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Energy poverty in EU: Using regional climatic conditions and incidence of electricity prices to map vulnerability areas across 214 NUTS2 European regions

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ABSTRACT

The rising political instabilities and the associated variations in energy prices have recently amplified the existing debate on energy poverty. Generally defined as the inability to afford enough energy services to live a comfortable life, energy poverty represents a serious issue affecting multidimensional elements of life. To address disparities and to achieve the 7th goal of the 2030 Agenda, EU Member States have been requested to track energy poverty within the National Energy and Climate Plans. The lack of a commonly adopted methodological approach makes however difficult to compare the energy poverty risks. To address this gap, this paper proposes, for the first time, an energy poverty vulnerability indicator that can be used to investigate the differences across NUTS2 European regions. By combining data on regional income, electricity prices and local climatic conditions, the proposed methodology uses a threshold approach to maps vulnerability risks for the years 2010 and 2020. Results show that in 2010 15% of the considered households classified into the highest vulnerability risk and by 2020, 40 additional regions moved to a higher category of risk. Mediterranean countries have been the most affected with extensive climatic and price incidence changes. The proposed indicator can support the definition of policies aiming to reduce regional disparities and improve the average European trends.

1. Introduction

The increased political instabilities and the associated rise of energy prices have recently amplified the existing debate on energy supply, allocation, and use. The unequal distribution of energy sources and the related difficulties in affording essential energy services have then boosted the political discussion on the socio-economic and environmental issues related to fuel and energy poverty [32],[80]. Often used as synonymous concepts, fuel and energy poverty are umbrella terms describing the inability to meet primary energy needs and denoting a complex social phenomenon alongside fundamental requirements of energy use [5],[6],[68],[83].

As recently highlighted by European Parliament [31] over 41 million Europeans were unable to keep their homes adequately warm. Energy poverty is a multi-dimensional phenomenon, considered to be caused by a combination of low-income, high-energy expenses, and poor energy efficiency in buildings". By affecting multidimensional elements of life, energy poverty represents a serios issue for human health, social inequalities, development possibilities and satisfaction of needs [64],[83]. Within this context, a large set of studies have then been orientated to investigate the possible impacts in terms of physical and mental health, violence [37],[56], criminality [15], digital literacy, entrepreneurship [58],[82], education, gender equality and energy justice [1],[34],[55],[73]. These analyses have highlighted the multi-faced nature of energy and fuel poverty, together with the spill-over effects on socio-economic inequalities. The multidimensional implications of energy access have also been recently highlighted by the 7th Goal of 2030 Agenda, that clearly identify "affordable, reliable, sustainable and modern energy" as a key objective of the SDGs [79]. Within this context international organizations and local governments have been developing a wide range of policies, infrastructural investments and energy subsides to move toward a more sustainable, reliable, and affordable energy structure [70]. The increasing energy demand related to the post COVID-19 economic recovery and the rising energy prices, driven by supply and environmental policy constraints, are however inducing serious challenges for the achievement of energy goals [6],[38].

Clear measurements and comparable set of indicators are then fundamental factors for the identification of areas of risks and for the design of the related policies. During the last few decades, a wide range of approaches have then been proposed and a variety of unidimensional

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and multidimensional indexes have been used [14],[75]. The different definitions and the related set of indicators make however difficult to have a clear and comparable overview of the energy and fuel poverty risks [18]. Some countries, with a long tradition in the analysis of fuel poverty, such as UK, have clear datasets across regions and years, while others lack consisted data and collection approaches [52].

Within EU, different attempts have been made to support governments in the definition of actions aiming to mitigate fuel poverty, together with energy efficiency increase, decarbonization, and clean energy uses [21]. The Energy Poverty Observatory, the Energy Poverty Advisory Hub and the Fit for 55 are just some examples of that [19], [23],[25],[29]. The legislative package on Clean Energy for All European has also been introduced to mandate Member States to include energy poverty within their National Energy and Climate Plans (NECP) [20]. Within this context, European countries have then developed national strategies, methodologies, and definitions. The multidimensional nature of the fuel poverty and the lack of an overall European approach makes, however, difficult to have a consistent overview of the problem and a comparable set of fuel risk data.

To mitigate these issues, European Commission has recently listed a set of indicators supporting governments in the energy poverty evaluation and amongst those, the "share of population unable to afford to keep home adequately warm" is one of most widely used [22],[28]. Collected within the EU Statistics on Income and Living Conditions (EU-SILC), the data identifies the percentage of household that are unable to keep rooms temperature above 18 °C. This indicator is however unable to account for local climatic conditions and whether the household needs to be kept adequately warm [33]. The data is also unable to account for additional energy-related elements, such as the need to cool down the house during the summer or the energy costs for additional uses, such as cooking or electrical appliances [62]. Given the fact that energy poverty is an issue affecting individual households, a more disaggregated level of analysis would be needed. Specific surveys, such as those conducted in UK, where a standard definition of fuel poverty and related indicators are adopted both at national and regional scales, would for example contributes to clarify the magnitude of the problem and the design of targeted strategies. As previously highlighted by Thomson et al. [77] and Castano-Rosa et al. [13] specific information, such as the inability to pay utility bills and the percentage of family living in dwelling with defects (e.g., leakages, damp walls, etc.), should be used to have a multidimensional view of the fuel poverty phenomenon. Most of these data are however collected at national scale and are unable to provide a micro-level and regional overview of the problem. The existing data gap and the lack of a common European definition makes then difficult to have consistent analyses of the regional disparities across EU.

Within this context, the present paper combines a set of harmonized information that are presently available at European regional scale and proposes a energy poverty vulnerability indicator that can be consistently used across NUTS2 EU regions. Building from existing energy poverty approaches [4],[13], and combining regional data on income, electricity prices and local climatic conditions, the proposed methodology uses a threshold approach to identify four categories of energy poverty risk. Results can be used to support the definition of policies aiming to reduce the regional disparities and to improve the average of European trends. The paper contributes to the existing literature in different ways: 1) It provides an overview of the main energy poverty measures, approaches and gaps; 2) It proposes a regional energy poverty vulnerability indicator that is able, for the first time, to provide a comparable set of information across NUTS2 geographic areas; 3) It contributes to the existing debate about multidimensional energy poverty and introduces a methodological attempt that can lead to the definition of more comprehensive energy poverty approaches.

