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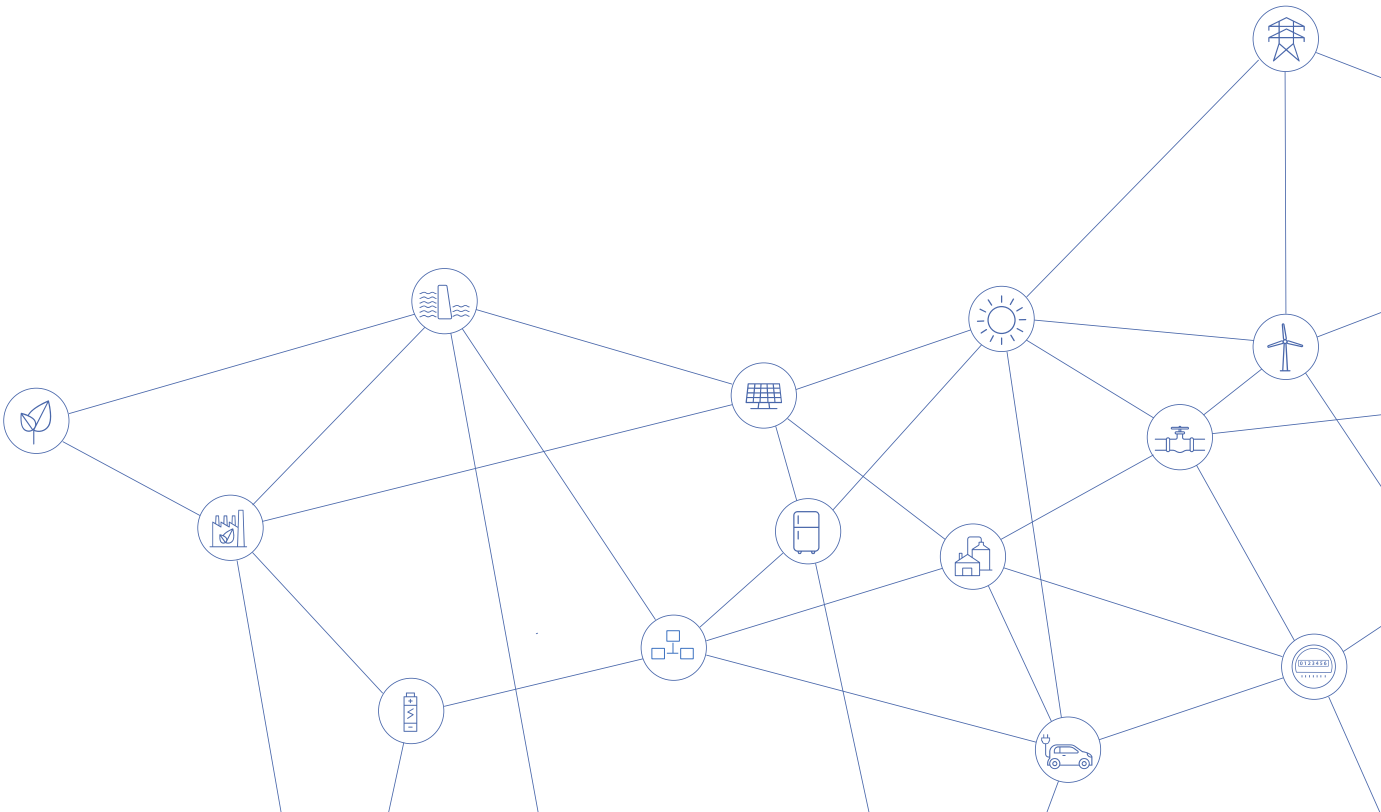

Alleviating Energy Poverty in Europe: Front-Runners and Laggards

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Abstract

In recent years, awareness of energy poverty has gained increasing attention in European countries. Comparative country studies can enhance our understanding of the causes and effects of this growing problem. This paper proposes a new model for the analysis of energy poverty. We define a theoretical framework and model to estimate an energy poverty frontier. The estimated frontier indicates the minimum level of energy poverty that a country can achieve given its income level, energy prices, and other country-specific features. We apply the approach to a sample of 30 European countries during the period 2005-2018. This allows us to contrast whether policy measures aimed at reducing the poverty among vulnerable individuals and households have been effective. The estimates indicate that financial aid aimed at especially vulnerable groups, reductions in energy prices, and improvements in energy efficiency seem to be beneficial to face energy poverty. The impact of these factors may partly explain why, despite the negative impact of the financial crisis, we have found a steady and general energy poverty reduction during the period in almost all the countries analysed.

Keywords: Energy poverty in Europe; Energy poverty determinants; Social protection; Stochastic frontier analysis.

JEL classification: C23, H53, I32, Q43, Q48.

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1. Introduction

Poverty takes many different forms and is a challenge faced by all countries across the world. In general, it is a central social policy issue for most governments. There is a vast literature on the socioeconomic that relates income, natural resources, poverty and inequality (e.g., Dollar and Kraay, 2002; Zeb et al., 2014; Apergis and Katsaiti, 2018). Better understanding of poverty and its determinants is the basis for design of effective social policies aimed at alleviating poverty (Collier and Dollar, 2002).

The present study analyses the determinants of energy poverty as a specific form of poverty that is gaining increasing policy attention. Indeed, affordability is one of the main pillars of sustainable energy transition. Energy poverty is often defined as a situation "where individuals are not able to adequately heat their homes or meet other energy service needs at affordable cost" (Pye et al., 2015, p.64).[1]

This topic has attracted considerable academic, political, and policy interest in the past decades around all the continents. For instance, in Oceania (Awaworyi Churchill et al., 2020; Awaworyi Churchill and Smyth, 2020), in Asia (Jiang et al., 2020; Khandker et al., 2012), in America (Pablo et al., 2019; Mohr, 2018), or in Africa (Nussbaumer et al., 2012). Europe, a pioneer in the definition of energy poverty with the studies of Boardman, (1991) and Bradshaw and Hutton (1983), has shown an increased interest in this issue, being a much-debated topic at the EU level (Bouzarovski and Thomson, 2020).

Comparative country studies can enhance our understanding of the causes and effects of this problem. According to recent reports from the European Commission,[2] approximately 34 million Europeans were unable to keep their homes adequately warm in 2018. Tackling a problem of this magnitude is a major challenge. In recent years, both the European Union (EU) and the member states are aiming to address this problem. Energy poverty has become a political priority since the 2018-19 approval of the Clean Energy for all Europeans Package (CEP) that addresses issues related to energy poverty such as energy efficiency or energy security.

Starting from the premise that the optimum degree of energy poverty for a country is zero, a number of factors challenge this objective. The present study aims to explore the determinants of energy poverty in a sample of European countries, given their income and energy prices, and taking into account their particular characteristics (e.g., income inequalities and energy efficiency, among others). Energy poverty can be reduced indirectly by reducing general poverty or directly by targeting energy poverty as a specific social policy priority. Examples of the latter are the establishment of specific measures to increase energy efficiency or cut energy prices. Also, access to gas network can reduce

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[1] In recent years, attention is also being paid to energy services such as to achieve adequate levels of indoor cooling (Thomson et al., 2019).

[2] https://ec.europa.eu/energy/topics/markets-and-consumers/energy-consumer-rights/energy-poverty_en?redir=1#eu-projects-tackling-energy-poverty.

household energy spending as gas is the main source of space heating for households and inter-fuel competition can also reduce electricity prices (Meier et al., 2013).

