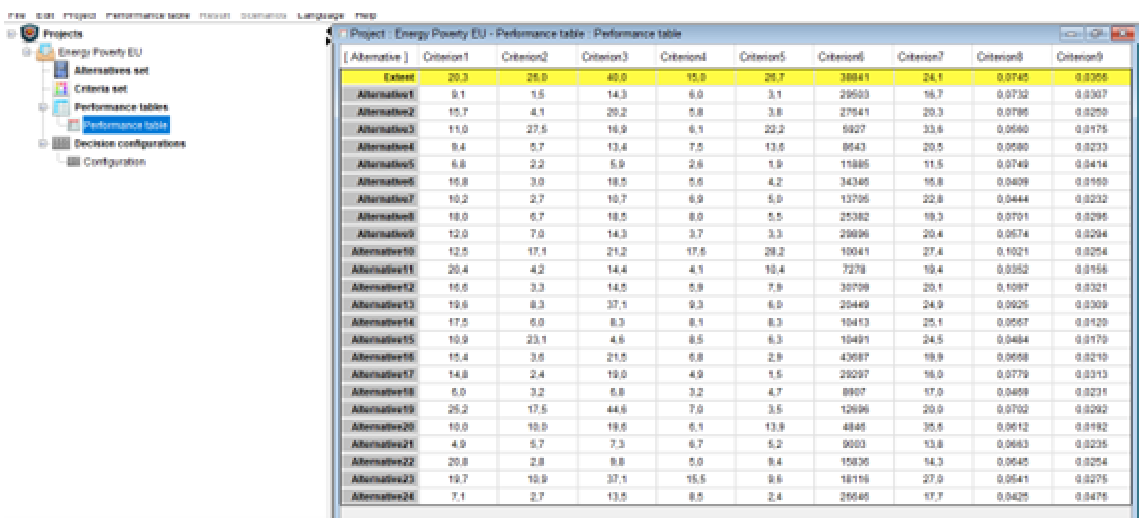


Figure 7.1: Alternatives



[x]	Name	Description	Measure
	Criterion1	Presence of leak, damp, rot	Cardinal
	Criterion2	Inability to keep home adequately warm	Cardinal
	Criterion3	Low education level	Cardinal
	Criterion4	Unemployment	Cardinal
	Criterion5	Arrears on utility bills	Cardinal
	Criterion6	Disposable income	Cardinal
	Criterion7	Risk of poverty	Cardinal
	Criterion8	Household electricity prices	Cardinal
	Criterion9	Household gas prices	Cardinal

Figure 7.2: Criteria



[Alternative]	Criterion1	Criterion2	Criterion3	Criterion4	Criterion5	Criterion6	Criterion7	Criterion8	Criterion9
Extent	20,3	25,0	40,0	15,0	26,7	38841	24,1	0,0745	0,0358
Alternative1	9,1	1,5	14,3	6,0	3,1	29503	16,7	0,0732	0,0307
Alternative2	15,7	4,1	20,2	5,8	3,8	27641	20,3	0,0786	0,0250
Alternative3	11,0	27,5	16,9	6,1	22,2	5927	33,6	0,0560	0,0175
Alternative4	9,4	5,7	13,4	7,5	13,6	8643	20,5	0,0580	0,0233
Alternative5	6,8	2,2	5,9	2,6	1,9	11885	11,5	0,0749	0,0414
Alternative6	16,8	3,0	18,5	5,6	4,2	34346	16,8	0,0409	0,0150
Alternative7	10,2	2,7	10,7	6,9	5,0	13705	22,8	0,0444	0,0232
Alternative8	18,0	6,7	18,5	8,0	5,5	25382	19,3	0,0701	0,0295
Alternative9	12,0	7,0	14,3	3,7	3,3	29896	20,4	0,0574	0,0294
Alternative10	12,5	17,1	21,2	17,6	28,2	10041	27,4	0,1021	0,0254
Alternative11	20,4	4,2	14,4	4,1	10,4	7278	19,4	0,0352	0,0156
Alternative12	16,6	3,3	14,5	5,9	7,9	30709	20,1	0,1097	0,0321
Alternative13	19,6	8,3	37,1	9,3	6,0	20449	24,9	0,0925	0,0309
Alternative14	17,5	6,0	8,3	8,1	8,3	10413	25,1	0,0567	0,0120
Alternative15	10,9	23,1	4,6	8,5	6,3	10491	24,5	0,0484	0,0170
Alternative16	15,4	3,6	21,5	6,8	2,9	43687	19,9	0,0658	0,0210
Alternative17	14,8	2,4	19,0	4,9	1,5	29297	16,0	0,0779	0,0313
Alternative18	6,0	3,2	6,8	3,2	4,7	8907	17,0	0,0469	0,0231
Alternative19	25,2	17,5	44,6	7,0	3,5	12696	20,0	0,0702	0,0292
Alternative20	10,0	10,0	19,6	6,1	13,9	4846	35,6	0,0612	0,0182
Alternative21	4,9	5,7	7,3	6,7	5,2	9003	13,8	0,0663	0,0235
Alternative22	20,8	2,8	9,8	5,0	9,4	15836	14,3	0,0645	0,0254
Alternative23	19,7	10,9	37,1	15,5	9,6	18116	27,0	0,0541	0,0275
Alternative24	7,1	2,7	13,5	8,5	2,4	25646	17,7	0,0425	0,0476

Figure 7.3: Performance table

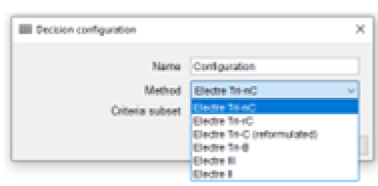
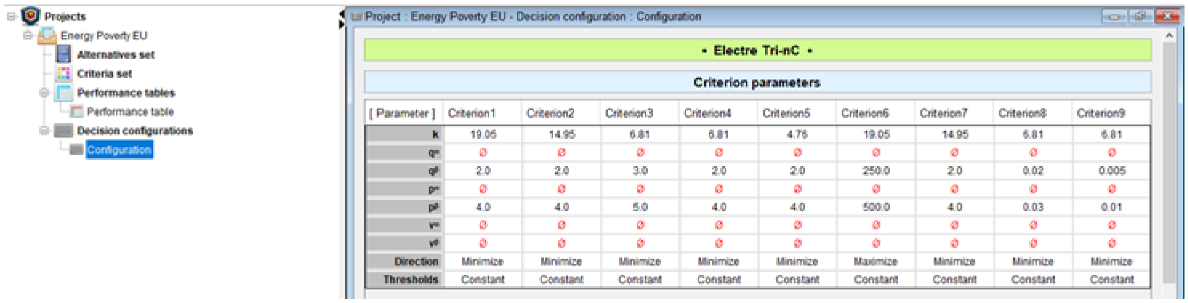