The paper is structured as follow: Section 2 reviews the main methodological approaches used to evaluate energy poverty. In Section 3 the methodology and the data are presented together with the main benefits and constraints. Section 4 maps the energy poverty vulnerability risks at EU NUTS2 level and Section 5 concludes.

2. Review of energy poverty approaches

Despite the wide range of indicators that are presently use in the energy poverty evaluation, three main methodological approaches can be broadly defined [38],[77], namely: Expenditure-based evaluation; Self-reported assessments; and Multidimensional approaches.

Expenditure-based evaluation usually compares the domestic energy expenditure to the level of income. The fist available definition proposed according to this approach was the "10% index" introduced in UK in 1991 [9]. Describing fuel poverty as "a household that needs to spend more than 10% of its income on fuel to maintain an adequate level of warm" the index has been largely used to estimate the number of households both at national and regional scale. Over the years, the indicator has been progressively improved with the introduction of the Low Income High Cost (LIHC) and the Energy Poverty Gap. Summarizing the difference between the expenditure faced by energy poor households and the medial level, defined as the 60% of the national median equalized residual income after all housing-related expenditures plus energy bill. These indicators are suitable to account for the fuel poverty rate and the magnitude of risk across different income groups [2]. More recently the Low Income Low Energy Efficiency (LILEE) has also been introduced. Defining fuel poor households as those characterized by building efficiency lower than D and disposable income (defined as income after housing and energy costs) below the poverty line, this indicator introduces energy efficiency into the fuel poverty evaluation and provides a more comprehensive evaluation than the LIHC approach [3],[54],[65]. These indicators have been largely used in UK to target and shape the decarbonization objectives of the Climate Change Act 2008 [3],[78].

Within EU, two main expenditure-based relative threshold indicators are presently used, namely: the Low Absolute Energy Expenditure (M/2) that quantifies the share of households with an absolute energy expenditure below half the national median (or mean); and the High Share of Energy Expenditure in Income (2 M) that focuses on the percentage of household whose energy expenditure share in income is more than twice the national median (or mean) [26],[71]. Being based on the use of a threshold these indicators are able to account for the distribution of income and expenses and the specific characteristics of countries [13], [61].

Despite the benefits related to the methodological clarity of these approaches, different authors have highlighted how different geographical and cultural conditions may impact on the reliability of results. Betto et al. [7], Ntaintasis et al. [59] Sanchez et al. [69] and Oliveria Panao [61] have for example pointed out that the use of expenditure-based approaches in Mediterranean regions, such as Italy, Greece, Spain, and Portugal, could generate an underestimation of the energy poverty phenomenon. That is because, the mild winter conditions and the low energy efficiency of building can induce cultural behaviours exposing people to colder conditions than in norther European areas. To address these issues, self-evaluation approaches have also been introduced. The objective is to account for individual and cultural perspectives and to have a more subjective evaluation of the energy poverty phenomenon.

- Self-reported assessments are usually based on survey designed to collect information on living conditions and social exclusion. The "share of population not able to keep their home adequately warm" and the "share of population having arrears on utility bills" are example of that. They are usually defined as primary indicators as directly connected to energy poverty. Secondary information, such as the "share of population with leaks, damp, or rot in their dwellings" and the "average number of rooms per person in rented dwellings" can also be used to complement energy poverty estimations. As reported above, these indicators are usually collected at national scale and being based on self-reported evaluations, can be affected by subjective elements and perceptions. Age, psychological and psychophysical conditions, health related factors and household compositions can for example impacts on the energy needs, as older people or family with young children could need higher temperature than other household groups [8],[13]. Within this context, previous studies have been specifically focused in analysing how indoor temperature, thermal comfort, and related health conditions can impacts on self-reported evaluations [17],[51],[81].

Within EU a wide range of analysis have used these subjective approaches. Thomson et al. [77] have for example combined health, well-being, and energy poverty data to provide a comparative analysis for European countries. Kahouli [49] investigated the relationships between housing hazard and health in residential fuel poverty in France; and Camboni et al. [10] combined survey data and energy performances for the Italian case. Despite the limitation reported above, these studies have highlighted that individual feelings and specific household experiences can provide useful information to complement the data of the expenditure-based approaches [14].

Within this context the EU Energy Poverty Advisory Hub has been specifically created to provide a platform of expertise where data, case study and analysis can be collected and shared between stakeholders, local authorities, and civil society. The objective is to provide multidimensional knowledge able to support the definition of policies designed in line with the just transition mechanisms. Based on the adoption of a participatory approach, the work of the EU Energy Poverty Advisory Hub has recently produced a publication that align to the guidelines of the Covenant of Mayors [16], and that aims to provide comprehensive energy poverty indicators. By including expenditure-based, socio-economic assessments, climatic conditions and building stock characteristics the report stress the importance of disaggregated and multidimensional analysis [36]. This approach has also been reflected in the recent revision of the Energy Efficiency Directive (2023/1791) that define energy poverty as a multifaced phenomenon that need to be urgently addressed in line with the EU principles of equality, inclusion and net-zero transition. Within this context, the revision of the Directive has introduced a set of multidimensional energy poverty indicators and have included the obligation to deliver a share of the end-use energy saving amongst the most affected households [30].