A number of studies have analysed the determinants of energy poverty in Europe from a microeconomic point of view at the individual or household level (see, e.g., Thomson et al., 2017; or Llorca et al., 2020; for a recent review). However, the literature comparing the situation between European countries is scarcer. Thomson and Snell (2013) use cross-sectional data from Eurostat EU-SCIL (European Union Statistics on Income and Living Conditions) for 2007 to analyse the explanatory factors for energy poverty at the household level. Their results indicate that energy poverty is more pronounced in southern and eastern European countries and in rural areas. Dubois and Meier (2016) explore an analytical framework of energy poverty using a sample of 28 EU countries for the period 2007-2014, concluding that energy poverty varies significantly across countries. While in some cases the main problem is energy services deprivation for a large share of the population, in other countries it is predominantly concentrated in certain groups of househols. Bouzarovski and Tirado Herrero (2017) analyse territorial inequalities through a descriptive analysis. They distinguish three groups of countries in Europe (north and west, east, and south) and find that the energy poverty is more prevalent in the periphery than in the centre.

At macroeconomic level, Cadoret and Thelen (2020) contrast the existence of the Kuznets curve between energy poverty and GDP per capita in Europe using a panel data from 28 European countries from 2004 to 2017 using aggregate data from Eurostat's EU-SILC survey. They find that an improvement in the standards of living of the population has made it possible to reduce energy poverty, particularly in the countries of southern and eastern Europe. However, they also find that more economic growth will not systematically induce less precariousness, so measures in favour of energy efficiency and/or measures aimed at increasing the purchasing power of households must be put in place at the national level.

In this study, we propose the use of a frontier methodology, which is standard for the analysis of the technological efficiency of companies or countries, but its application to the study of poverty or inequality is uncommon.[3] The main novelty of our study is to present a new theoretical framework and methodological approach to analyse the socioeconomic determinants of energy poverty. The study contributes to the literature by identifying the determinants of energy poverty using a stochastic frontier analysis approach. This methodology will allow us to quantify and better understand the level the energy poverty of European countries and their potential for improvement.

To our knowledge no previous studies have estimated an energy poverty frontier function. This frontier function envelopes the data, not allowing observations to be below the estimated frontier. The most efficient countries are those that achieve, *ceteris paribus*, the lowest poverty levels given their per capita income and the country's own idiosyncrasy.

[3] See, for some exceptions, Afonso et al. (2010); Rodriguez-Alvarez et al. (2019) or Valls Fonayet et al. (2020).

Once the energy poverty frontier is estimated, it is possible to analyse the observations that are above the estimated frontier and obtain an efficiency ranking of the countries, ordering them by their distance from the energy poverty frontier, given its income level and other country-specific characteristics. In this sense, the concept of frontier is relative and not absolute.

The analysis of the determinants that prevent a country from reaching its minimum level of energy poverty is important from a policy point of view. For instance, policy makers might be interested in evaluating whether specific aids could alleviate energy poverty inefficiency. In this regard, we analyse, among other determinants, whether social protection policies aimed at vulnerable groups affected by a specific set of social risks and needs have reduced energy poverty.

The remainder of the paper is as follows. Section 2 presents the theoretical model on which the study is based. Section 3 presents the proposed empirical model to estimate the energy poverty stochastic frontier. Section 4 describes the data. Section 5 presents the results and discusses policy issues emerging from the estimation of the model. Section 6 concludes.

2. The Theoretical Model

We define $\bar{V}^z$ as the utility level that allows individuals in a country to live above the energy poverty line (z). We then define the following ratio:

$$EP = \frac{\bar{V}^z}{V^0} \tag{1}$$

where $\bar{V}^z$ represents the utility level obtained from a bundle of goods that would permit people to be above the energy poverty line (energy poverty threshold), and V^0 is the observed utility obtained by the bundle of goods that the consumer actually has. Under these definitions, when $V^0 < \bar{V}^z$ the consumer will be in an energy poverty situation. Thus, when *EP* takes values greater than one, this index represents energy poverty. In this case, the higher the value of the *EP* index in Equation (1), the higher the degree of energy poverty.

In logarithmic terms, Equation (1) is expressed as:

$$\ln EP = ln\,\bar{V}^z - \ln V^0 \tag{2}$$

We also assume that, among other objectives, the state seeks to reduce the energy poverty level as much as possible. Given this assumption, the state seeks:

$$min \ln EP = min\,(\ln \bar{V}^z - \ln V^0) \tag{3}$$

$$such\ as{:}\ V = V(GDP, P) \tag{4}$$

where V is the indirect utility function that represents the consumer's maximal attainable utility or well-being with a bundle of goods when faced with a vector of prices (*P*) and an amount of income. In this study, we are interested in estimating the extent to which a country can potentially reduce its level of energy poverty with a given level of income and prices. Therefore, we consider income as GDP per capita at the aggregate level. V fulfils the following properties:

$$\frac{\partial V(GDP,P)}{\partial GDP} > 0; \ \frac{\partial V(GDP,P)}{\partial P} < 0; \tag{5}$$

From Equations (3) an (4), we obtain:

$$min \ln EP = min\left(ln \bar{V}^{z} - \ln V^{0} \left(GDP, P\right)\right) \tag{6}$$

We can define: $\ln f(GDP, P) \ = ln \bar{V}^{z} - \ln V^{0} \left(GDP, P\right)$ (7)

where f is the function to minimise. Under these assumptions, f will have a positive relationship with P, and a negative relationship with GDP:

$$\frac{\partial f(GDP,P)}{\partial GDP} < 0; \ \frac{\partial f(GDP,P)}{\partial P} > 0; \tag{8}$$

The difference between the current energy poverty level (Equation 2) and function f that indicates the minimum energy poverty level for a country given its income and prices, is considered as a measure of the efficiency in which each country is able to tackle energy poverty.

If we call this difference u, we obtain:

$$\ln EP = \ln f(GDP, P) + u \tag{9}$$

This implies that we can obtain an energy poverty efficiency index of the countries, if we take the ratio of the minimum to the current energy poverty level, which is the same as:

$$\exp(-u) = f(GDP, P)/EP \tag{10}$$

By definition, the ratio in Equation (10) is bounded between 0 and 1, and could be considered as a measure of efficiency in relation to what minimum level of energy poverty would be attainable for each country. Moreover, we are interested in identifying the factors that can explain the reasons why a country has an energy poverty index higher than its minimum potential. For instance, policy makers might be interested in knowing whether social protection that encompasses interventions from public or private bodies intended to relieve households and individuals of the burden of a defined set of risks or needs, have been effective. As explained in next section, we tackle this issue allowing the variance of the u term to be a function of covariates (inefficiency explanatory variables) in which we include, among other factors, social protection expenditure.

3. The Empirical Model

We propose the application of a stochastic frontier analysis approach to estimate an energy poverty frontier function. This allows us to calculate the difference between the minimum energy poverty level feasible for a country (given its income, prices, and other factors), and its current level of energy poverty. In other words, we can obtain the potential maximum reduction of energy poverty for the analysed countries. We take advantage of a panel data framework and the application of a True Fixed Effects (TFE) model (Greene, 2005a; 2005b) to control for unobserved country-specific heterogeneity, while we propose a heteroscedastic specification of the inefficiency term to understand the differences in the occurrence of energy poverty among countries.