Figure 7.4: Method's selection



Project : Energy Poverty EU - Decision configuration : Configuration

• Electre Tri-nC •

Criterion parameters

[Parameter]	Criterion1	Criterion2	Criterion3	Criterion4	Criterion5	Criterion6	Criterion7	Criterion8	Criterion9
k	19.05	14.95	6.81	6.81	4.76	19.05	14.95	6.81	6.81
q^{α}	∅	∅	∅	∅	∅	∅	∅	∅	∅
q^{β}	2.0	2.0	3.0	2.0	2.0	250.0	2.0	0.02	0.005
p^{α}	∅	∅	∅	∅	∅	∅	∅	∅	∅
p^{β}	4.0	4.0	5.0	4.0	4.0	500.0	4.0	0.03	0.01
v^{α}	∅	∅	∅	∅	∅	∅	∅	∅	∅
v^{β}	∅	∅	∅	∅	∅	∅	∅	∅	∅
Direction	Minimize	Minimize	Minimize	Minimize	Minimize	Maximize	Minimize	Minimize	Minimize
Thresholds	Constant	Constant	Constant	Constant	Constant	Constant	Constant	Constant	Constant

Figure 7.5: Criterion parameters

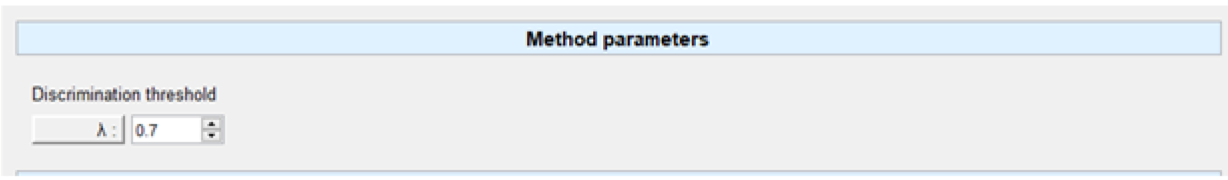


Figure 7.6: Method parameters

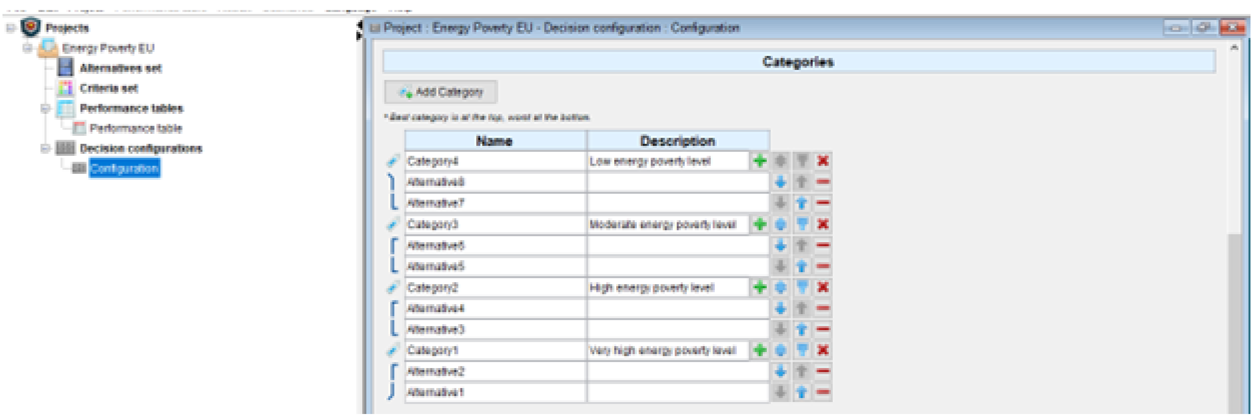
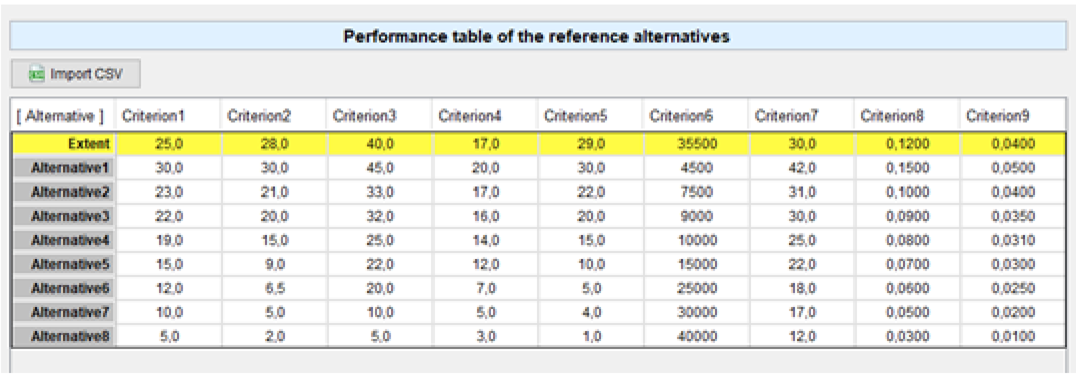


Figure 7.7: Categories



Performance table of the reference alternatives

Import CSV

[Alternative]	Criterion1	Criterion2	Criterion3	Criterion4	Criterion5	Criterion6	Criterion7	Criterion8	Criterion9
Extent	25,0	28,0	40,0	17,0	29,0	35500	30,0	0,1200	0,0400
Alternative1	30,0	30,0	45,0	20,0	30,0	4500	42,0	0,1500	0,0500
Alternative2	23,0	21,0	33,0	17,0	22,0	7500	31,0	0,1000	0,0400
Alternative3	22,0	20,0	32,0	16,0	20,0	9000	30,0	0,0900	0,0350
Alternative4	19,0	15,0	25,0	14,0	15,0	10000	25,0	0,0800	0,0310
Alternative5	15,0	9,0	22,0	12,0	10,0	15000	22,0	0,0700	0,0300
Alternative6	12,0	6,5	20,0	7,0	5,0	25000	18,0	0,0600	0,0250
Alternative7	10,0	5,0	10,0	5,0	4,0	30000	17,0	0,0500	0,0200
Alternative8	5,0	2,0	5,0	3,0	1,0	40000	12,0	0,0300	0,0100

Figure 7.8: Performance table of reference alternatives

8 Results

The results of the energy poverty level in the European Union taking into account 24 EU member states and their performances in 2020 according to the chosen 9 criteria, the weights determined by the expert, and the parameters determined by the analyst are presented in tables 8.13 and 8.14.