- Multidimensional approaches are based on the idea that the multidimensional and the subjective nature of the energy poverty phenomenon cannot be reflected by the use of single-dimensional indicators, the multidimensional approaches propose a combination of different metrics, such as self-reported, and expenditure-based evaluations [50],[57],[60],[67],[74]. The Index of Vulnerable Homes, proposed by Castano-Rosa et al. [11],[12] and applied for Spain and UK, is for example based on a combination of income-related dimensions, dwelling characteristics, and thermal-comfort variables. By accounting for multi-dimensional elements of energy poverty, this indicator aims to identify the variables of risks and to support the definition of targeted strategies. The Vulnerability Index for Energy Poverty, introduced by Papada and Kaliampalos [63], quantifies vulnerability in comparison to reference population and accounts for different variables such as local climatic conditions, economic elements, energy performances and energy prices. In a similar way, Gouveia et al. [35] proposed a high-resolution spatial scale composite indicator accounting for heating and cooling needs, socio-economic characteristics and building performances. These approaches have for example been used to estimate fuel poverty in mountain regions of Greece and in 3092 civil parishes of Portugal. Despite providing detailed information, these vulnerability indicators are usually focused on specific geographical areas. That is because, the large set of data required are usually collected for specific research initiatives and are not consistently available across the different European regions. As previously highlighted by Pelz et al. [64], multidimensional indicators can provide comprehensive perspectives of the energy poverty phenomenon. However, the need of several and specific variables limit the use on different geographical areas. Within this context, the various types of indicators that have been adopted, makes difficult to have a consistent approach across the different European regions.

To address this problem, the present paper suggests the use of a energy poverty vulnerability indicator based on a set of regional and reliable data that are regularly collected by the European statistical office. Compared to the existing multidimensional approaches, the proposed methodology includes a lower range of evaluation metrics, but allows, for the first time, to have consistent and comparable estimations of the energy poverty vulnerability risk across 214 NUTS2 regions. In addition, the use of a threshold approach, previously adopted in UK and European studies, allows to consider the regional vulnerabilities in comparison to the European average. The methodology and the related results are functional to support the design of regional, national, and European policies aiming to reduce regional disparities and to improve the overall European trends. In addition, the identification of the main benefits and gaps can support the research community in the definition of more efficient metrics and in the promotion of the collection of consistent data across European regions.

3. Data and methodology

In this section, the methodological approach used to estimate the energy poverty vulnerability indicator for the 214 NUTS2 European regions is presented together with the data, the main benefits and the related limitations.

3.1. Methodological approach

Since the traditional energy poverty metrics cannot be consistently applied at European regional level, an energy poverty vulnerability indicator is calculated in this paper by combining two types of risks, namely:

- The Climatic Risk (CLR), defined as the regional exposure to adverse climatic conditions. Given the increase occurrence of extreme weather events (such as cold spells and heat waves) this element of risk is particularly relevant to identify the geographical areas with the largest climatic hazards and to evaluate how vulnerability can change over periods of time.
- The Electricity Price Risk (EPR) defined by the incidence of the electricity prices on the net household disposable income. This element of risk can be largely influenced by economic growth and recessions, regional income distribution and energy taxes. The overall energy prices and the related instabilities on imports and supply can also have an incidence on costs.

Following the approach previously adopted by the LILLEE indicator and the European threshold methodology [4],[26], the Climatic and the Electricity Price Risk are calculated as follows:

- The Climatic Risk (CLR) is estimated in line with the Eurostat methodology that accounts for the difference between the mean outdoor air temperature and the average degrees that are needed to maintain a home at the required average indoor base temperature.

The Climatic Risk is then calculated by combining the Cooling Degree Days (CDD) and the Heating Degree Days (HDD):

$$\mathrm{CLR} = \mathrm{CDD} + \mathrm{HDD} \tag{1}$$

Where the Cooling and the Heating Degree Days are respectively defined as:

$$CDD = T_m \geq 24^{\circ}\mathrm{C}\ \mathrm{Then}\left[\mathrm{CDD} = \sum\nolimits_i \mathrm{T}_m^i - 21^{\circ}\mathrm{C}\right]\mathrm{Else}[\mathrm{CDD} = 0] \tag{2}$$

$$\mathrm{HDD} = T_m \geq 15^{\circ}\mathrm{C}\ \mathrm{Then}\left[\mathrm{HDD} = \sum\nolimits_i 18^{\circ}\mathrm{C} - \mathrm{T}_m^i\right]\mathrm{Else}[\mathrm{HDD} = 0] \tag{3}$$

where $\mathrm{T}_\mathrm{m}^\mathrm{i}$ is the mean air temperature of day i

- The Electricity Price Risk (EPR) is estimated in line with the approach proposed by Broadman [9] that considers the incidence of the electricity price for household consumers on the household disposable income, and it is calculated as:

$$\mathrm{EPR} = (100 \times \mathrm{ElectricityPriceforHouseholdConsumers} / \mathrm{HouseholdDisposableIncome}) \tag{4}$$

The average European values (EA), are then calculated as follows:

$$\mathrm{EACLR} = \sum \mathrm{CLR}_r / 214 \tag{5}$$

$$\mathrm{EAEPR} = \sum \mathrm{EPR}_r / 214 \tag{6}$$

Where r is the 214 NUTS2 European regions

The average European values are than used to classify the regional performances according to the following approach:

- If (EPR) >= (EA EPR) and (CLR) >= (EA CLR) then 'above average incidence of electricity prices and above average adverse climatic conditions'

  It is defined as areas of high electricity price risk and high climatic risk as the incidence of the energy prices on the net household disposable income and the number of heating and cooling days is above the European average.

- If (EPR) < (EA EPR) and (CLR) >= (EA CLR) then 'below average incidence of electricity prices and above average adverse climatic conditions'

  It is defined as areas of low electricity price risk and high climatic risk as the incidence of the electricity prices on the net household disposable income is below the European average and the number of heating and cooling days is above the European average.

- If (EPR) < (EA EPR) and (CLR) < (EA CLR) then 'below average incidence of electricity prices and below average adverse climatic conditions'

  It is defined as areas of low electricity price risk and low climatic risk as the incidence of the electricity prices on the net household disposable income and the number of heating and cooling days is below the European average.

