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Industrial Energy Efficiency Versus Energy Poverty in the European Union: Macroeconomic and Social Relationships

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Abstract

This paper examines the impact of industrial energy efficiency on household energy poverty in the twenty-seven Member States of the European Union for the period 2003–2023. Although the literature has widely discussed energy efficiency as an enabler of decarbonisation and economic performance, its direct link to energy poverty at the macro level has rarely been analysed, let alone with respect to structural changes in industry. Filling this gap, this paper evaluates whether reductions in industrial energy intensity result in reduced energy poverty, understood as the share of households unable to maintain adequate indoor thermal comfort. Empirical analysis relies on a balanced panel dataset and uses fixed-effects regression models to take into account unobserved country-specific and time-specific heterogeneity. In addition, potential endogeneity between industrial energy intensity and labour productivity is addressed by the instrumental variable approach using two-stage least squares. The main models also include key macroeconomic and social control variables: real GDP per capita, social benefit expenditure, electricity prices for households, and unit labour costs. The results yield a robust and statistically significant positive link between industrial energy intensity and energy poverty, suggesting that efficiency improvements in industry make a quantifiable difference in household energy deprivation. This effect even increases in strength after the correction for endogeneity, thereby corroborating the causal relevance of productivity-driven efficiency gains. The findings also show substantial heterogeneity between EU Member States, indicating that national structural features will determine baseline levels of energy poverty. However, no strong evidence is found for an indirect price-mediated transmission mechanism or for moderation effects bound to income levels or social expenditure. This study provides sound empirical evidence that industrial energy efficiency is an important but structurally conditioned lever to alleviate energy poverty in the European Union. The results emphasise the integration of industrial efficiency policies with social and institutional frameworks while designing strategies for a just and inclusive energy transition.

Keywords: energy efficiency (EE); energy intensity; energy poverty (EP); macroeconomic factors; industry sector; European Union countries

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1. Introduction

The relationship between energy efficiency and energy poverty is complex and multidimensional, involving economic, social and environmental factors. Improving energy efficiency is widely recognised as an effective solution to reducing expenditure on energy needed to meet basic needs and alleviating energy poverty [1–3]. It is pointed out that through better insulation of homes, efficient appliances and optimised heating systems, energy consumption can be reduced and energy bills made more affordable for households, especially those on low incomes [4–6]. These elements are also highlighted in the EU's Energy Efficiency Directive, which explicitly links energy poverty to poor energy efficiency and urges Member States to consider energy poverty when designing policy instruments to meet national energy saving obligations [1,7].

Renovating buildings to improve energy efficiency, especially in social and affordable housing, is a key strategy promoted by the European Commission, although, as practice shows, funding for such initiatives is often limited and short-term [2,7]. However, the literature points to many barriers to improving energy efficiency in order to reduce energy poverty. These include, among others, initial investment costs [3], limited access to capital and efficient technologies [8], and financial inclusion [9].

Countries with a long tradition of addressing energy poverty, such as France and the UK, have more integrated policies that connect social and energy policy through energy efficiency measures [4]. However, not everywhere has a tradition of implementing policies directly aimed at reducing energy poverty [10,11], and energy consumption preferences among end-users can vary greatly [12], which hinders the effectiveness of any measures to reduce energy poverty.

The literature recognises technological changes, rather than structural changes, as the main factor influencing the reduction in energy intensity in the economy (and thus the increase in energy efficiency) [13], which may indicate the key role of industrial sectors here. The question is whether the increase in energy efficiency in industry and the decrease in energy intensity in the industrial economy lead to a reduction in energy poverty in EU Member States.

The literature to date is poor in examining this relationship, which constitutes a research gap. Most often, energy efficiency in industry is seen as a promising way to solve problems related to climate change [14,15]. In addition, it is pointed out that energy intensity in industry can increase productivity and support economic growth in the long term [13], which can already be linked to the impact on energy poverty, or that low-carbon energy transition mitigates energy poverty [16]. Thus, in the literature, there are links between energy efficiency (or energy intensity) and energy poverty, but there is a lack of direct analysis of the relationship between the two phenomena, especially with regard to changes in industry, which the authors attempt to explore.