Considering the previous comments and including a random term to capture noise (v), Equation (9) becomes:

$$Ln\ EP_{it} = \alpha_i + \ln f(GDP_{it}, P_{\ it}) + u_{it} + v_{it} \tag{11}$$

where i indicates country, t time, α_i are country dummies that capture time-invariant country characteristics. We assume v_{it} is i.i.d. $N(0,\sigma_v^2)$. Moreover, we follow Wang and Schmidt (2002) who propose a modelling strategy in which the random variable u (representing inefficiency), has the following form:

$$u_{it} \sim h_{it}(z_{it}, \delta)\ u^* \tag{12}$$

where $h(.) \geq 0$ is a non-stochastic function (scaling function) of at set of exogenous explanatory variables, z, δ is a vector of parameters to be estimated, and $u^* \geq 0$ is a random variable that follows a half-normal distribution, common to all observations, and not depending on z-variables.

The model specified in Equation (12) implies that the inefficiency term (u_{it}) follows a common distribution given by $u*$, but each observation is weighted by a different, observation-specific scale of $h_{it}(z_{it}, \delta)$. In sum, the model is specified as:

$$Ln\ EP_{it} = \alpha_{it} + \ln f(GDP_{it}, P_{\ it}) + u_{it} + v_{it} \tag{13}$$

$$u_{it} \sim h(z_{it}, \delta) \cdot u^* = h(z_{it}, \delta) \cdot N^+(\tau, \sigma_u^2) \equiv exp(z_{it}'\delta)\ N^+(\tau, exp(c_u)) \tag{14}$$

$$v_{it} \sim N^+(0, \sigma_v^2) \tag{15}$$

where τ and c_u are constant parameters. As Kumbhakar et al. (2015) point out, an attractive feature of this specification of the model is that it satisfies the scaling property, which captures the idea that the shape of the distribution of u_{it} is the same for all countries. The scaling function $h(\cdot)$ essentially stretches or shrinks the horizontal axis, so that the scale of the distribution of u_{it} changes but its underlying shape does not change. Moreover, modelling heteroscedasticity is justified from an empirical point of view, as both parameters in the model and the inefficiency estimates can be biased when heteroscedasticity is neglected (Caudill and Ford, 1993).

4. Data

The data used in this study has been collected from Eurostat, the statistical office of the European Union, using the EU-SILC survey, based on data reported by the countries. The period analysed covers 2005-2018. In order to estimate the model (Equations 13-15), we first need to proxy our dependent variable, i.e., an energy poverty index. Energy poverty is inherently difficult to measure. In the literature different models can be found to approximate it. Following Healy and Clinch (2002) or Thomson et al. (2017), we can distinguish different types of measures of energy poverty. First, a direct and objective measurement (temperature approach), where the level of energy services achieved in the home is compared to a set standard (e.g., Oreszczyn et al., 2006). Second, a subjective measure (consensual approach) based on self-reported assessments of indoor housing conditions (e.g., Bouzarovsky and Tirado-Herrero, 2017). Third, an also objective expenditure approach, by means of indicators such as income, housing costs or energy costs (e.g., Legendre and Ricci, 2015; or Burlinson et al., 2018).

Due to their greater availability, the last two types of measurements are the most used. Moreover, there are studies that combine both measures, that is to say, consensual approach which is subjective, and expenditure approach which is objective (see, e.g., Kahouli, 2020, Llorca et al. 2020; or Waddams Price et al., 2012). Although objective measures may appear to be more reliable than subjective measures, some studies argue that subjective measures have several advantages, for example, capturing the 'feeling' of material deprivation perceived by individuals (Fahmy et al., 2011). As Garcia Alvarez and Tol (2020) point out, subjective measures allow the researcher to identify not only the incidence but also intensity of energy poverty.

In order to achieve the objectives of this work, we need comparable data for different European countries. However, as Thomson et al. (2017) highlight, there is no standardised household micro-data on energy expenditure, energy consumption, or energy efficiency across EU countries. As a result, researchers are mainly reliant on consensual data concerning the consequences of energy poverty, such as ability to keep the house adequately warm, arrears on utility bills, and the presence of damp in the home. In this study we use these three indices. Thomson et al. (2017) also point out that as energy poverty is multi-dimensional, the most desirable approach would be the widest possible combination of indicators to build a detailed picture of energy poverty. We propose using a composite index. Different composite indices have been proposed in the literature (see Healy and Clinch, 2002; or Thomson and Snell, 2013). In order to avoid arbitrary weighting, we follow the Thomson and Snell (2013) weighting that is the most used in the literature (e.g., Bouzarovski and Tirado Herrero, 2017; or Cadoret and Thelen, 2020). Therefore, we define the following composite index:

$$\textit{Energy poverty} = 0.5\cdot \textit{Inhability} + 0.25\cdot \textit{Arrears} + 0.25\cdot \textit{Housing Faults} \qquad (16)$$

where:

Inability indicates the percentage of people from the total population who are in a state of enforced inability to keep their home adequately warm.

Arrears is the percentage of people from the total population who are in a state of arrears on utility bills (heating, electricity, gas, water) on time, due to financial difficulties.

Housing Faults captures the percentage of population living in a dwelling with a leaking roof, damp walls, floors or foundation, or rot in window frames or floor.

In this way*, Energy poverty* can be considered a proxy of the energy poverty defined in Equation (1). A value of *Energy poverty* greater than zero indicates the percentage of the population of a country that has an observed utility V^0 lower than the corresponding to the poverty threshold V^z. For this percentage of the population, *EP* measure in Equation (1) is greater than 1. The higher *Energy poverty* index, the higher the rate of energy poverty in a country.[4]

Following the theoretical model in Equation (9), we include income and prices as explanatory variables:

GDP per capita (in Euro) which is widely used for comparison of living standards within the European Union. This variable has been deflated using the Harmonised Index of Consumer Prices (2015=100).

Energy prices is a weighted average of electricity and gas prices. On the one hand, electricity prices for households are defined as the average national price (in Euro per kWh) including taxes and levies for medium size household consumers (annual consumption until 3,500 kWh). On the other hand, gas prices for household consumers are defined as the average national price (in Euro per kWh) including taxes and levies for medium size household consumers (small and medium consumption). We utilise the share of electricity and gas in final energy consumption in household as weights of this average energy price.

Moreover, in order to capture specific characteristics of the different countries that can affect the energy poverty indices, we include country-specific dummy variables.[5] These dummies capture time-invariant factors, for example its geographical situation, weather, or geographic conditions. However, the energy poverty frontier can also be affected by time-variant country-specific factors, such as income inequality, energy efficiency or urbanisation degree. With the aim of considering these specific factors, we have also included the following variables in the energy poverty frontier:

Population density is the total population (on 1 January each year) per square kilometre. This variable indicates how the degree of urbanisation of the different countries has evolved during the period considered.

Gini index is a measure of the distribution of income across a population. It is used as a gauge of economic inequality, measuring income distribution. According to Eurostat this index is defined as the relationship of cumulative shares of the population arranged according to the level of equivalised disposable income, to the cumulative share of the

[4] We have tried to compare this energy poverty index with another that equally weights the three energy poverty factors. However, in the latter case, when trying to estimate the proposed model, this does not converge.

[5] This can be seen as a 'brute force maximum likelihood' approach (Filippini et al., 2008) for estimating the TFE model originally proposed by Greene (2005a; 2005b).

equivalised total disposable income received by them. The coefficient ranges from 0 to 100%, with 0 representing perfect equality and 100% representing perfect inequality.

Energy intensity is one of the indicators to measure the energy needs and the structure of the economy. It is often used as an approximation of energy efficiency. Following Eurostat, this variable reflects the structure of economy and its cycle, general standards of living, and weather conditions in the reference area. Energy intensity is calculated as units of energy consumed per unit of GDP (the indicator is expressed in chain linked volumes).