- If (EPR) >= (EA EPR) and (CLR) < (EA CLR) then 'above average incidence of electricity prices and below average adverse climatic conditions'

  It is defined as areas of high electricity price risk and low climatic risk as the incidence of the electricity prices on the net household disposable income is above the European average and the number of heating and cooling days is below the European average.

The energy poverty vulnerability areas calculated with this approach are then mapped for the 214 NUTS2 European regions considered in this paper.

3.2. Data

The entire sets of data used to estimate the climatic and the electricity price risks have been obtained from the Eurostat database that collect consistent information across the NUTS2 European regions.

The information included in Table 1 have been used to estimate the Climatic Risk and the information included in Table 2 have been used to calculate the Electricity Price Risk.

Given the availability of data, the energy poverty vulnerability risk is calculated in this paper for the year 2010 and for the year 2020, that are the first and the last years for which consistent information have been published. In Table 3, the European average values used for the threshold approach are reported.

3.3. Benefits and limitations of methodology and data

The main benefits of the proposed approach relate to the fact that the use of data consistently collected across EU NUTS2 regions allows to

Table 1
Eurostat data used to quantify the Climatic Risk.

Data	Definition
Heating degree days (HDD)	HDD is a weather-based technical index designed to describe the heating requirements in building. The HDD is calculated by considering the severity of the cold in a specific time-period, by considering the daily outdoor temperature, the required average indoor temperature (18 °C) and a base temperature. The base temperature is defined as the lowest daily mean air temperature not leading to indoor heating. It depends by factors associated with building and surrounding environment but based on a general climatological approach it has been set to a constant value of 15 °C. Data are consistently produced for the NUTS2 regions based on observations from about 3000 weather stations across Europe.
Cooling degree days (CDD)	CDD is a weather-based technical index designed to describe the cooling (air conditioning) requirements in building. The CDD is calculated by considering the severity of the heat in a specific time-period, by considering the daily outdoor temperature, the required average indoor temperature (21 °C) and a base temperature. The base temperature is defined as the highest daily mean air temperature not leading to indoor cooling. It depends by factors associated with building and surrounding environment but based on a general climatological approach, it has been set to a constant value of 24 °C. Data are consistently produced for the NUTS2 regions based on observations from about 3000 weather stations across Europe.

Source: Eurostat database.

Table 2
Eurostat data used to quantify the Electricity Price Risk.

Data	Definition
Electricity prices for household consumers	Electricity prices for household consumers are defined as average national price in Euro per kWh including taxes and levies per medium size household (defined as consumption band DC with annual consumption between 2500 and 5000 kWh). Data are consistently provided at Member State level.
Household disposable income	The household disposable income is defined as the net disposable income of private households and is calculated as the balance of primary income (operating surplus/mixed income plus compensation of employees plus property income received minus property income paid) and the redistribution of income in cash (such as social contributions paid, social benefits in cash received, current taxes on income and wealth paid, as well as other current transfers).

Source: Eurostat database.

Table 3
Average European values used to estimate the energy poverty vulnerability risk.

European Average Climatic Risk	Year 2010 = 3165 Year 2020 = 2511	Defined as the European Average degrees days that are needed to maintain n home at the require based temperature.
European Average Electricity Price Risk	Year 2010 = 0,145 Year 2020 = 0.130	Defined as electricity prices per household consumer per kilowatt-hour as a percentage of the household disposable income

compare the Climatic and the Electricity Price Risks and to map energy poverty vulnerabilities across space and time. In addition, by considering the relative performances of European regions in relation to the European average, this indicator is particularly useful to account for the existing gaps and to support the design of policies aiming to address the regional disparities. As reported in Table 3, the average values of the Climatic and Electricity Price Risks have reduced between the considered years. However, the increasing gaps across regions could potentially amplify the existing differences of the energy poverty impacts. The identification of the main elements of risks and the analysis of the overtime variations can then contribute to the definition of European energy strategies aiming to levelling down the average risks and to reduce the regional discrepancies. Existing limitations mainly relate to the categories of data that are presently collected at European regional scales. As previously highlighted by other studies (e.g., [13],[77]) energy performances of buildings and self-reported evaluations of energy needs would contribute to provide a more comprehensive overview of the energy poverty phenomena. In addition, the expected publication of the European household census will provide the opportunity to further disaggregate the analysis of this paper into the number of households that in each region can be classified into the designated energy poverty risk categories. When available, this information can be easily integrated into the proposed indicator and provide a more disaggregated and multidimensional map of the energy poverty at European regional scale.

4. Results

The energy poverty vulnerability indicator, calculated with the approach reported above, is analysed in this section for 214 NUTS2 European regions. The study investigates how the energy poverty vulnerability risk has changed between the years 2010 and 2020 that, as reported above, are the first and the last years for which consistent Eurostat data are presently available. The period of study is particularly interesting as various EU policies have been implemented to further harmonize the energy governance approaches of the different Member States. The Energy Union Framework Strategy, the Clean Energy for All Europeans package and the Electricity Market Directive are just some examples of that. The objective is to increase the security of supply, the energy solidarity across MS and the creation of an integrated energy market. The promotion of renewable energy sources and the energy efficiency increase are also listed as priorities for the reduction of the import dependence and for the achievement of the climate targets. Within this context, electricity is expected to play an important role, as the share of electricity in final energy consumption is targeted to increase from 20% in 2018 to 53% in 2050, with renewable energies expected to reach 50% of the total electricity production by 2030 [39]. Given the fact that the choice of the fuel mix used for electricity generation falls within the sovereignty of the MS, extensive difference currently exists across countries, with shares of fossil fuels ranging from 90% in Poland and less than 10% in Sweden and France. Nuclear generation accounts for the largest electricity source in the EU, as European Union has the world largest operating nuclear fleet. In France, Slovakia, Belgium, Hungary, Sweden, and Slovenia nuclear power produce more than 40% of the national electricity supply, with France generating over the 72% in 2017 [40]. The ageing of the power plants is however representing a critical element for the future of the nuclear power, as most of the reactors were built in the 1970s and 1980s. Member States need then to take decisions on adopting phase-out policies, such as Germany, or in building new reactors, such as France, Hungary, and Slovakia [24]. All countries have however increased the investments in renewable energy sources with Sweden and Spain considering the existing nuclear plants as a temporary measure needed to support the transition toward renewable production. Poland, Bulgaria, and Czechia, on the contrary, have pro-nuclear energy policies aiming to use the nuclear power to reduce the fossil fuel dependency [40]. Up to now, nuclear production remains an important source of energy, accounting, in 2017, for 25% of the total EU generation. As reported in Fig. 1, the nuclear electricity generation has however constantly declined since the year 2004, with renewable sources replacing the overall electricity supply (Fig. 2) (IEA, website).