Industrial energy intensity is theoretically justified as a key determinant of energy poverty because it represents a systemic measure of how efficiently energy is transformed into economic value within the production structure of an economy, with implications that extend beyond the industrial sector itself. From the perspective of the energy–economy nexus, reductions in industrial energy intensity reflect technological upgrading, process optimisation, and improved resource allocation, all of which lower aggregate energy demand per unit of output and reduce cost pressures across the entire energy system. In economies where industry constitutes a substantial share of final energy consumption, efficiency gains at this level contribute to greater stability of energy supply, reduced exposure to price volatility, and lower marginal costs of energy generation and distribution, thereby indirectly improving affordability for households. Moreover, industrial energy

intensity is closely linked to labour productivity and capital modernisation, which influence income generation, employment stability, and fiscal capacity for social and energy policies.

Unlike household-level efficiency indicators, industrial energy intensity captures these macro-structural dynamics and long-run adjustment processes, making it a theoretically appropriate variable for analysing energy poverty as a socio-economic outcome embedded in broader production, pricing, and institutional systems rather than solely in household consumption behaviour.

The aim of this study is to assess, using panel data models, the impact of improved energy efficiency (decreased energy intensity) in industry on the level of energy poverty in European Union countries, taking into account the macroeconomic environment (income, social, energy and labour market) in EU economies. Since EU economies are diverse and develop at different rates, as does production efficiency, and since the literature indicates that higher labour productivity is associated with improved energy efficiency and lower CO_2 emissions, especially in industry [17–19], and there are dynamic interactions between investment expenditure and deployed renewable capacity [20], this paper additionally assumes the potential endogeneity of energy intensity in industry relative to labour productivity.

The following research questions were formulated:

- RQ1: Does a reduction in industrial energy intensity lead to a statistically significant decrease in household energy poverty across European Union Member States?
- RQ2: To what extent does the strength of the relationship between industrial energy efficiency and energy poverty differ across EU countries?
- RQ3: Are countries characterised by lower industrial energy intensity systematically associated with lower average levels of energy poverty?
- RQ4: Does industrial energy efficiency (EE) reduce energy poverty (EP) indirectly through the stabilisation of electricity prices for household consumers?
- RQ5: Do macroeconomic and social conditions—specifically income levels, social expenditure, and labour costs—moderate the impact of industrial energy efficiency on energy poverty?
- RQ6: Does higher labour productivity in industry indirectly reduce energy poverty by improving industrial energy efficiency?

The following research hypotheses (Hs) were adopted in the paper:

H1: *Reducing the energy intensity of industry in European Union countries leads to a statistically significant reduction in energy poverty.*

H2: *The impact of improved energy efficiency in industry on household energy poverty varies between EU countries and depends on their macroeconomic and social conditions (GDP per capita, labour productivity, expenditure on social benefits, and labour cost in industry).*

H3: *Countries with lower energy intensity in the industrial sector show a lower average level of energy poverty.*

H4: *Improvements in energy efficiency in industry, measured by a decrease in energy intensity in industry, indirectly reduce energy poverty by stabilising electricity prices.*

H5: *The scale of the impact of energy intensity in industry on energy poverty is modified by income levels, social support levels and wages in the labour market.*

H6: *Higher real labour productivity in industry indirectly reduces energy poverty by improving energy efficiency in industry (decrease in energy intensity in industry).*