Regarding the *z*-variables that are introduced as inefficiency determinants, we include: *Population Density, Time* (trend variable), *Crisis* (dummy variable that takes value 1 for the period between 2008 and 2013), and *Social protection.*[6] This variable indicates social protection benefits (as % of the GDP) provided to household and individuals (national residents) affected by a specific set of social and economic risks and needs. The eight main risks and needs that are recognised are: disability, sickness/health care, old age, survivors, family/children, unemployment, housing, and social exclusion.[7] Table 1 shows the descriptive statistics of the data used in this study.

[Insert Table 1 here]

Figure 1 shows the evolution of the average of the *Energy poverty* index for the whole sample. In general terms, the index increases as of 2008, decreasing as of 2013 with a worsening at the end of the period. The effect of the economic cycle marked by the financial crisis seems clear in this evolution. This phenomenon is also reflected in Figure 2, where the evolution of Social Protection in Europe is presented. In order to face the adverse effects of the crisis on the most vulnerable groups, social aids soared from 2008 on, with a steady decrease from 2013. However, Figures 1 and 2 suggest that *Energy Poverty* and *Social Protection* increase in parallel, something that could be interpreted as that social protection aids have been ineffective in alleviating energy poverty.

[Insert Figures 1 and 2 here]

However, if we analyse the evolution of these variables by country, we observe a positive relationship between *Social Protection* investment and *Energy Poverty* reduction. Thus, in general terms, Figures 3 and 4 suggest that countries that invest a high percentage of their GDP in social protection (i.e., Austria, Belgium, Denmark, Finland, France, or the Netherlands) have lower energy poverty rates. However, countries such as Slovakia or Estonia jointly present low energy poverty and social protection levels.

[Insert Figures 3 and 4 here]

[6] Note that *Social Protection* does not 'shift' the frontier for efficient observations, but it is a determinant of inefficiency. Therefore, it should not be included in the energy poverty frontier.

[7] Social benefits (gross) are recorded without deduction of taxes or other compulsory levies payable by recipients. 'Tax benefits' (tax reductions granted to households as part of social protection) are generally excluded.

On the other hand, Figure 5 shows the relationship between *Energy poverty* and *GDP per capita*, with an expected negative relationship. The energy poverty frontier would be defined by the observations that have a lower level of energy poverty by income per capita, but taking into account other variables that also affect the Energy poverty variable such as prices, the degree of urbanisation of the country, the degree of equality in the distribution of wealth, the energy efficiency and other factors that are part of the idiosyncrasy of each country and can affect the prevalence of energy poverty.

[Insert Figure 5 here]

In sum, it is necessary to conduct a more exhaustive analysis of the relationship between energy poverty and socioeconomic factors and policies, which motivates the objective of the present paper.

5. Empirical Results and Discussion

The results obtained from the estimation of the model (Equations 13-15)[8] are shown in Table 2. As expected, and similarly to Cadoret and Thelen (2020), energy poverty has a negative relationship with income and positive with energy prices. Concretely, results indicate that, at the mean, an increase of 1% in *GDP per capita* reduces, on the average of the sample mean, the energy poverty index in 1.37%, and does not rule out that this relationship is linear. Also, *Energy Prices* increase energy poverty. An increase of 1% in *Energy Prices* increases, on the average of the sample mean, the potential level of energy poverty by 0.28%. Energy intensity has a significant and positive coefficient indicating, as expected, that countries with higher energy efficiency have more facility to alleviate energy poverty. Concretely, the *Energy Poverty* index will increase, on average, with 0.001% with a one-unit increase in the *Energy Intensity* index.

[Insert Table 2 here]

An increment in the degree of urbanisation of the country, measured in terms of the density of the population, implies a higher rate of energy poverty. Concretely, a one-unit increase in the density of the population increases the *Energy Poverty* index by 0.0065%. As expected, the degree of inequality in the countries, measured by the *Gini* index, implies higher levels of energy poverty in less egalitarian countries. The *Energy Poverty* index will increase 0.024% for an increase of 1% in the *Gini* index.

Once the model is estimated, it is also possible to calculate the marginal effect for the determinants that prevent European countries from reaching their minimum level of energy poverty. These marginal effects represent changes in expected value of the inefficiency term (u) when there is a change in an explanatory variable, i.e., $\frac{\partial E(u_{it})}{\partial z_{it}}$ (see Appendix A for details). The average marginal effect of *Social Protection* is -0.0124. This

[8] In the estimation, all variables have been lagged one period (predetermined variables) in order to address the potential endogeneity in the model.

means that the *Energy Poverty* index is reduced by 1.24% for 1% increase in the social protection benefits. In other words, this result confirms a positive relationship between *Social Protection* and energy poverty reduction. Efficiency increases as more is spent on social protection aids.

The marginal effects for other determinants also report interesting results. Specifically, an increase in one-unit in *Population Density* means that the country is moving away from its maximum energy poverty reduction by 0.025%. This result implies that the most populated (more urbanised) countries are farthest from their energy poverty minimum level. This result is in line with the study of Roberts et al. (2015), which compares the level fuel poverty in rural and urban areas of the UK. They find that, on average, the experience of fuel poverty in urban areas is longer with a higher probability of fuel poverty persistence. Also, this result can complement those found in Bouzarovski and Thomson (2020), where no differences are found between densely and thinly populated areas when two self-reported indicators of energy poverty (arrears on utility bills and inability to keep warm) are considered.

The financial crisis has had a negative and significant impact on energy poverty. During the financial crisis period, the distance to the energy poverty frontier increased by 9% with respect to the non-crisis period. In the past, changes in the price of energy have been viewed as a major cause of energy poverty. However, the financial crisis of 2008 and COVID-19 pandemic in 2020 have shown that sudden negative incomes shocks can quickly become a source of energy poverty. The effect of energy price change on energy poverty is direct and can, for instance, be addressed through price subsidies. However, the effect of economic crisis on income and energy poverty is less direct. The income support mechanisms have the advantage that they enable the recipients to allocate the extra funds among competing needs than allocating them only to energy needs. In the UK, research has shown that Winter Fuel Allowance paid to the elderly was primarily used towards energy bills although this was not a condition for receiving the support (Beatty et al., 2014). Some of this effect has been attributed to the importance of labelling of policy instruments to nudge the recipients in a certain consumption path. Moreover, we have found that time has a positive effect on reducing energy poverty (with a mean energy poverty reduction by 3.4%). This trend is also clearly observed in Figure 6.

[Insert Figure 6 here]

Figures 7 and 8 report the Energy Poverty Efficiency by country. Figure 7 shows the means of the indices of energy poverty efficiency according to Equation (10). Malta, Turkey, and Estonia have the lowest efficiency rates, while Sweden, Finland, Denmark have the highest. The evolution of the efficiency shown in Figure 8 seems to corroborate what has already been indicated in Table 2 of results. In general terms, all countries show improvements in the evolution of energy poverty efficiency, with the possible exception of Ireland. Interestingly, it is this country that seems to have a decrease in investment in social protection benefits during the period. Finally, the main descriptive statistics by country are reported in Appendix B.