The output of the model is the allocation of each country to a worst and a best category, this is, an interval of categories. Therefore, for the member states that get allocated to different worst and best categories, a category interval is presented in table 8.13.

As it can be observed in tables 8.13 and 8.14, the majority of the member states (50%) were classified as having a moderate energy poverty level. Seven EU member states (29.167%) were classified as having low energy poverty. Three EU member states (12.5%) were classified as having a high energy poverty level. Moreover, two member states, Bulgaria and Romania, were assigned to an interval of categories whereas all the other countries were assigned to one category only. Bulgaria was classified as having an energy poverty level between very high and high and thus, being the country with the worst level of energy poverty. Romania was classified as having an energy poverty level between high and moderate.

Table 8.13: Results - energy poverty level in EU member states

Alternative	Member State	Category/Category interval	Energy Poverty level
a_1	Austria	C_4	Low
a_2	Belgium	C_3	Moderate
a_3	Bulgaria	[C_1,C_2]	[Very high, High]
a_4	Croatia	C_3	Moderate
a_5	Czechia	C_4	Low
a_6	Denmark	C_4	Low
a_7	Estonia	C_3	Moderate
a_8	France	C_3	Moderate
a_9	Germany	C_4	Low
a_{10}	Greece	C_2	High
a_{11}	Hungary	C_3	Moderate
a_{12}	Ireland	C_3	Moderate
a_{13}	Italy	C_3	Moderate
a_{14}	Latvia	C_3	Moderate
a_{15}	Lithuania	C_3	Moderate
a_{16}	Luxembourg	C_3	Moderate
a_{17}	Netherlands	C_3	Moderate
a_{18}	Poland	C_4	Low
a_{19}	Portugal	C_2	High
a_{20}	Romania	[C_2, C_3]	[High, Moderate]
a_{21}	Slovakia	C_4	Low
a_{22}	Slovenia	C_3	Moderate
a_{23}	Spain	C_2	High
a_{24}	Sweden	C_4	Low

Table 8.14: Results description: energy poverty level in EU member states

Category/Category interval	Energy poverty level	Percentage of alternatives	Number or alternatives
$[C_1, C_2]$	[Very high, High]	4.167%	1
C_2	High	12.500%	3
$[C_2, C_3]$	[High, Moderate]	4.167%	1
C_3	Moderate	50.000%	12
C_4	Low	29.167%	7

A different perspective on the results can be obtained by analysing figures 8.1 and 8.2 that display, respectively, the worst possible category of each EU member state within its assigned interval (pessimistic) and the best possible category of each EU member state within its assigned interval (optimistic). In both figures 8.1 and 8.2, the countries with the highest levels of energy poverty, this is, the countries that were allocated to the very high energy poverty level and to the high energy poverty level categories, are clearly from two different regions of member states, Eastern Europe (Romania and Bulgaria for the pessimistic allocation, and Bulgaria for the optimistic allocation) and Southern Europe (Portugal, Spain, and Greece). Moreover, one can observe that the countries with the lowest energy poverty level are from Northern Europe (Sweden and Denmark) and from central Europe (Germany, Poland, Czechia, Slovakia, and Austria). Finally, the countries with moderate energy poverty are from Western Europe (France, Belgium, Netherlands, Luxembourg, and Ireland), Northern Europe, in particular the Baltic countries (Lithuania, Latvia, and Estonia), Central Europe (Croatia, Hungary, and Slovenia), one Southern European country (Italy), and one Western European country for the optimistic allocation (Romania).

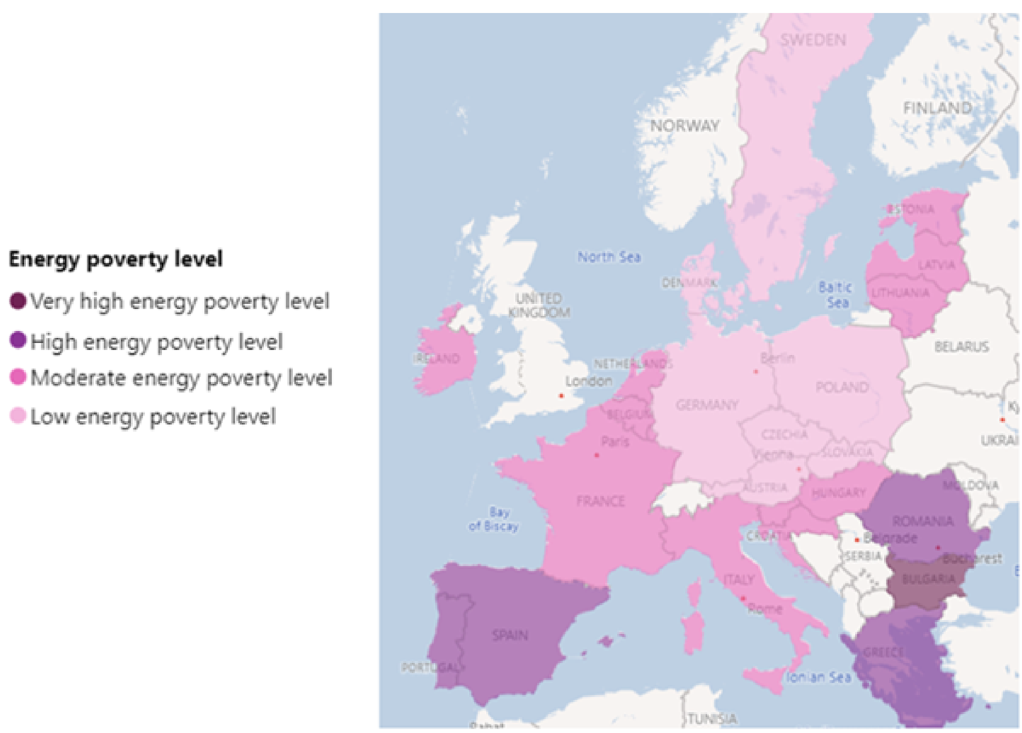


Figure 8.1: Energy poverty level in EU member states (pessimistic)