The contribution of this paper is threefold. First, an analysis of the impact of energy efficiency on energy poverty in EU countries will be conducted. As indicated in the research gap, the existing literature is scarce in examining this relationship, and there is a lack of direct analyses of the link between the two phenomena. It has most often been analysed in the context of the link between energy efficiency in industry and decarbonisation processes [14,15]. However, the link with energy poverty has only been made indirectly, by pointing to the role of economic development [13]. Secondly, analyses of the direct links between energy efficiency and energy poverty have only been carried out for selected countries or Asian countries [16]. Thirdly, the panel models used here will allow us to capture the relationships for the EU as a whole and the differences between Member States. This will be achieved by analysing the impact of the decline in energy intensity in industry, and thus the improvement in energy efficiency, on the level of energy poverty in European Union countries, taking into account the macroeconomic environment (income, social, energy and labour costs) in EU economies. In addition, the potential endogeneity of energy efficiency in industry with respect to labour productivity is assumed.

The structure of the paper is as follows. After the introduction, the authors will present the theoretical background of the analysed relationships, followed by the research methodology, i.e., the conceptual model and the research methods used. The authors will then present the research results, followed by a discussion of the results and conclusions from the paper, enriched by recommendations.

2. Background of Analysis

2.1. General Political Background of EP

With the strong promotion of climate policy at the international level, new research areas have emerged—one of them being energy efficiency, and another, energy poverty (EP). The issue of energy poverty was already recognised in the 1970s [21], accompanied by early attempts to measure the phenomenon [22]. The driving factor at that time was the fuel crisis, which exposed the impact of high energy costs on low-income households. Scholars such as Brenda Boardman [23] refined this concept in the 1990s, defining it as spending more than 10% of household income on energy in order to maintain a comfortable indoor temperature. The governments of the United Kingdom and France officially adopted and legislated this definition around the turn of the millennium. Since then, the scope of interest has expanded to include access to clean and modern energy, particularly in developing countries [24,25].

In the contemporary world, energy poverty results from the overlap of numerous global, regional, and local trends, as well as from the influence of various policies—energy, fiscal, credit (banking), and financial—implemented in individual countries. In recent years, the main determinant of energy poverty has been the energy crisis that emerged after the COVID-19 pandemic [15]. The United Nations recognises energy as a key driver of economic development, and the eradication of energy poverty is inherently a political process forming a central part of the 2030 Agenda for Sustainable Development [24]. Energy poverty in the 2030 Agenda refers to the lack of access to affordable, reliable, sustainable, and modern energy services for all, as targeted by SDG 7 [26]. Global electricity access increased from 84% in 2010 to 92% in 2023 [27].

Following the signing of the Paris Agreement by numerous countries [28], actions to reduce greenhouse gas emissions under climate policy accelerated. In its current radical form, climate policy in the European Union is implemented through the European Green Deal, whose overarching objective is to achieve net-zero emissions by 2050 [29]. An important measure supporting this strategy is the Net-Zero Industry Act, which aims to strengthen Europe's production capabilities for net-zero technologies to ensure that the

green transition remains both secure and independent of critical external dependencies. Additionally, the EU introduced the Clean Industrial Deal [30] to promote industrial decarbonisation, together with several complementary policy initiatives.

Energy poverty arises when households are forced to limit their energy consumption to such an extent that it harms the health and overall quality of life of the inhabitants. It is primarily driven by three key factors: high energy-related costs within the household budget, insufficient income, and low energy efficiency of dwellings and appliances [31]. While promoting its climate policy, the European Union has made significant efforts to mitigate emerging socio-economic challenges, including energy poverty. The EU strives to create a reliable, affordable, and sustainable energy system; however, substantial disparities in economic conditions among Member States persist.

The EU introduced the energy poverty indicator for the first time in 2021, measuring the proportion of Europeans unable to adequately heat their homes. At that time, the rate was 6.9%. By 2024, it had reached 9.2%, although it was still lower than the 10.6% recorded in 2023 [31]. This decline resulted from the combined effects of implementing energy efficiency measures across EU countries and the growing awareness of energy poverty and the social groups affected by it. It is expected that the implementation of subsequent regulations—including the Energy Performance of Buildings Directive, the Energy Efficiency Directive, and the Renewable Energy Directive—will confirm and reinforce this downward trend.