[Insert Figures 7 and 8 here]

In summary, this study concludes that, for the sample of European countries and the period studied, which includes the 2008 financial crisis, income support measures for vulnerable groups are significantly effective in fighting against energy poverty. It is therefore to be expected that specific measures expressly aimed at alleviating energy poverty will also be (and even more) effective. Along these lines are the recommendations of the European Union. As Bouzarovski and Thomson (2020) point out, alleviating energy poverty is a key precondition for achieving just transitions towards sustainability. They also point out that at the end of 2016, there were a relatively limited number of policies and actions at the level of the EU and member states related to energy poverty. However, in recent years, energy poverty has been mainstreamed into various EU directives and member state policies. Thus, several projects have been developed throughout Europe in order to alleviate energy poverty. For example, as part of the 2018 call of Horizon 2020 Energy Efficiency, three projects have been addressed with this aim (STEP –Solutions to Tackle Energy Poverty–, EmpowerMed and SocialWatt). Other examples are the Clean Energy for all Europeans Package (CEP) and the Green Deal strategy, presented at the end of 2019, that continues and extends the CEP's objectives with the aim of making the EU economy sustainable, and "this transition must be just and inclusive" (p.2).[9]

Moreover, the recent health crisis has also brought an unprecedented economic crisis that is affecting the entire population, with special incidence on the most vulnerable groups (Bouzarovski and Thomson, 2020). Therefore, due to the consequences of the COVID-19 pandemic, both energy and income poverty are expected to become more acute in the near future (Nagaj and Korpysa, 2020). Against this background, repairing the short-term damage of the crisis, in a way that also involves investing in the long-term future, has become a priority for the EU. This is the centrepiece of the NextGenerationEU and the Recovery and Resilience Facility European programmes.[10] Member states will be able to use this instrument to carry out sustainable infrastructures and the renovation of the existing housing stock. All of this "will help save money on energy bills, provide healthier living conditions and reduce energy poverty" (p.7).[11]

In summary, it is possible to apply different types of measures in European countries to fight against energy poverty. Fist, financial assistance to vulnerable and marginalised social groups, that this study has found effective. Second, act on energy prices, that we have also found to be positively and significantly related to energy poverty. Third, more specific measures aimed at reducing energy poverty via increases in energy efficiency in line with those proposed by the EU. Our results also support these last measures, finding that increasing energy efficiency has a significant and positive impact on the fight against energy poverty. However, the design and implementation of these specific measures has proven in some cases difficult, as well as their evaluation (Garcia Alvarez and Tol, 2020).

[9] https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en.

[10] On 18 December 2020, the European Parliament and the Council reached an agreement on the Recovery and Resilience Facility, the key instrument at the heart of NextGenerationEU (https://ec.europa.eu/info/strategy/recovery-plan-europe_en#next-steps).

[11] Com/2020/456_final. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52020DC0456&rid=1.

Therefore, these specific measures addressed to improve energy efficiency (e.g., energy retrofits or energy-saving appliances) can be complemented with short-term solutions aimed at improving the financial situation of especially vulnerable groups (see, e.g., Castaño-Rosa et al., 2020; for the case of Spain).

6. Conclusions

New tools that not only explain the incidence of energy poverty but also explain and quantify the effect of the determinants that influence this type of poverty, could be useful for evaluating the different measures and instruments that are used to mitigate this problem. This paper addresses, within an appropriate theoretical framework, the analysis of the determinants that influence energy poverty. The methodology used, based on the estimation of relative frontiers, is used to estimate and explain the maximum potential reduction in energy poverty in a country given its characteristics. It also allows better understanding and quantifying the determinants that facilitate or hinder achieving this potential, for example, to evaluate the effect on energy poverty of policies aimed at protecting vulnerable groups.

We applied this methodology to a sample of 30 European countries in the period 2005-2018. As expected, countries with higher economic development (measured by per capita income) and more egalitarian countries have a lower incidence of energy poverty, while higher rates in energy prices exacerbate the problem. Moreover, social protection has been a significant factor in reducing energy poverty. We show that this reduction has been a steady and general trend in almost all the countries analysed. This means that despite the negative and significant effect of the economic cycle (which includes the financial crisis of 2008), it has been possible to contrast the countercyclical effect of these aids, and its contribution to the general improvement in reducing energy poverty. Energy efficiency measured by the energy intensity is also significant to fight energy poverty. Therefore, the results conclude that policies aimed at improving the financial situation of vulnerable groups, reducing energy prices and/or energy efficiency measures can significantly help against energy poverty. On the other hand, the results indicate that energy poverty worsens in urban areas, which may be indicating the presence of energy poverty that hides in large cities.

Finally, note that this study has been carried out at the aggregate level, which offers the advantage of being able to make a comparison of the different European countries. However, at this aggregate level, the exact causes of energy services deprivation of vulnerable group cannot be identified. Nevertheless, it is also noteworthy that, although the study is carried out at the macro-scale, the model is also applicable at a microeconomic level to evaluate factors and policies carried out at the state, provincial or even local level. In this sense, it is possible to compare a region or locality with others within a country. The availability of more detailed data on the individual and household characteristics in terms of income, degree of urbanisation, quality, and type of dwelling among others, will make it possible to obtain more targeted conclusions.

Table 1. Descriptive statistics

Variables	Mean	Std. Dev.	Minimum	Maximum
Energy poverty	12.88	8.83	2.53	49.10
Inability	11.75	12.01	0.30	67.40
Arrears	11.31	9.30	1.10	44.00
Housing	16.73	7.83	4.20	42.20
GDP per capita	0.03	0.02	0.01	0.10
Energy Prices	0.11	0.04	0.04	0.29
Population Density	155.89	228.54	14.33	1425.36
Gini	30.04	4.40	22.50	44.20
Energy Intensity	185.41	89.23	53.19	552.59
Social Protection	22.17	5.54	10.30	33.10

Note: 357 observations

Table 2. Parameter Estimates

Variable	Coef.		z	P>|z|
Frontier				
ln (GDP per capita)$_{-1}$	-1.371	**	-2.15	0.031
ln (GDP per capita)$^2_{-1}$	-0.038		-0.46	0.649
ln (Energy Prices)$_{-1}$	0.278	***	4.70	0.000
Population Density$_{-1}$	0.007	***	3.41	0.001
Gini$_{-1}$	0.024	***	3.94	0.000
Energy Intensity$_{-1}$	0.001	*	1.66	0.098
Intercept	-3.556	***	-2.89	0.004
(Energy Poverty) Inefficiency Determinants				
Social Protection$_{-1}$	-0.031	***	-3.04	0.002
Time	-0.085	***	-3.59	0.000
Population Density$_{-1}$	0.001	***	2.68	0.007
Crisis	0.098	*	1.88	0.060
tau				
Intercept	1.244	***	5.28	0.000
cu				
Intercept	-2.044	***	-4.34	0.000

Note: 357 observations. Significance code: * p<0.1, ** p<0.05, *** p<0.01.
The variables in the model have been estimated jointly with country dummies. The coefficients of these dummies are not reported in the table.