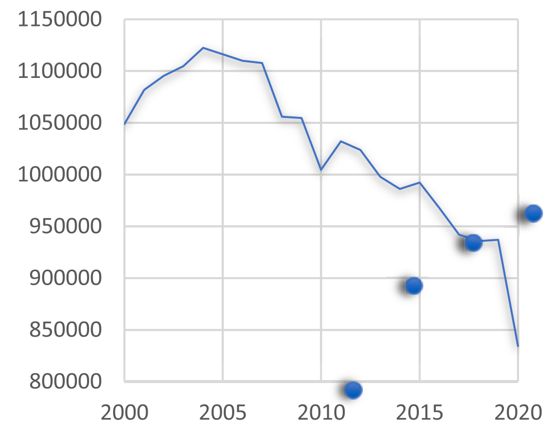

Fig. 1. Nuclear electricity generation in Europe (GWh).
Source: IEA website

The wide range of electricity sources and the different policies of Member States largely influence the availability of internal production and the related energy prices. Despite the recent efforts to harmonize the energy market,[1] extensive differences still exist and the incidence of electricity costs on the household disposable income has generally increased. As reported in Fig. 3, electricity prices for the household consumers have risen for all MS, with exception of Hungary, Netherland, Slovakia, and Sweden.

[1] Regulation (EU) 2019/943 and Directive (EU) 2019/944

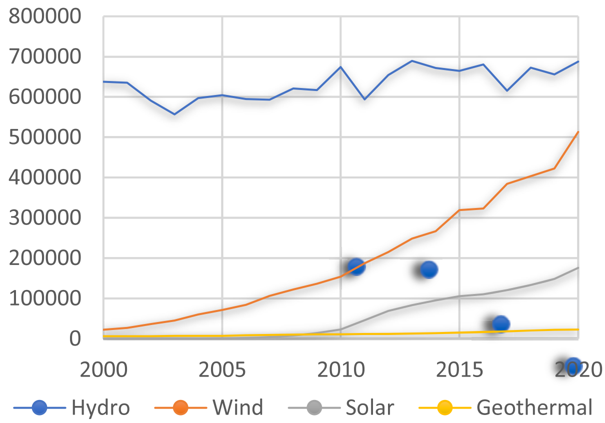

Fig. 2. Renewable electricity generation in Europe (GWh).
Source: IEA website

According to data reported by the IEA [41] the average household electricity prices in Hungary are generally lower than in other European countries, accounting in 2020 for 107.3 Euro/MWh compared to the EU average of 210.3 Euro/MWh. The application of the Universal Service Scheme, covering 99.6% of the electricity provided to households, obliges companies to supply electricity at prices regulated by government. In addition, during the last decade, electricity generation has seen a consistent upward trend with nuclear power accounting for half of total electricity production. The increased investments in renewable energy sources have also contributed to reduce the imported fossil fuels characterized, during the last few years, by rising prices. In line with the cross-border harmonization objectives of EU, Hungary has also been able to largely increase the electricity interconnectivity, as the cross-border capacity reached 55% in 2020, significantly above the 15% of the 2030 EU target [41].

In Netherlands, the extensive competition across electricity providers and the inclusion in the wholesale electricity market, that manages day-ahead and intraday electricity trading between interconnected European bidding zones, have contributed to largely reduce the overall electricity price. As reported by IEA [42], the number of electricity supplies constantly increased during the last few years, moving form 9 in 2004 to 59 in 2018. The price transparency and the low switching costs also facilitated the creation of a costumer attitude willing to move across supplies based on prices and renewable energy provisions. Despite the recent price increase, mainly due to the rising costs of imported gas and coal and to the higher carbon prices under the EU ETS, the average electricity household prices have constantly decreased since 2008 ([42].

Sweden is one of the leading countries in the energy transition toward a low-carbon economy. The share of fossil fuels is lower than 2% and Sweden aims to achieve 100% of renewable electricity generation by 2040 [43]. Most of the electricity is today produced by hydropower and nuclear sources, accounting for more than 80% of the total supply (plus 11% from wind and 8% from bioenergy and waste). The well interconnected energy grid, together with the stable internal demand and the increased renewable capacity also allowed Sweden to be a net electricity exporter. During the last decades, electricity prices have then been relatively low and the large competition existing between more than 120 suppliers allows consumer to easily switch between providers. In addition, the development of a centralised information system orientated to collect electricity market data, increased the transparency of the energy market and facilitated the switching of suppliers [76].

In Slovakia nuclear power account for half of the total electricity generation with an increasing trend due to the installation of new nuclear units. Hydropower is the second electricity source and the recent increase in biofuels and wind power production has contributed to compensate the decline in the use of coal. The distribution grid is characterized by significant cross-border capacity, well above the 2030 EU objective. For these reasons, electricity prices have progressively declined since the year 2010. Government regulations are also in place to cap electricity prices for the household consumers that are generally lower than the EU average [45].

Greece and France reported the largest electricity price increase. According to data provided by IEA [44], despite the efforts in diversifying the electricity fuel mix, coal, gas, and oil remain the key electricity sources in Greece, accounting for almost 70% of the total electricity production. In addition, the electricity systems of the non-interconnected island, mainly characterized by the use of diesel-fuelled generations, has been largely affected by the rising costs of the imported energy sources [44]. The extensive economic recession that affected the country since the crisis of 2008, also impacted on the incidence of the electricity prices. According to data provided by Eurostat, the net household disposable income decreases for all the considered regions, with the North Aegean Region accounting for the largest drop.