2.2. Macroeconomic Background for EP-EE

Energy poverty is a serious problem in many countries worldwide, with social and economic implications that are closely linked to broader economic trends. Given the multifaceted nature of the factors influencing energy poverty (EP), the present study outlines only the key conditions (determinants) that may affect energy efficiency (EE). In assessing the impact of energy efficiency on energy poverty, the main factors analysed include access to energy (supply, including imports), the level of urbanisation, GDP per unit of energy consumption (as an efficiency indicator), and net national income per capita (as an indicator of financial capacity), together with comprehensive control variables [32–35]. Macroeconomic factors such as energy intensity, urbanisation, and income levels are identified as the primary drivers of energy poverty [34].

Assuming that macroeconomic determinants constitute a crucial dimension of energy poverty, Ben Cheikh et al. (2023) [34] examined the relationship between energy efficiency, income distribution, and energy poverty in Europe. Their findings indicate that income inequality significantly influences energy poverty. Similarly, Primc et al. (2019) [36] confirmed that warm climates, low income levels, and energy prices exacerbate energy poverty across the EU Member States. Other studies show that higher energy consumption per unit of GDP contributes to energy inefficiency [37,38]. Slabe-Erker et al. (2024) [35] demonstrated that changes in GDP, inflation, and employment rates directly affect both the severity and the extent of energy poverty in the EU. Additional significant determinants influencing energy poverty levels in selected EU countries include household electricity prices (including all taxes) and net electricity imports [39]. The role of income in reducing energy poverty is also confirmed by Wolde-Rufael (2006) [39].

In contrast to industry, energy poverty constrains the optimisation of energy consumption structures and consequently hampers improvements in sectoral energy efficiency, for example, in the construction industry [40]. At the same time, technological advancement and the degree of commercialisation play a moderating role, potentially weakening or strengthening the negative impact of energy poverty on sectoral energy efficiency, such as in the steel industry [41].

At the macroeconomic level, urbanisation is another determinant of the EP–EE nexus. On the one hand, it increases energy demand; on the other, it improves access to energy infrastructure [42,43]. Dokupilová et al. [44] found that energy poverty in most EU countries strongly depends on geographic location and regional development. The nature of energy poverty also differs substantially between developed and developing economies, reflecting different stages of economic development [37,45,46]. In the industrial context, industrialisation itself is a key determinant of the EP–EE relationship. Djeunankan et al. (2024) [47] show that reducing energy poverty, on average, supports industrialisation, particularly in developing countries.

Within the EU, the promotion of the European Green Deal (EGD) aims to reduce energy poverty in the long term through improvements in energy efficiency. In this context, energy market diversification and the development of renewable energy sources (RES) play a crucial role. Although essential for achieving sustainable energy and carbon-reduction targets, these reforms are often associated with high upfront investment costs—such as energy retrofitting of buildings, deployment of renewable technologies, and reductions in industrial energy intensity. Research highlights that different energy sources exert varying effects on the EP–EE relationship. As emphasised by Slabe-Erker et al. [35], limited financial resources constitute a major barrier to such investments, even though they would yield the greatest long-term benefits through lower energy costs. This challenge is further intensified by limited access to financing options and government support programmes, which are often insufficient or difficult to obtain. Such financial burdens not only exacerbate existing inequalities but may also undermine the core objective of improving energy efficiency and reducing energy poverty.

Nagaj (2024) [32] argues that among the dimensions of the European Green Deal's impact, energy policy—particularly the development of energy efficiency, renewable energy promotion policies, renewable energy production levels, and macroeconomic stability—exerts a significant influence on energy poverty. These findings align with those of Tamasiga et al. (2024) [48], Lehtonen et al. (2024) [49], and García-Vaquero et al. (2024) [50], who emphasise the leading role of socio-economic factors. Furthermore, economic decarbonisation through CO_2 emissions reduction may affect the EP–EE relationship [51]. The use of "may" reflects mixed empirical evidence: some studies find no direct effect of decarbonisation on energy poverty (Nagaj, 2024 [32], for Poland), while others report a significant impact (Jayalath et al., 2024) [52].