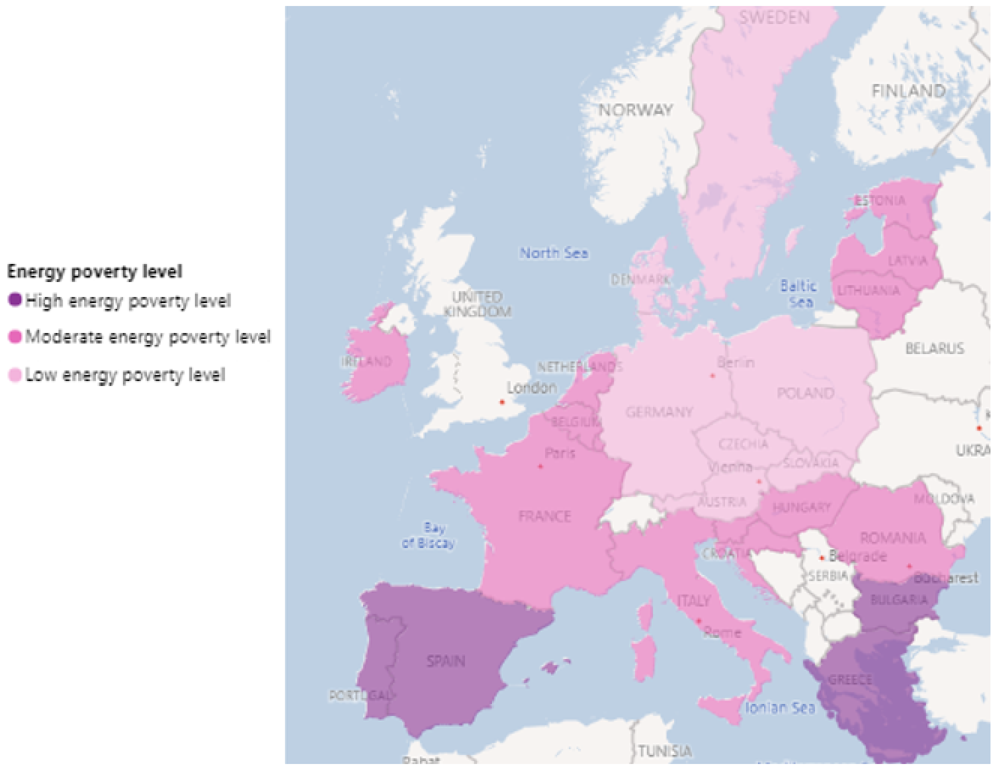


Figure 8.2: Energy poverty level in EU member states (optimistic)

9 Analyses

9.1 Stability analysis

Two stability analysis were carried out in the MCDA ULaval software. A stability analysis was conducted to the λ value used in this study. The stability interval of λ=0.7 is [0.69711304, 0.74139404].

Another stability analysis was carried out for the weights of the criteria, as depicted in table 9.15. Criteria g_8 and g_9 are quite stable, since their stability intervals are considerable. However, regarding criteria g_3 and g_4, table 9.15 shows low stability when compared to the stability intervals of the other criteria. Further insights on the impact of the weights on the results is obtained in the following section 9.2.

Table 9.15: Stability analysis for criteria weights

	g_1	g_2	g_3	g_4	g_5	g_6	g_7	g_8	g_9
w_j	[16.4265, 19.1641]	[14.8314, 15.7407]	[6.4335, 6.9379]	[6.0538, 6.9379]	[3.3922, 5.6458]	[18.9371, 21.5066]	[14.7940, 15.7407]	[0.0000, 6.9379]	[0.0000, 6.9379]

9.2 Sensitivity analysis

This subsection provides different results of the ELECTRE-Tri-nC method for different values of λ and different values of the z ratio, in order to assess separately, how the credibility level and the weights of the criteria influence the results of the model.

9.2.1 Changing parameter λ

As described in the methodology section 5, λ is the minimum degree of credibility to validate, or invalidate of an outranking statement. Therefore, bigger values of λ require a higher degree of credibility for the validation, or invalidation, of an outranking statement, and vice versa.

Since the credibility level directly affects both the ascending and descending joint rules, changes to the credibility level results in changes in the assignments: On the one hand, with an increase in the credibility level λ, the ascending rule tends to increase the category allocated to a certain alternative. While the descending rule tends to decrease the category assigned for that same alternative. Generally, both rules have a propensity to converge in the category to be allocated to an alternative, possibly coinciding in a single category. On the other hand, when the credibility level λ decreases, the ascending rule tends to decrease the category allocated to a certain alternative. While the descending rule tends to increase the category assigned for that same alternative. Generally, both rules have a propensity to diverge in the category to be allocated to an alternative, possibly leading to an interval of categories. This suggests that there is a critical λ value for which most alternatives are allocated to a single category (Almeida-Dias, 2011).

For that, four λ values were tested, λ_1= 0.55, λ_2 = 0.6, λ_3 =0.65, and λ_4 =0.75. Table 9.16 depicts the outcome of each of the λ values, as well how the results change in comparison to the results using the original λ parameter.

For λ_1 = 0.55, the results differ from the results with the originally selected λ value (λ=0.7) in the following way:

- Bulgaria's result worsens, as it is assigned to C_1, very high energy poverty level.
- Croatia's, Estonia's, Luxembourg's, and Slovenia's results improve, as these are allocated between categories C_3 (Moderate energy poverty level) and C_4 (Low energy poverty level).
- Denmark's, Germany's, Poland's, and Slovakia's results worsen, as these are allocated between categories C_3 (Moderate energy poverty level) and C_4 (Low energy poverty level).
- Romania's result improves, as it is assigned to C_3, moderate energy poverty level.
- There is an increase in the number of alternatives assigned to an interval of categories.

For λ_2 = 0.6, the results differ from the results with the originally selected λ value (λ=0.7) in the following way:

- Croatia's, Estonia's, and Luxembourg's results improve, as these are allocated between categories C_3 (Moderate energy poverty level) and C_4 (Low energy poverty level).
- Denmark's, and Germany's results worsen, as these are allocated between categories C_3 (Moderate energy poverty level) and C_4 (Low energy poverty level).
- Romania's result improves, as it is assigned to C_3, moderate energy poverty level.

- There is an increase in the number of alternatives assigned to an interval of categories, however, this number is lower than for λ_1=0.55.