In France, the closure of two nuclear reactor and the ageing nuclear generation fleet has contributed to rise the overall electricity cost. In addition, despite the increasing market liberalization, costumers are not keen to switch away from the national EDF (Electricité de France) that is the largest incumbent supplier. According to data provided by IEA [46], between 2014 and 2020 the switching rate just increased from 1% to 3% per year. France is also characterized by one of the highest taxation rates in Europe, accounting for 34% of the household electricity costs.

When considering the energy poverty vulnerability risk, France and

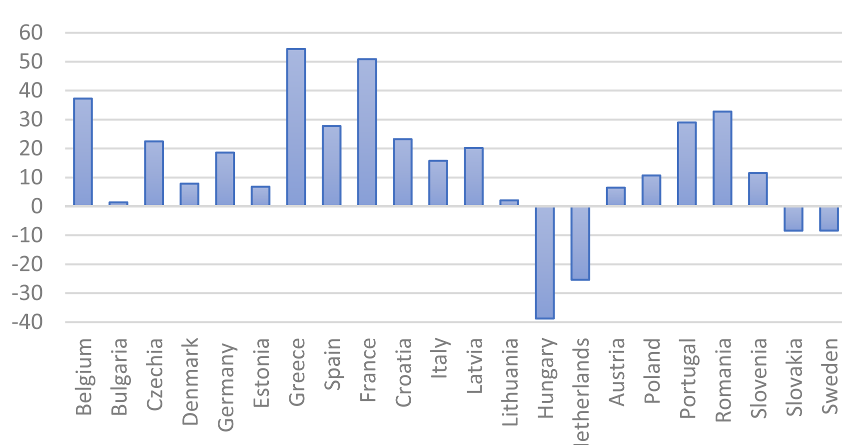

Fig. 3. Electricity prices for household consumers% variations between 2010 and 2020 - PPS all taxes and levies included.
Source: Eurostat data

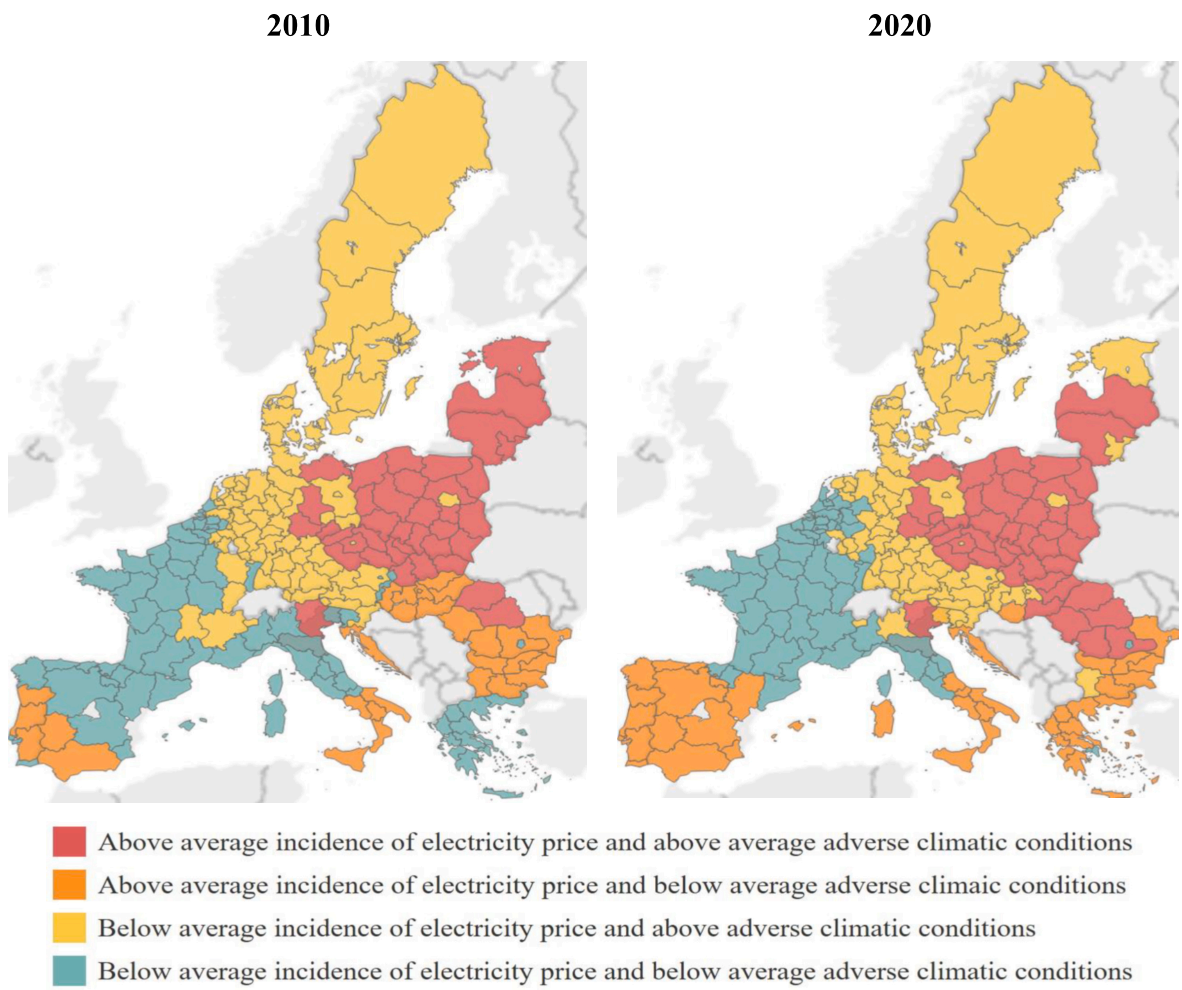

Fig. 4. Energy poverty vulnerability risk.