In economies whose energy mix is heavily reliant on non-renewable sources such as coal—including the Czech Republic, Poland, and Slovakia—research continues to explore the underlying causes of energy poverty [38]. Due to differences in the adaptive capacity of economies and societies to "Net Zero" targets (2050), it remains difficult to clearly assess how decarbonisation affects both industry [53–58] and households [51]. Industry primarily experiences these effects through required investments aimed at reducing greenhouse gas emissions or improving production productivity [55,59], while households face higher energy prices and expenditures [60], which may ultimately intensify energy poverty.

Macroeconomic pressures can, however, be mitigated through effective public policy, as demonstrated by Certomà (2023) [61]. Based on panel data models, the author shows that strong government effectiveness, high regulatory quality, secure property rights, contract enforcement, and corruption control are significantly associated with lower energy poverty levels. Moreover, Gielen et al. (2019) [62] emphasise that energy efficiency and renewable energy technologies are central pillars of the energy transition, with their synergy being particularly important. Countries, especially developing countries, can reduce energy intensity through energy efficiency initiatives [63]. Positive determinants of the EP–EE relationship include favourable economic conditions, abundant resources, scalable

technologies, and substantial socio-economic benefits. Renewable energy alone could meet up to two-thirds of global energy demand and contribute significantly to greenhouse gas emission reductions required by 2050 to limit global temperature increases to below 2 °C.

Nevertheless, industrial energy efficiency constitutes a key component of the broader energy system that can help reduce overall energy costs [39], thereby indirectly alleviating energy poverty. Thus, despite their contrasting orientations—industrial efficiency being business- and environment-driven, and energy poverty representing a challenge to social and individual welfare—there exists a systemic interdependence: improving the overall efficiency of the energy system, including industrial processes, can contribute to lowering total energy costs. If these savings are transferred to consumers, energy may become more affordable, mitigating the prevalence of energy poverty. Systemic actions, such as enhancing the efficiency of buildings and industrial processes, are therefore essential to achieving long-term solutions to both challenges.

In conclusion, energy poverty represents a complex socio-economic phenomenon, and its relationship with energy efficiency is not straightforward. It cannot be captured by a single indicator, yet sustained research efforts are essential. The results of such studies can provide valuable guidance for local and national policies aimed at improving energy efficiency and reducing energy poverty.

The analysis presented in this paper contributes to the broader academic discourse on the interplay between energy efficiency (EE) and energy poverty (EP) across various research domains. This paper presents an analysis of the relationship between industrial energy efficiency and energy poverty in the European Union, approached from both macroeconomic and social perspectives. The authors examine the impact of improvements in energy efficiency on energy prices and the potential implications for real incomes and employment in the industrial sector. Industrial energy efficiency refers to the optimisation of firm-level processes to reduce energy consumption [55], while energy poverty denotes the inability of households to secure adequate heating, cooling, and electricity [36]. These two concepts differ in focus: industrial energy efficiency emphasises economic and environmental benefits for enterprises, whereas energy poverty addresses the social and economic difficulties faced by individuals and families. Energy transition is a complex process, influenced by numerous psychological factors that shape both societal responses and the experience of energy poverty during this shift [57]. Moreover, the dynamics of energy transformation differ significantly between two groups of countries: longstanding EU member states and newer entrants [58]. The study of the determinants of energy poverty within the context of climate and energy policy is crucial because (i) at the macro level, energy poverty increases income poverty and constrains social development; (ii) at the micro level, it constitutes a barrier to achieving the well-being of household members; and (iii) at the level of climate policy, households affected by energy poverty are unable to effectively benefit from its instruments or to consciously participate in active actions aimed at improving energy efficiency based on the principles of sustainable energy consumption [32,53,54].