For λ_3 = 0.65, the results differ from the results with the originally selected λ value (λ=0.7) in the following way:

- Estonia's and Luxembourg's results improve, as these are allocated between categories C_3 (Moderate energy poverty level) and C_4 (Low energy poverty level).
- Germany's result worsen, as it is allocated between categories C_3 (Moderate energy poverty level) and C_4 (Low energy poverty level).
- Romania's result improves, as it is assigned to C_3, moderate energy poverty level.
- There is an increase in the number of categories assigned to an interval of categories, however, this number is lower than for λ_1=0.55 and λ_2=0.6.

For λ_4 = 0.75, the results differ from the results with the originally selected λ value (λ=0.7) in the following way:

- Czechia's result worsens, as it is allocated between categories C_3 (Moderate energy poverty level) and C_4 (Low energy poverty level).
- Three alternatives are compared to an interval of categories.
- There is an increase in the number of alternatives assigned to an interval of categories, however, this number is lower than for λ_1=0.55, λ_2=0.6, and λ_3=0.65.

The results of table 9.16 show that the critical credibility level, must be a λ value close to 0.7, since this was the credibility level that resulted in the smallest number of EU countries assigned to an interval of categories.

Table 9.16: Sensitivity analysis λ parameter

Alternatives	λ_1 = 0.55	λ_2 = 0.6	λ_3 = 0.65	λ_0 = 0.7 (original)	λ_4 = 0.75
	Category/Category interval				
a_1 Austria	C_4	C_4	C_4	C_4	C_4
a_2 Belgium	C_3	C_3	C_3	C_3	C_3
a_3 Bulgaria	C_1	$[C_1, C_2]$	$[C_1, C_2]$	$[C_1, C_2]$	$[C_1, C_2]$
a_4 Croatia	$[C_3, C_4]$	$[C_3, C_4]$	C_3	C_3	C_3
a_5 Czechia	C_4	C_4	C_4	C_4	$[C_3, C_4]$
a_6 Denmark	$[C_3, C_4]$	$[C_3, C_4]$	C_4	C_4	C_4
a_7 Estonia	$[C_3, C_4]$	$[C_3, C_4]$	$[C_3, C_4]$	C_3	C_3
a_8 France	C_3	C_3	C_3	C_3	C_3
a_9 Germany	$[C_3, C_4]$	$[C_3, C_4]$	$[C_3, C_4]$	C_4	C_4
a_{10} Greece	C_2	C_2	C_2	C_2	C_2
a_{11} Hungary	C_3	C_3	C_3	C_3	C_3
a_{12} Ireland	C_3	C_3	C_3	C_3	C_3
a_{13} Italy	C_3	C_3	C_3	C_3	C_3
a_{14} Latvia	C_3	C_3	C_3	C_3	C_3
a_{15} Lithuania	C_3	C_3	C_3	C_3	C_3
a_{16} Luxembourg	$[C_3, C_4]$	$[C_3, C_4]$	$[C_3, C_4]$	C_3	C_3
a_{17} Netherlands	C_3	C_3	C_3	C_3	C_3
a_{18} Poland	$[C_3, C_4]$	C_4	C_4	C_4	C_4
a_{19} Portugal	C_2	C_2	C_2	C_2	C_2
a_{20} Romania	C_3	C_3	C_3	$[C_2, C_3]$	$[C_2, C_3]$
a_{21} Slovakia	$[C_3, C_4]$	C_4	C_4	C_4	C_4
a_{22} Slovenia	$[C_3, C_4]$	C_3	C_3	C_3	C_3
a_{23} Spain	C_2	C_2	C_2	C_2	C_2
a_{24} Sweden	C_4	C_4	C_4	C_4	C_4

Table 9.17: Sensitivity analysis credibility level description

	λ_1= 0.55		λ_2=0.6		λ_3= 0.65		λ_0=0.7(original)		λ_4=0.75	
Category/ Category interval	Percentage	Number	Percentage	Number	Percentage	Number	Percentage	Number	Percentage	Number
C_1	4.167%	1	0	0	0	0	0	0	0	0
$[C_1, C_2]$	0	0	4.167%	1	4.167%	1	4.167%	1	4.167%	1
C_2	12.500%	3	12.500%	3	12.500%	3	12.500%	3	12.500%	3
$[C_2, C_3]$	0	0	0	0	0	0	4.167%	1	4.167%	1
C_3	37.500%	9	41.667%	10	45.833%	11	50.000%	12	50.000%	12
$[C_3, C_4]$	33.333%	8	20.833%	5	12.500%	3	0	0	4.167%	1
C_4	12.500%	3	20.833%	5	25.000%	6	29.167%	7	25.000%	6

9.2.2 Changing z ratio

As mentioned in chapter 5, the z ratio is the number of times the last criterion in the ranking (g_5 in the case of the current study) is more important than the first one (g_1 and g_6 in the case of this study). Two different values of z were tested: z_1=2 and z_2=6. By changing the z ratio, the weights assigned to each category change by applying the SRF method, as depicted in table 9.18 and thus, these changes influence the results of the ELECTRE-Tri-nC method, presented in the same table.

As presented in tables 9.18, the results for z_1=2 differ from the results with the originally selected z ratio value

($z = 4$) in the following way:

- Bulgaria's result improves, as category C_2 (High level of energy poverty) is assigned to it.
- Estonia's result improves, as it is allocated between categories C_3 (Moderate level of energy poverty) and C_4 (Low level of energy poverty).
- Germany's result worsens, as it is allocated between categories C_3 (Moderate level of energy poverty) and C_4 (Low level of energy poverty).

These changes show that the model is consistent, since only three alterations of categories were registered for z_1=2, and no alterations of categories were registered for z_2=6.