Figure 1. Evolution of Energy Poverty Index

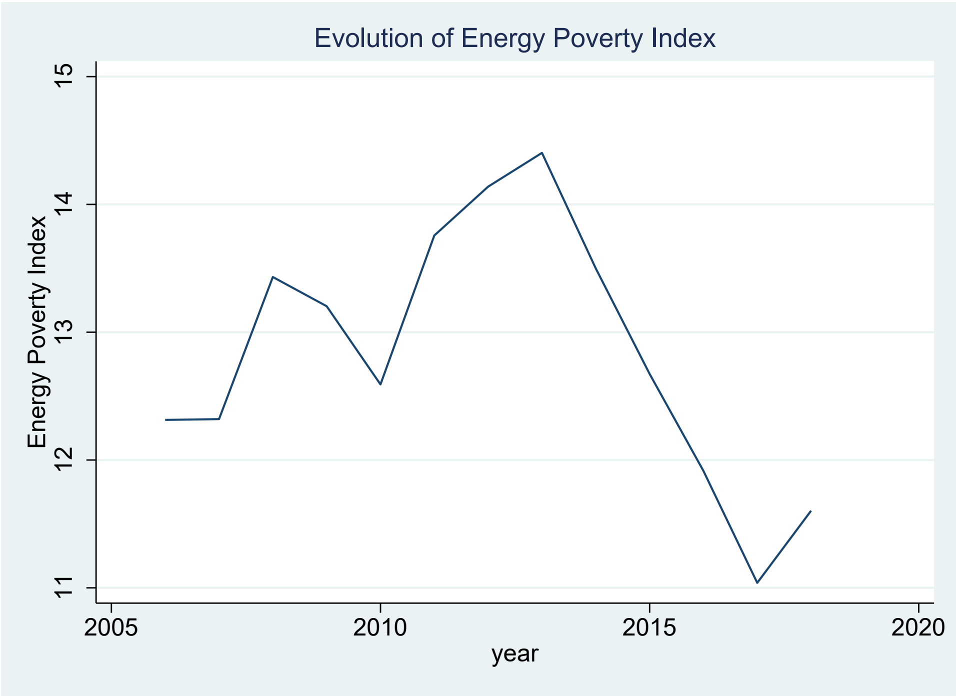

Figure 2. Evolution of Social Protection Benefits

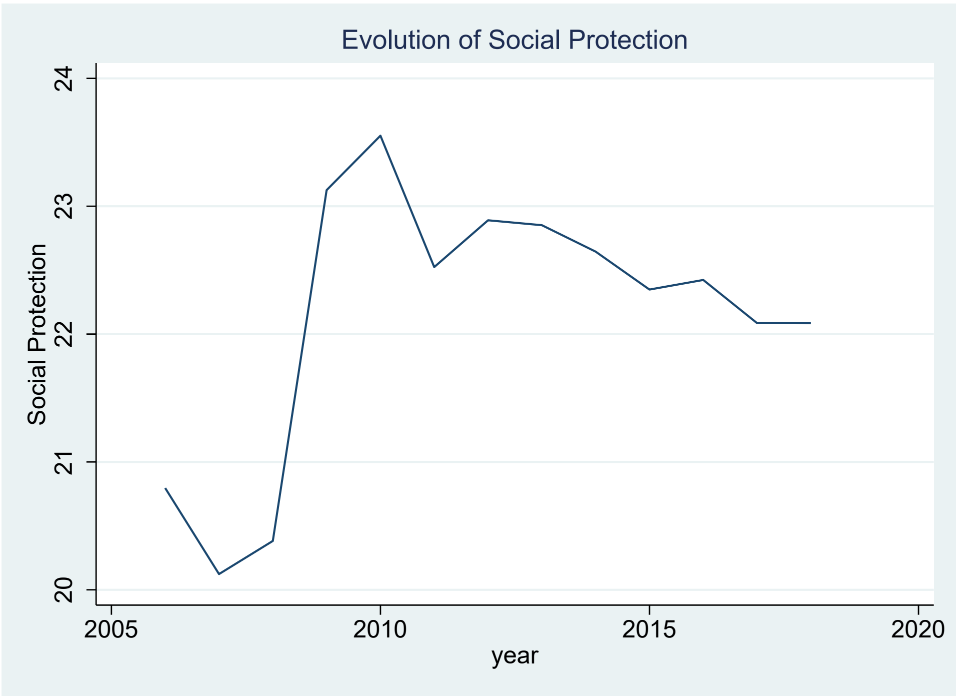

Figure 3. Energy Poverty Index by Country

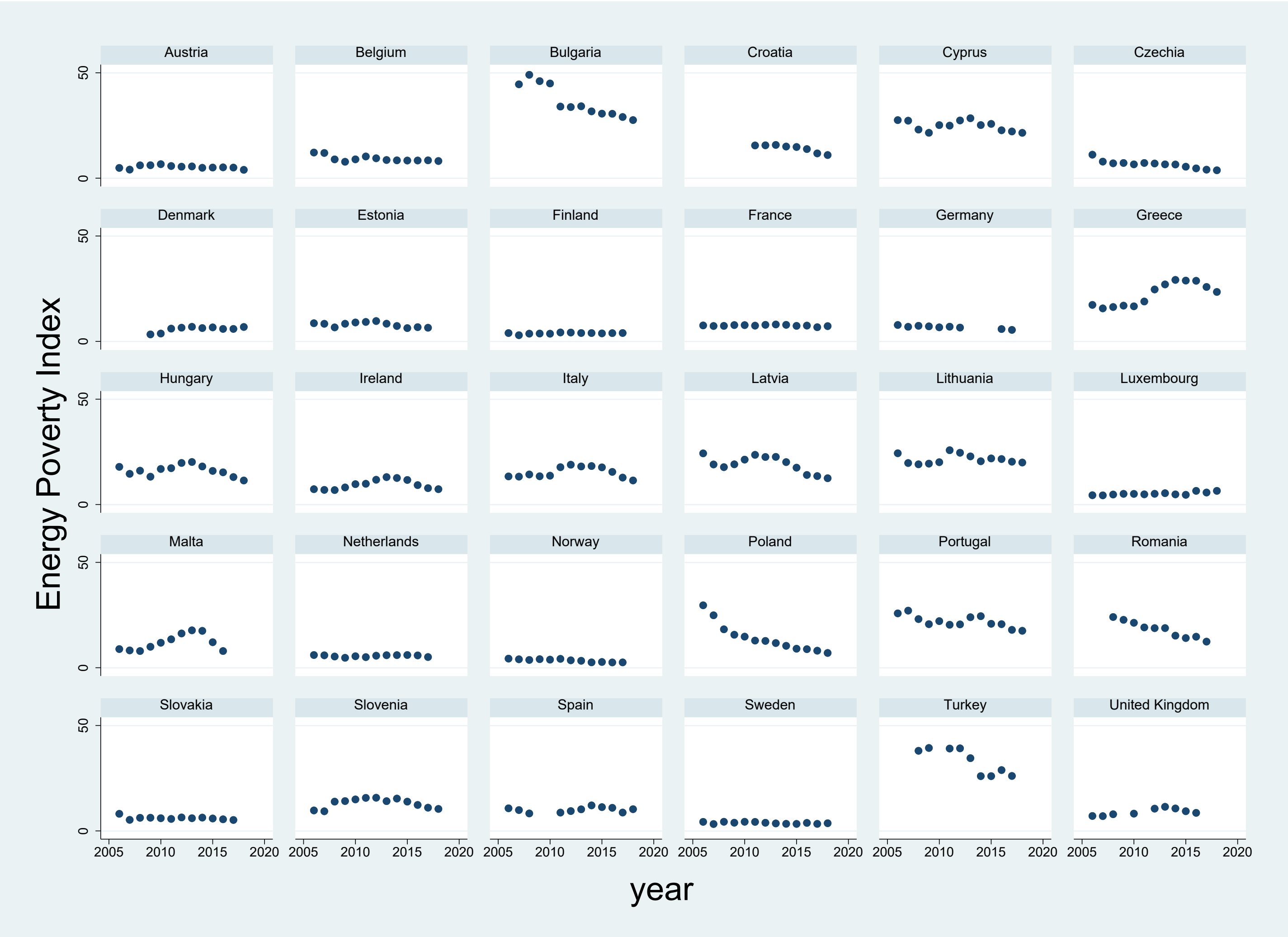

Figure 4. Social Protection by Country