Table 1 below synthetically presents the most relevant academic works on the connection between industrial energy efficiency and the problem of energy poverty, including both developing and developed countries. The abstracted sources emphasise the empirical and conceptual link between the challenges of decarbonisation, the industrial topic, and the social side of energy access. The scope of the sources involves the study of domestic energy affordability in Ukraine, the existing differences in the construction industry in China, the comparison of the European countries with declining coal production, as well as international studies on the connection between energy poverty, efficiency, and the carbon neutrality paradigm. In consideration of the methods, the sources apply the broadest

possible range of techniques, from econometric modelling to the study of literature, because of the interdisciplinary nature of the topic itself.

The conclusions from these studies are generally harmonised on some crucial points. The upgrading of industrial and building-level energy efficiency is often seen to substantially alleviate energy poverty, although its distributional aspects are conditioned by different considerations, including energy pricing strategies, financial transfer mechanisms, and regional economic development dynamics. Economic growth and industrial structural transformation are also believed to contribute towards the reduction in energy poverty, often over the long run, and the temporary impacts of decarbonisation sometimes contribute to the aggravation of energy poverty due to increased energy prices or social adjustment costs, respectively [64].

Notably, Table 1 indicates the gradual convergence of the body of literature exploring the interface between technological efficiency and social well-being, situating the current study in the continuing international and European discourses on the socio-economic consequences of industrialised decarbonisation, respectively.

Table 1. Scopes of scientific research on the topic: industrial energy efficiency versus energy poverty.

Source	Scope	Methods	Conclusions
Li et al. (2022) [65]	Energy poverty and low household energy efficiency in Ukraine.	Least squares analysis for time series (1999–2018).	A percentage increase of 1% in the average spending on domestic energy leads to a 3% increase in the poverty rate. A USD 100 growth in per capita GDP reduces the national poverty rate by 6%. Economic growth offsets energy poverty, leading to greater energy efficiency.
Zhang et al. (2021) [66]	Energy efficiency in the construction sector vs. regional development in China.	Panel data (30 provinces, 2008–2017); calculation of energy poverty index and sectoral energy efficiency.	Regional inequalities and the inadequacy of the energy infrastructure are major sources of energy poverty, but the solution also lies in the restructure of the energy mix.
Janikowska, O.J. (2024) [67]	Energy transition and energy poverty risks in former coal regions of Poland, Greece, and Bulgaria.	Qualitative and quantitative analyses of policy documents and national statistics.	The rate of industrial transformation and the degree of social compensation help shape regional dynamics in energy poverty during the green transition.
Streimikiene et al. (2021) [68]	Comparative study of energy poverty and just transition in Lithuania and Greece.	Multi-criteria assessment using national indicators and EU-SILC data.	Equal treatment policies in the context of just transition can minimise the social impacts of the process of decarbonizing.
Lu and Ren (2025). [56]	Global review of energy poverty–efficiency nexus under carbon neutrality objectives.	Systematic literature review (2000–2023).	Upgrading energy efficiency is necessary but not sufficient, with the role of inequality or the pricing of energy acting to mediate the decarbonisation-poverty reduction effect.
Nagaj (2022) [69]	Fiscal and macroeconomic determinants of energy poverty in Poland.	Econometric modelling based on 2005–2020 data.	Support schemes run by the government will help alleviate fuel poverty in the shorter term but, in the process, could also reduce the incentive to improve the efficiency of energy use.
Carfora et al. (2025) [3]	Analysis of EU energy efficiency policies and their impact on household energy poverty.	Fixed-effects panel regression for EU27 (2010–2022).	More public expenditures on efficiency upgrades lead to lower levels of energy poverty, particularly in Southern Europe.
Simionescu et al. (2023) [2]	Determinants of energy poverty in European households.	Dynamic panel model for EU27 (2004–2021).	Economic growth and energy efficiency are important drivers in combating energy poverty, while the price of energy and inflation exacerbates energy poverty.
Nordensvärd et al. (2025). [7]	The role of energy efficiency measures in achieving energy justice.	Policy review and econometric correlation of energy efficiency scores and affordability indicators.	The gain in efficiency must be matched with the means of redistributive justice in having accessible, affordable energy services.