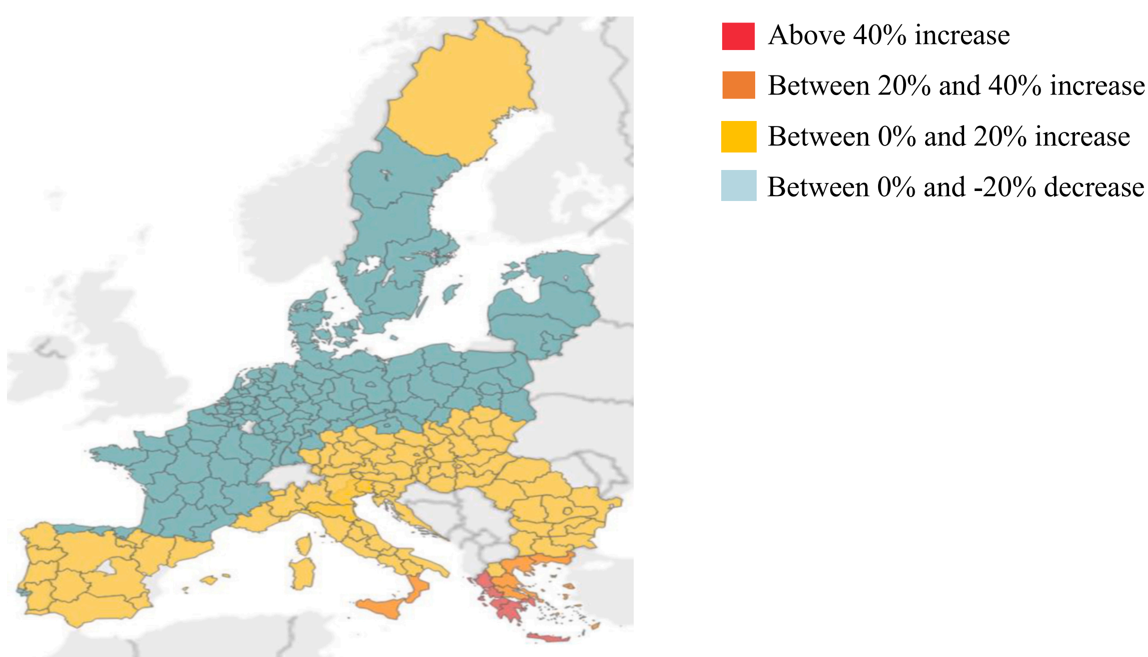

Fig. 5. Percentage variation of cooling and heating degrees days.

Greece have however been characterized by two opposite trends. As reported in Fig. 4, that summarizes the changes in the energy poverty vulnerability risk for the 214 NUTS2 regions, Greece results to be largely affected by the rising energy costs and the decreasing economic growth rate, as all the regions, with exception of Attica that include the capital Athens, have experienced an energy poverty vulnerability risk increase. Between the year 2010 and the year 2020, the regions have moved from being “below average incidence of electricity price” to being “above average incidence of electricity price”.

In France, on the contrary, all the regions have been able to maintain or reduce the energy poverty risk. That is because, despite the rising electricity cost, all the French areas accounted for a household disposable income increase. In addition, the adverse climatic conditions, expressed in terms of number of cooling and heating days, have also been reduced, contributing to move the Rhône-Alpes, Auvergne, Franche-Comté and Lorraine regions from “above average adverse climatic conditions” to “below average adverse climatic conditions”. In Fig. 5, an overview of the climatic conditions changes is reported as a percentage variation between 2010 and 2020. The data clearly highlight an increasing incidence of extreme weather events in the Mediterranean and in the South-Eastern regions. Both Romania and Bulgaria, together with the most eastern areas of Hungary have experienced increased adverse climatic events, with most of the regions moving from orange to red colour in the map. All the regions, with exception of the capitals, also accounted for an incidence of electricity prices that remained above the European average. On the contrary the most western regions of Hungary have moved from being “above average incidence of electricity price” to “below average incidence of electricity price”. As discussed above the extensive reduction in electricity price together with the economic growth rate of Hungary, contributed to that.

Italy, Portugal, and Spain also experience an increased number of heating and cooling days together with increasing energy costs and some of the lowest European economic growth rates. Most the Spanish regions, except for Comunidad Foral de Navarra, País Vasco and Cataluña are in 2020 classified as “above average incidence of electricity price” and the same applies to all the Portuguese areas. According to data provided by IEA [47] the household electricity price of Portugal is affected by one of the highest tax components (49%). However, in 2019 various VAT rates have been introduced based on the consumption level of household. The objective was to promote efficiency and reduce the overall energy demand [27]. In Spain the household electricity prices are amongst the highest in EU with a tax rate accounting for 21% and the overall costs largely above the other Mediterranean countries (287.7 USD/MWh in 2019, compared to 289.2 USD/MWh in Italy and 242.4 USD/MWh in Portugal) ([48]. During the last few years, the large introduction of renewable sources contributed, however, to reduce the electricity prices. Spain also committed to the nuclear phase-out, expecting to replace, by 2035, the nuclear electricity generation with renewable and natural gas ([48]. Similarly to the trends of Portugal and Spain, most of the southern Italian regions have also been affected by increasing energy costs and decreasing level of income. Sardinia, Moise and Abruzzo have been added to Sicily, Calabria, Puglia, Basilicata, and Campania as the regions experiencing “above average incidence of electricity price”. In addition, most of northern regions (e.g., Lombardia, Valle d’Aosta, Trentino alto Adige, Veneto and Friuli Venezia Giulia) are experiencing increasing level of adverse climatic conditions, with energy requirements classified as above the EU average.