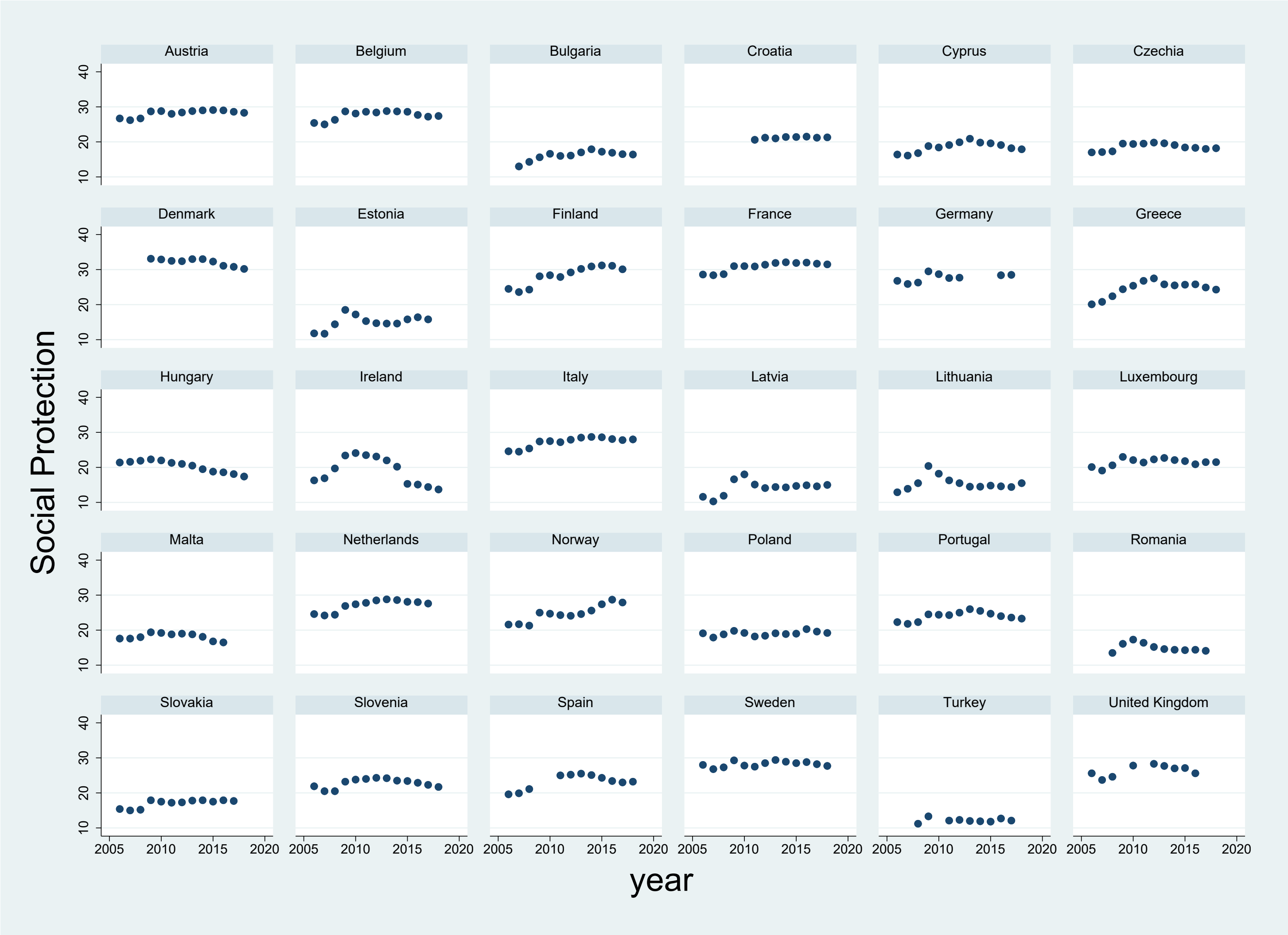

Figure 5. Energy Poverty Index and GDP per capita Relationship

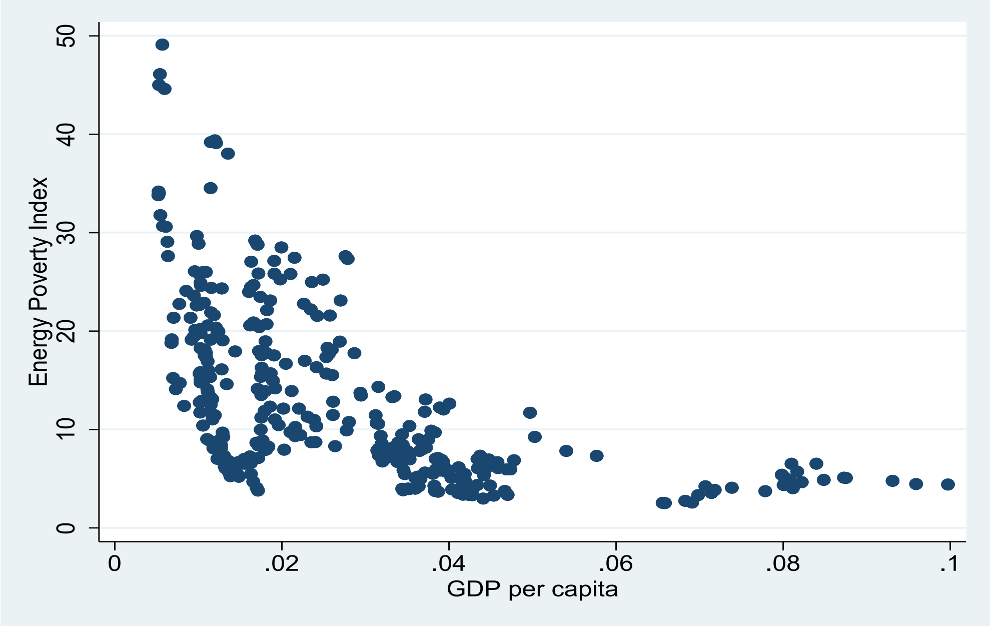

Figure 6. Evolution of Energy Poverty Efficiency

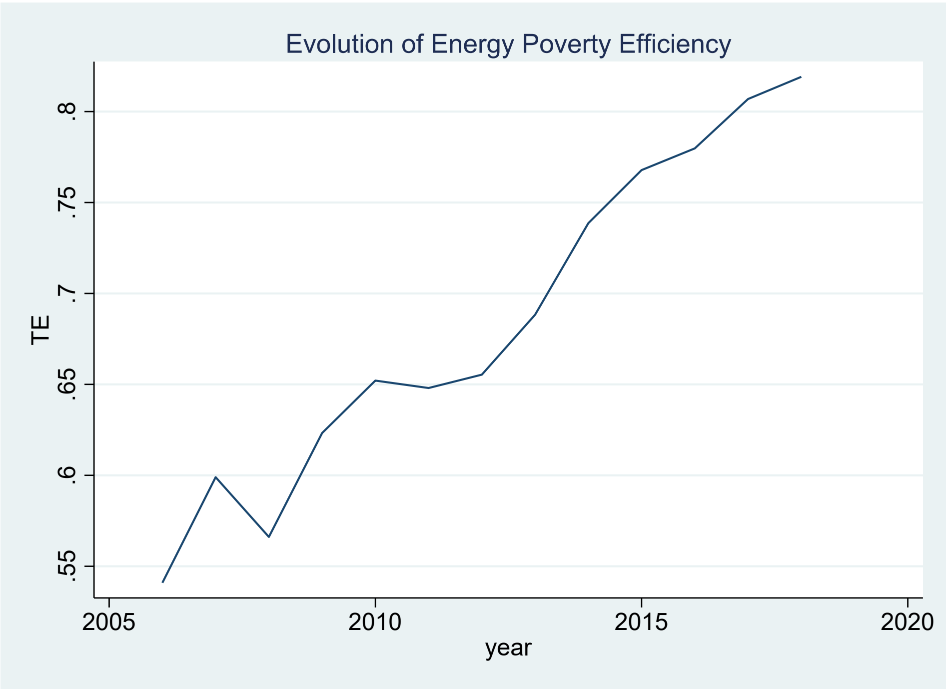

Figure 7. Energy Poverty Efficiency by Country (mean values)