Table 1. *Cont.*

Source	Scope	Methods	Conclusions
Ozturk et al. (2010) [63]	Energy intensity and energy efficiency initiatives	Analysis of energy initiatives and energy intensity case study: developing countries (households).	Developing countries can reduce energy intensity through energy efficiency initiatives, which can reduce the energy burden (energy expenditure).
Ben Cheikh et al. (2023) [34]	Energy efficiency, income distribution, and energy poverty	Scope: Europe, stistical analysis.	Increasing energy efficiency can alleviate energy poverty.
Nagaj (2024) [32]	Commitments on decarbonisation, renewable energy, and energy efficiency under the European Green Deal (EGD) affect the scale of energy poverty.	Regression analysis, scope: energy poverity in Poland.	The results of the study indicated that, in the long term, energy poverty is influenced by the macroeconomic stability of households, renewable energy production, and energy efficiency, while in the short term, since the introduction of the Green Deal, macroeconomic stability has proven to be the strongest factor.
Ghosh (2025) [33]	Access to clean fuels and technologies as a basic measure of energy poverty	Econometric approaches: two-way fixed-efects models to control for unobserved heterogeneity, instrumental variable techniques to address endogeneity concerns, and quantile regression to examine distributional effects across deciles of clean fuel access.	There are correlations, based on panel data from 1991 to 2023 for BRICS countries, between access to clean fuels and technologies and their impact on energy poverty.

3. Materials and Methods

The aim of this study is to assess the impact of energy efficiency in industry on the level of energy poverty in European Union countries, taking into account the macroeconomic environment in EU economies. To achieve this objective, the analysis will be carried out using panel data models, controlling for key economic and social conditions (real GDP per capita, expenditure on social benefits, electricity prices, labour costs) and taking into account potential endogeneity using an instrumental variable, i.e., the impact of labour productivity in industry on energy efficiency in industry. The inclusion of such control variables stems from the fact that, as the literature indicates, energy efficiency can mitigate energy poverty by reducing energy demand and expenses, making energy more affordable for vulnerable populations [3,5,6,70]. As the literature indicates, energy poverty is influenced by a mix of low household income, poor household energy efficiency, and high energy prices [71]. Furthermore, improving energy efficiency can reduce energy prices, which may translate into energy poverty [72], and energy poverty itself is largely due to climate and energy policies that affect energy prices [73]. This justifies the inclusion of GDP per capita and electricity prices for end-users. In addition, energy poverty is sensitive to the social policy of the state and mainly affects the poorest, hence the model also includes labour costs and expenditure on social benefits [50]. The endogenous variable is justified by the fact that the vast majority of the literature indicates that in industry in most countries, higher labour productivity is associated with improved energy efficiency [19,74–76]. Only a few studies suggest that labour productivity does not always ensure improving energy efficiency or may have a limited [77,78], or even negative effect on energy efficiency [74].

The paper analyses the impact of energy efficiency on energy poverty. Therefore, the following variables are adopted in the model:

Y—energy poverty of households, measured by the indicator of inability to keep home adequately warm (% of total households)

X1—energy intensity of industry as a measure of energy efficiency (EEff = 1/X1),

X2—real GDP per capita (2015 = constant; in EUR/Ma),

X3—expenditure on social benefits (as % of GDP);

X4—electricity prices for household consumers (EUR/kWh);

X5—nominal unit labour cost based on hours worked by industry (2015 = 100);

X6—real labour productivity per person in industry (2015 = 100)—endogenous variable affecting X1.