Table 9.18: Sensitivity analysis z ratio

	z_1=2	z_0=4 (original)	z_2=6
Criteria		Weights	
g_1	15.41	19.05	20.7
g_2	13.18	14.29	15.77
g_3	8.78	7.14	5.9
g_4	8.78	7.14	5.9
g_5	7.7	4.76	3.45
g_6	15.41	19.05	20.71
g_7	13.18	14.29	15.77
g_8	8.78	7.14	5.9
g_9	8.78	7.14	5.9
Alternatives		Category/ Interval of categories	
a_1 Austria	C_4	C_4	C_4
a_2 Belgium	C_3	C_3	C_3
a_3 Bulgaria	C_2	$[C_1, C_2]$	$[C_1, C_2]$
a_4 Croatia	C_3	C_3	C_3
a_5 Czechia	C_4	C_4	C_4
a_6 Denmark	C_4	C_4	C_4
a_7 Estonia	$[C_3, C_4]$	C_3	C_3
a_8 France	C_3	C_3	C_3
a_9 Germany	$[C_3, C_4]$	C_4	C_4
a_{10} Greece	C_2	C_2	C_2
a_{11} Hungary	C_3	C_3	C_3
a_{12} Ireland	C_3	C_3	C_3
a_{13} Italy	C_3	C_3	C_3
a_{14} Latvia	C_3	C_3	C_3
a_{15} Lithuania	C_3	C_3	C_3
a_{16} Luxembourg	C_3	C_3	C_3
a_{17} Netherlands	C_3	C_3	C_3
a_{18} Poland	C_4	C_4	C_4
a_{19} Portugal	C_2	C_2	C_2
a_{20} Romania	C_3	$[C_2 , C_3]$	$[C_2 , C_3]$
a_{21} Slovakia	C_4	C_4	C_4
a_{22} Slovenia	C_3	C_3	C_3
a_{23} Spain	C_2	C_2	C_2
a_{24} Sweden	C_4	C_4	C_4

Table 9.19: Sensitivity analysis z ratio description

Category/ Category interval	z_1=2		z_0=4 (original)		z_2=6	
	Percentage	Number	Percentage	Number	Percentage	Number
[C1, C2]	0	0	4.167%	1	4.167%	1
C2	16.667%	4	12.500%	3	12.500%	3
[C2, C3]	0	0	4.167%	1	4.167%	1
C3	50.000%	12	50.000%	12	50.000%	12
[C3, C4]	8.333%	2	0	0	0	0
C4	25.000%	6	29.167%	7	29.167%	7

9.3 Scenarios analysis

A scenario analysis was carried out to complete the sensitivity analysis and determine how far the classifications of the EU countries might change by varying several parameters of the constructed model at once. The following parameters were varied: the credibility level, the z ratio, and the preference, indifference and veto thresholds changed according to the values presented in tables 9.20, 9.21, 9.22, and 9.23, respectively.

The scenarios were built by using values from tables 9.20 to 9.23, as presented in table 9.24. The outcome of the built scenarios is presented in table 9.25.

Table 9.20: Scenario analysis: λ values

λ_1	λ_2	λ_3	λ_0 (original)	λ_4
0.55	0.6	0.65	0.7	0.75

Table 9.21: Scenario analysis: z ratio values

z_1	z_0	z_2
2	4	6

Table 9.22: Scenario analysis: preference and indifference thresholds values

	g_1	g_2	g_3	g_4	g_5	g_6	g_7	g_8	g_9
q_{j1}	1	1	2	1	1	150	1	0.01	0.003
p_{j1}	3	3	4	3	3	400	3	0.02	0.005
q_{j0} (original)	2	2	3	2	2	250	2	0.02	0.005
p_{j0} (original)	4	4	5	4	4	500	4	0.03	0.01
q_{j2}	3	3	4	3	3	350	3	0.03	0.01
p_{j2}	5	5	6	5	5	600	5	0.04	0.02

Table 9.23: Scenario analysis: veto thresholds values

	g_1	g_2	g_3	g_4	g_5	g_6	g_7	g_8	g_9
v_{j0} (original)	-	-	-	-	-	-	-	-	-
v_{j1}	15	15	20	15	15	10000	15	-	-

Table 9.24: Scenario analysis: scenarios

	Scenario 0 (original)	Scenario 1	Scenario 2	Scenarios 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7	Scenario 8	Scenario 9	Scenario 10
λ	λ_0	λ_1	λ_2	λ_3	λ_3	λ_4	λ_4	λ_2	λ_0	λ_3	λ_4
z ratio	z_0	z_1	z_2	z_0	z_2	z_1	z_2	z_2	z_1	z_2	z_1
q_j, p_j	q_{j0}, p_{j0}	q_{j1}, p_{j1}	q_{j2}, p_{j2}	q_{j1}, p_{j1}	q_{j2}, p_{j2}	q_{j1}, p_{j1}	q_{j0}, p_{j0}	q_{j1}, p_{j1}	q_{j2}, p_{j2}	q_{j1}, p_{j1}	q_{j2}, p_{j2}
v_j	v_{j0}	v_{j1}	v_{j0}	v_{j1}	v_{j1}	v_{j0}	v_{j1}	v_{j1}	v_{j1}	v_{j1}	v_{j0}

Table 9.25: Scenarios analysis

	Scenario 0 (original)	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7	Scenario 8	Scenario 9	Scenario 10
a_1	C_4	C_4	C_4	C_4	C_4	C_4	C_4	C_4	C_4	C_4	C_4
a_2	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3
a_3	$[C_1, C_2]$	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2
a_4	C_3	C_3	$[C_3, C_4]$	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3
a_5	C_4	C_3	C_4	C_3	C_3	C_4	C_3	C_3	C_3	C_3	C_4
a_6	C_4	C_4	$[C_3, C_4]$	C_4	C_4	C_4	C_4	C_4	C_4	C_4	$[C_3, C_4]$
a_7	C_3	C_3	$[C_3, C_4]$	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3
a_8	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3
a_9	C_4	C_3	$[C_3, C_4]$	C_3	$[C_3, C_4]$	C_3	C_4	C_3	$[C_3, C_4]$	C_3	$[C_3, C_4]$
a_{10}	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2
a_{11}	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3
a_{12}	C_3	C_3	$[C_3, C_4]$	C_3	$[C_3, C_4]$	C_3	C_3	C_3	C_3	C_3	C_3
a_{13}	C_3	C_3	C_3	C_3	C_3	C_2	C_3	C_3	C_3	C_3	C_3
a_{14}	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3
a_{15}	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3
a_{16}	C_3	C_4	$[C_3, C_4]$	C_4	C_4	C_3	C_4	C_4	C_4	C_4	$[C_3, C_4]$
a_{17}	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3
a_{18}	C_4	C_3	$[C_3, C_4]$	C_3	C_3	C_4	C_3	C_3	C_3	C_3	C_4
a_{19}	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2
a_{20}	$[C_2, C_3]$	C_2	C_3	C_2	C_2	$[C_2, C_3]$	C_2	C_2	C_2	C_2	$[C_2, C_3]$
a_{21}	C_4	C_3	$[C_3, C_4]$	C_3	C_3	C_4	C_3	C_3	C_3	C_3	C_4
a_{22}	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3
a_{23}	C_2	C_3	C_2	C_3	C_3	C_2	C_3	C_3	C_3	C_3	C_2
a_{24}	C_4	C_4	C_4	C_4	C_4	C_4	C_4	C_4	C_4	C_4	C_4

As observed in table 9.25, there are 72 changes out of 240 assignments, which is equivalent to 30%. This suggests that our model is consistent. Scenarios 2 is the one with the most changes, whereas scenario 3 is the one with the least changes.