When considering the northern European regions, Estonia and the capital region of Lithuania have moved from being “above average incidence of electricity price” to “below average incidence of electricity price”. The limited electricity price increase together with the extensive economic growth largely contributed to reduce the incidence of the electricity price. In a similar way, most of the Netherland regions experienced decreasing electricity prices together with decreasing numbers of cooling and heating degrees days. Most of the central and norther European regions have maintained a similar energy poverty vulnerability risk. As discussed above, the unavailability of consistent regional data summarizing the specific energy characteristics of building does not provide the opportunity to disaggregate the vulnerability risk at household level. However, the adopted approach allows to compare the energy poverty vulnerability risk at regional scale and analyse the number of households included in each category. In Table 4 the main results are reported based on the number of households listed in the Eurostat census of 2011.

Since the household data for the 2021 census are not presently available in the Eurostat website, it is not possible, at the present stage, to calculate the variations across the period considered in this paper. However, based on the information included in Fig. 4 and in Table 5, that lists the number of regions that in every country have moved to a different category of risk, it is reasonable to expect that the number of

Table 4
Number of households included into the designated energy poverty vulnerability risk categories (2010).[21]

Country	High price and high climatic risks	High price and low climatic risks	Low price and high climatic risks	Low price and low climatic risks
Belgium			4727,831	
Bulgaria		3005,589		
Czechia	3792,909		579,176	
Denmark			2524,001	
Germany	3845,199		33,087,839	
Estonia	599,832			
Greece				4134,540
Spain		3512,200		14,571,490
France			4819,810	23,092,744
Italy	4876,205	8270,569	5352	13,141,422
Latvia	859,823			
Lithuania	1267,316			
Hungary		4105,708		
Netherlands			5772,951	1670,850
Austria			2694,933	954,376
Poland	10,559,654		2872,835	
Portugal		1505,089		2538,637
Romania	1820,034	4753,655		896,740
Slovenia			435,092	378,439
Slovakia	1802,071			
Sweden			4002,005	
Total	25,391,071	21,482,194	64,613,265	61,618,301

Table 5
Number of regions that have moved to a different energy poverty vulnerability risk category.

Country	High price and high climatic risks	High price and low climatic risks	Low price and high climatic risks	Low price and low climatic risks
Belgium			−2	+2
Bulgaria		−1	+1	
Czechia				
Denmark				
Germany	+2		−5	+3
Estonia	−1		+1	
Greece		+12		−12
Spain		+9		−9
France			−4	+4
Croatia				
Italy		+4	+1	−5
Latvia				
Lithuania	−1		+1	
Hungary	+3	−6	+3	
Netherlands			−5	+5
Austria			+2	−2
Poland				
Portugal		+4		−4
Romania	+3	−3		
Slovenia				
Slovakia				
Sweden				

households classified as orange and red have increased. According to data reported in Table 5, 60 regions have moved to a different category of risk, 40 of which experienced a vulnerability increase. Most of them are located in Mediterranean and eastern European countries, as Italy, Spain, Portugal and Greece accounts for 29 of them. Greece has been the largest impacted country with 12 regions over 13 moving from blue to orange. Portugal and Spain also experienced large vulnerability changes with the number of orange regions increasing from 3 to 7 and 2 to 11, respectively. In Nethreland, Belgium and France, on the contrary 9 regions moved from yellow to blue, denoting a reduction of the energy poverty vulnerability risk.

As discussed above, when additional regional data will be available, the proposed indicator can be easily used to further disaggregate the energy poverty vulnerability risk at regional scale and to compare the household change across the considered years. At the present stage, the proposed approach can however be used to inform the design of policies accounting for the local climatic conditions and the incidence of electricity prices.

5. Conclusion

A wide range of studies have been conducted to quantify the incidence of energy poverty across European areas. The lack of a consistent European approach and the use of different indicators, makes however difficult to have a clear overview of the energy poverty phenomenon. The extensive range of definitions and the inconsistency across metrics and data have also generated different results within the same European areas, making difficult to design an effective policy approach. In addition, the lack of regional information does not allow to account for local characteristics that could largely impact on the energy poverty of household and communities [53],[66],[72]. Given the fact that energy poverty is largely influenced by local conditions, regional analysis should be performed, and policy interventions should be designed to address the specific vulnerability elements. Within this context, a regional energy poverty vulnerability risk has been proposed in this paper. By considering the local climatic conditions and the incidence of the electricity prices, the vulnerability areas have been investigated by mapping the energy poverty vulnerability changes that have taken place across 214 NUTS2 EU regions between the years 2010 and 2020. Results show that in 2010 15% of the considered households classified into the highest vulnerability risk and by 2020, 40 additional regions moved to a higher category of risk. Mediterranean countries have been the most affected with Greece suffering the largest energy poverty vulnerability increase. A combination of climatic extreme events and rising incidence electricity price have contributed to that. The possibility to map vulnerability areas across European regions and analyse the changes that have taken place over the years, allow to investigate how specific climatic, economic and energy settings have impacted on the energy poverty risks. As reported above, this paper contributes to the existing literature in different ways. From a theoretical perspective, this work aligns to the principles of the EU Energy Poverty Advisory Hub and the recent revision of the Energy Efficiency Directive, that recognize energy poverty as a multifaced and complex phenomenon. Within this context, the multidimensional approach adopted in this paper support the recent attempts devoted to extending the energy poverty overview. From a methodological perspective, these analyses contribute to the existing debate about energy poverty and related indicators, by proposing an approach that use available and consistent information to track the energy poverty vulnerability risk at EU regional scale. Results provide important metrics for the definition of policies aiming to address the highlighted element of risks and the local vulnerability condition. The proposed methodology is also suitable to be complemented by further data on energy efficiency of building and subjective evaluation of energy need. This information will contribute to provide a more disaggregated overview of the number of households classified according to the four vulnerability categories and to produce detailed maps of the distributions of the households across the regions. Future research developments should then be orientated to extend the collection of harmonised data at European regional scale and to complement the proposed approach with additional multidimensional energy poverty information.

[2] Croatia is not included in the household 2011 census provided by Eurostat.

CRediT authorship contribution statement

Andreoni Valeria: Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

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

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