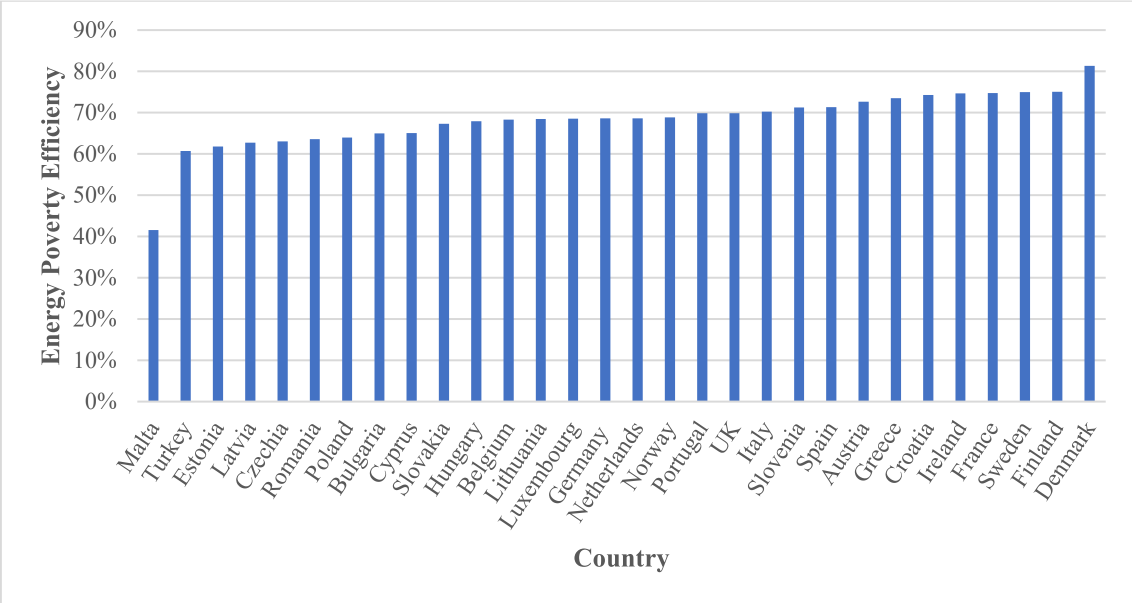

Figure 8. Evolution of Energy Poverty Efficiency by Country

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APPENDIX A

From the model presented in Equations (13-15), we can obtain the marginal effects (see Kumbhakar et al., 2015). From Equation (14), we have:

$$\mathrm{E}(u_{it}) = exp(z_{it}'\delta)\ E(u^{*})\ where\ u^{*} \sim N^{+}(\tau, \sigma_u^2)$$

Then,

$$\frac{\partial E(u_{it})}{\partial z_{it}} = \delta \exp(z_{it}'\delta)\, E(u^{*})$$

Being $E(u^{*})$ a scalar, which can be calculated from:

$$E(u^{*}) = \sigma_u \left[\frac{\tau}{\sigma_u} + \frac{\phi\left(\frac{\tau}{\sigma_u}\right)}{\Phi\left(\frac{\tau}{\sigma_u}\right)} \right]$$

where $\phi(.)$ *and* Φ (.) represent the probability density and probability distribution functions, respectively. To get the estimated value, it is possible to replace τ and σ_u by $\hat{\tau}$ and (1/2$\hat{c}_u$).

APPENDIX B

Table B1. Main Descriptive Statistics by Country

Country	Obs.	Energy Poverty Index	Per Capita GDP	Energy Prices	Gini	Pop. Density	Social Protection	Energy Intensity	Energy Poverty Efficiency
Austria	13	5.338	0.038	0.116	27.208	101.031	28.177	110.959	0.618
Belgium	13	9.285	0.036	0.107	26.423	360.427	27.608	172.370	0.588
Bulgaria	12	36.379	0.006	0.097	35.975	65.923	16.125	465.317	0.612
Croatia	8	14.203	0.011	0.091	30.375	74.537	21.200	190.789	0.641
Cyprus	13	24.871	0.024	0.209	30.785	89.267	18.538	149.984	0.561
Czechia	13	6.575	0.017	0.101	24.900	132.653	18.554	270.183	0.555
Denmark	10	5.845	0.046	0.189	27.190	130.659	32.130	74.836	0.814
Estonia	12	7.950	0.014	0.086	32.675	29.365	15.067	351.652	0.566
Finland	12	3.860	0.038	0.100	25.692	15.927	28.292	184.765	0.650
France	13	7.542	0.033	0.111	29.215	101.410	30.854	129.260	0.642
Germany	9	6.772	0.034	0.124	29.078	229.077	27.711	126.696	0.586
Greece	13	22.296	0.020	0.145	33.762	83.130	24.569	140.862	0.639
Hungary	13	16.158	0.012	0.064	27.469	106.830	20.338	246.133	0.592
Ireland	13	9.425	0.044	0.130	30.262	65.137	19.054	77.653	0.634
Italy	13	15.287	0.028	0.127	32.346	197.833	27.246	105.873	0.604
Latvia	13	19.100	0.011	0.104	35.900	32.032	14.269	232.775	0.560
Lithuania	13	21.575	0.011	0.099	35.400	46.550	15.462	254.495	0.613
Luxembourg	13	5.190	0.086	0.076	29.069	204.334	21.469	104.312	0.583
Malta	11	12.007	0.018	0.182	27.655	1328.531	18.164	297.473	0.412
Netherlands	12	5.606	0.041	0.106	26.458	398.286	27.075	145.236	0.583
Norway	12	3.460	0.072	0.110	24.358	15.292	24.742	92.103	0.575
Poland	13	14.154	0.011	0.090	30.838	121.691	19.038	260.582	0.572
Portugal	13	21.954	0.017	0.147	34.638	113.657	23.977	140.378	0.606
Romania	10	18.140	0.007	0.057	34.620	84.062	15.030	247.839	0.575
Slovakia	12	6.085	0.014	0.099	24.958	110.094	17.025	244.481	0.583
Slovenia	13	13.131	0.019	0.118	23.823	100.877	22.785	189.865	0.610
Spain	11	10.070	0.024	0.150	33.564	91.245	23.209	128.190	0.615
Sweden	13	3.798	0.042	0.126	26.038	21.140	28.208	131.562	0.642
Turkey	9	33.019	0.011	0.056	42.678	96.305	12.156	169.602	0.555
UK	9	8.983	0.034	0.087	32.100	258.967	26.378	106.952	0.601

Notes: The panel is unbalanced due to missing values in some variables necessary for the analysis. The European countries that have not been included in this study (such as Switzerland or Iceland) do not show values for the relevant variables. Following Nierop (2014) Denmark data for the period 2005-2007 has been eliminated due to having inconsistent data for the variable *Inability*.