9.4 Conclusion of analyses section

For the sensitivity analysis to the λ parameter, there were 21 alterations out of 96 assignments, For the sensitivity analysis to the z ratio, there were 3 changes out of 48 assignments. Lastly, for the scenario analysis, there were 72 changes out of 240 assignments.

In total, in 384 assignments generated, there were 96 alterations to the original model, which is equivalent to 25%. This outcome suggests that the model constructed with the help of the energy poverty experts is robust.

10 Discussion

10.1 Results and the performance table

To generally analyse the countries with the highest energy poverty levels (very high energy poverty level and high energy poverty level) we look and comment on the performance of those member states in regards to certain criteria. This is, we look at table 7.8 of section 7 (Model Building and Use).

Bulgaria was the only country allocated to the worst possible category, very high energy poverty level, in the pessimistic allocation. In the optimistic allocation, there is no member state allocated to the worst category. By analysing table 7.8, we realize that Bulgaria has the highest share of the population not able to keep their home adequately warm (27.5%), the second highest share of population with arrears on utility bills (22.2%), the second lowest yearly disposable income (5927€/capita), and the second highest percentage of the population at risk of poverty and social exclusion (33.6%).

Greece was allocated to the high energy poverty level category in both pessimistic and optimistic allocations of the method. If we observe the data depicted in table 7.8, it can be observed that Greece has a high share of the population not able to keep their home adequately warm (17.1%), the highest percentage of unemployment (17.6%), a high percentage of population at risk of poverty and social exclusion (27.4%), and the highest electricity prices for household consumers (0.1021€/kWh).

Portugal was also allocated to the high energy poverty level category in both pessimistic and optimistic allocations of the method. By looking at the performance of the country according to the different chosen criteria depicted in table 7.8, one can note that this member state has the highest share of the population living in a dwelling with a leaking roof, damp walls, floors or foundation, or rot in window frames or floor (25.2%), a high share of the population not able to keep their home adequately warm (17.5%), and the highest share of adults with a low education level.

Spain, like Greece and Portugal, was also allocated to the high energy poverty level category in both the pessimistic and optimistic allocations of the method. By examining table 7.8, we notice that this country has a high share of the population not able to keep their home adequately warm (19.7%), the second highest share of adults with a low education level (37.1%), the second highest percentage of unemployment (15.5%), and a high percentage of the population at risk of poverty and social exclusion (27%).

Romania was allocated to the high energy poverty level in the pessimistic allocation of the method and to the moderate energy poverty level in the optimistic allocation of the method. In fact, if we analyse the performance of the country according to the different chosen criteria depicted in table 7.8, we observe that Romania is the country with the lowest equivalised disposable income (4846 €/capita) and the country with the highest percentage of the population at risk of poverty and social exclusion.

In the pessimistic allocation of the member states, Bulgaria was the only country allocated to the worst category, very high energy poverty level. As it can be observed in 7.8, Bulgaria has the highest percentage of population that reported an inability to keep home adequately warm, with 27.5%. Furthermore, it is the country with the second highest percentage of population with arrears on utility bills, following Greece. Bulgaria is also the second country with the lowest equivalised disposable income, following Romania. Bulgaria also has the second highest percentage of people in risk of poverty or social exclusion, followed by Romania.

It is important to note that in regards to the performance of the alternatives according to the different chosen criteria, there are member states allocated to the moderate energy poverty level that have bad performances in certain criteria. This is the case for Croatia, that has a low equivalised disposable income (8643€/capita); Hungary, that has a high share of population living in a dwelling with a leaking roof, damp walls, floors or foundation, and a low equivalised disposable income (7278€/capita); Italy, that has a high share of adults with low education level (37.1%), and high household gas prices (0.0935€/capita); Lithuania, that has a high share of the population not able to keep their home adequately warm (23.1€/capita), and Slovenia, that has a high share of the population living in a dwelling with a leaking roof, damp walls, floors or foundation, or rot in window frames or floor (20.8%).

10.2 Comparison of results with general findings in the literature

Some of the results obtained overlap with the studies by the authors described in subsection 4.5 of the literature review, while others are slightly different.

As stated in subsection 4.5, the general findings of other studies are that the worst performing countries in regards to energy poverty are Southern and Eastern European countries, whereas the best performing countries are Northern and Western European countries.

According to our findings, most Southern European countries have a high energy poverty level, which coincides with the findings of other studies, however, surprisingly, according to the result of our study, Italy has a moderate energy poverty level. Our study only covers two countries of the Eastern Europe, Bulgaria and Romania. The results of this work in regards to these two Eastern European countries are in line with the results of other works, since in the results of this work Romania has an energy poverty level between high and moderate and Bulgaria has an energy poverty level between very high and high. When it comes to Northern European countries, our study's outcome matches with the outcome of other findings, since Northern European countries were found to have a low or a moderate energy poverty level. Our study goes even further, there is a clear distinction amongst the Northern European member states. The Baltic member states are classified as having a moderate energy poverty level and the others Nordic countries are classified as having a low energy poverty level. Central European member states were found to have low energy poverty levels and moderate energy poverty levels, which is in line with the findings of other studies. Nonetheless, our project's results of Western European countries slightly deviate with the findings of other works, since none of the Western European member states were classified in our study as having a low energy poverty level, instead, all were classified in our study as having a moderate energy poverty level.

According to the findings of the current study, Central European countries have a slightly better performance when it comes to energy poverty than Western European countries, which is not in line with the general findings of other studies. This could be because most of the work found in the literature regarding the assessment of energy poverty within the European Union dates from before 2020, the year being analysed in this work.

10.3 Comparison of results with particular findings in the literature

To comment on the results, this section compares our findings to the ones drawn by the only other study that assesses energy poverty in the European Union in 2020. As it can be observed in table 4.5 of the literature review section, this is the work of Kryk and Guzowska (2023).

Before comparing these findings, it must be noted that our work includes Luxembourg whereas Kryk and Guzowska (2023)'s work does not. Moreover, the study of Kryk and Guzowska (2023) included the United Kingdom whereas our study does not. Hence, our findings in relation to Luxembourg and the findings of Kryk and Guzowska (2023) related to the UK will not be discussed in this section.

Similarly to our study, Kryk and Guzowska (2023) classified European Union member states according to four categories: very high energy poverty level, high energy poverty level, average energy poverty level, and low energy poverty level. The only difference between the categories used in Kryk and Guzowska (2023)'s classification and our study's classification is that a slightly different term is used for third best category, however, we find these terms to be equivalent.

Table 10.26 depicts the results of Kryk and Guzowska (2023)'s study and our study, presenting them side by side, so that they can be easily compared.

The first noticeable difference between the results of both studies depicted in table 10.26 is that Kryk and Guzowska (2023)'s work seems to make a harsher assessment of the EU countries, as the results of Kryk and Guzowska (2023) have more countries allocated to the very high and high energy poverty level categories, and less countries allocated to the low energy poverty level.

There are differences when it comes to the classification of certain member states. The member states with the biggest difference in classification between the methods are Germany and Poland, which are considered to be high energy poverty level countries in the work of Kryk and Guzowska (2023), and low energy poverty level countries in our work. The other member states are either in the same category in both studies, which is the case for 12 out of 23 countries, or are in different but adjacent categories, which is the case for 9 out of 23 countries, if we consider the pessimistic or the optimistic allocation.

Table 10.26: Comparison of results

Kryk and Guzowska (2023)	This dissertation	
	Pessimistic	Optimistic
Very high energy poverty level	**Very high energy poverty level**	
Portugal	Bulgaria	
Spain		
High energy poverty level	**High energy poverty level**	
Greece	Greece	Greece
Romania	Romania	
Bulgaria		Bulgaria
Italy	Portugal	Portugal
Slovenia	Spain	Spain
Poland		
Germany		
Average energy poverty level	**Moderate energy poverty level**	
Belgium	Belgium	Belgium
Croatia	Croatia	Croatia
France	France	France
Hungary	Hungary	Hungary
Ireland	Ireland	Ireland
Lithuania	Lithuania	Lithuania
Netherlands	Netherlands	Netherlands
Latvia	Latvia	Latvia
Czechia	Italy	Italy
Slovakia	Slovenia	Slovenia
Denmark	Estonia	Estonia
		Romania
Low energy poverty level	**Low energy poverty level**	
Austria	Austria	Austria
Sweden	Sweden	Sweden
Estonia	Czechia	Czechia
	Denmark	Denmark
	Slovakia	Slovakia
	Germany	Germany
	Poland	Poland

11 Conclusion

The objective of this work was to classify EU member states in terms of energy poverty. To do that we defined the following research questions in the Introduction (section 2): (1) How can we assess the energy poverty of EU member states in a structured framework? (2) Can energy poverty patterns be discerned across the EU based on the varying levels of energy poverty among member states?

In this study we have successfully implemented a structured framework that provided robust results for the classification of fuel poverty of 24 EU countries. Due to the multidimensional nature of the energy poverty issue, this framework consisted of taking a multi-criteria classification approach, the ELECTRE-Tri-nC method to assess energy poverty of EU member states. The SRF method was also used to complement the ELECTRE-Tri-nC method, since it was applied to determine the weights of the chosen criteria. This approach was adopted with the help of four energy poverty experts, from which we gathered information to develop the model. Moreover, the platforms MCDA-ULaval and DecSpace were used to implement the model.

After successfully implementing the previously described methodology, we were able to identify energy poverty patterns across the European Union. Generally, Eastern Europe and Southern Europe have a high energy poverty level, whereas the Scandinavian countries studied in this work, and Central Europe, have a low energy poverty level. Western Europe and the Baltic countries were found to have an overall moderate energy poverty level.

11.1 Limitations

Our work has some limitations that must be mentioned. Firstly, there was a problem with data availability at a EU-wide level as there was not enough data available that fully reflected the chosen energy poverty definition or the opinion of the four energy poverty experts consulted. The unavailability of the data in some cases was related to the fact that there was not enough data collected in the dataset for certain EU member states. In other cases, it was related to the non existence of the relevant indicators. We tried to solve these problems by excluding Cyprus, Finland, and Malta from the study. However, there were still important criteria missing from the chosen areas of concern, as mention in section 6.

Secondly, the data utilized for this study represents imperfect proxies obtained from surveys, which creates uncertainty. Thirdly, certain criteria, namely g_1 presence of leak, damp, rot, g_2 inability to keep home adequately warm, and g_5 arrears on utility bills, were based on indicators that are dependent on other people's answers and not on measurable and precise data, thus, there is some degree of subjectivity associated with these. However, the ELECTRE-Tri-nC takes into account imperfect knowledge of data and some arbitrariness associated with the construction of the criteria.

Fourthly, the findings of this analysis are highly dependent the weights of the criteria, which were defined with the help of one energy poverty expert. Despite having four experts with whom we developed the set of criteria, only one of those four, collaborated with us to define the weights. Thus, we were deprived of generating more results from our model that would allow us to compare different perspectives on the energy poverty problem. Having access to other energy poverty experts would have allowed us to test the model's adaptability to other opinions. We recognized this issue and minimized it by doing sensitivity analysis by changing the z ratio, which consequently changes the weights.

11.2 Future Research and Policy implications

It is important to note that this study only assesses fuel poverty at a certain moment in time, this is, the year of 2020. Thus, in future research, it would be interesting to use this model to assess energy poverty's evolution in the European Union throughout the years. Specifically, it would be relevant to evaluate the impact of the current conflict between Russia and Ukraine, and the consequent energy crisis, on the EU. Furthermore, as new data on the matter will start to become available, it would be pertinent to make adjustments to the model by adding new adequate criteria to it.

By outlining in section 3 the developed EU directives and initiatives that had, or have, the objective of eradicating energy poverty, we stress the vagueness, impracticality, and inadequacy of those policies. Therefore, we propose a practical model of energy poverty assessment with easily interpreted results, in which a common EU wide fuel poverty definition is adopted, in the hopes of contributing to the development of new policies.

This study can have different policy implications aimed at reducing the energy poverty in the European Union. As new policies are going to be developed, this model could be used to monitor the impact of newly developed policies and make further adjustments to the policies. What is more, the model could be used to identify the critically energy poor areas within the EU and develop national or regional policies in those areas.

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