The source of data for all variables is Eurostat, which ensures methodological comparability of data. Sources for particular parameters:

Source for Y—Eurostat, Inability to keep home adequately warm. https://ec.europa.eu/eurostat/databrowser/view/ILC_MDES01__custom_18806689/default/table (8 November 2025); https://doi.org/10.2908/ILC_MDES01 [79].

Sources for X1—Eurostat, Simplified energy balances, https://doi.org/10.2908/NRG_BAL_S (11 November 2025); [80], Eurostat, Gross value added and income by detailed industry (NACE Rev.2) (11 November 2025) [81].

Source for X2—Eurostat, Real GDP per capita. https://doi.org/10.2908/TIPSNA40 (11 November 2025) [82].

Source for X3—Eurostat, Expenditure on social benefits by function. https://doi.org/10.2908/SPR_EXP_FUNC (11 November 2025) [83].

Sources for X4—Eurostat, Electricity prices for domestic consumers—bi-annual data (until 2007), https://doi.org/10.2908/NRG_PC_204_H (11 November 2025) [84]; Eurostat, Electricity prices for household consumers—bi-annual data (from 2007 onwards), https://doi.org/10.2908/NRG_PC_204 (11 November 2025) [85].

Source for X5—Eurostat, Labour productivity and unit labour costs by industry (NACE Rev.2). https://doi.org/10.2908/NAMA_10_LP_A21 (13 November 2025) [86].

Source for X6—Eurostat, Labour productivity and unit labour costs by industry (NACE Rev.2). https://doi.org/10.2908/NAMA_10_LP_A21 (13 November 2025) [86].

The analytical framework on which the research is based presumes that energy poverty is a macro-social phenomenon that depends on structural attributes of the production system and broader economic factors. A core variable within the framework is industrial energy intensity (X1), which belongs to a proxy variable for industry energy efficiency and represents the main transmission mechanism that might affect energy deprivation within households as a consequence of production-side technological changes (H1). The analytical framework presumes that as a result of lowering industrial energy intensity, there would be an improvement in process efficiency and industry organisational improvements that affect energy demands positively and reduce cost pressures associated with energy production. Accordingly, it lays a foundation for testing the impact associated with energy poverty and reduced energy intensity within specific Member States within the European Union.

As foreseen by hypotheses H2 and H3, it is specified within the model that there may be country-specific heterogeneity, taking into account fixed effects that embody national traits. Examples of these traits include housing stock quality, weather, institutional settings, and energy market organisation. Unobserved variables should thus affect energy poverty on a conditional level as well as interactions with industrial energy efficiency. Moreover, aiming at hypothesis H6 and correcting for endogeneity because of energy intensity within industry, a covariate included as an instrument within the model as per hypothesis H6 would be labour productivity within industry, represented as variable X6. Productivity per se would be a measure reflecting technological advancements as well as capital. It would thus be assumed within theoretical stands that it would act as an assist mechanism that would reduce energy usage per value added without any influence on energy poverty. At last, as suggested by hypotheses H4 and H5, the model accounts for the set of macro variables that comprise real GDP per capita (X2), expenditure on social benefits (X3), and prices for residential electricity consumption (X4), as well as unit labour costs within

industry (X5). It should be noted that these variables correspond to alternative explanatory factors, taking into account income capabilities, redistribution factors, price sensitivities, and production costs. By incorporating these elements into a comprehensive framework, it becomes possible for this model to offer a structured empirical representation equivalent to those outlined within the Introduction.

Table 2 provides a structured overview of all variables employed in the empirical analysis and clarifies their role within the research framework. It distinguishes the dependent variable capturing household energy poverty from the key explanatory variable representing industrial energy efficiency, as well as from macroeconomic and social control variables that account for income capacity, redistribution mechanisms, price exposure, and cost conditions. In addition, the table explicitly identifies real labour productivity in industry as an instrumental variable, highlighting its function in addressing the potential endogeneity of industrial energy intensity. By specifying the definition, unit of measurement, analytical objective, data source, and variable type for each indicator, the table enhances methodological transparency and ensures that the selection and interpretation of variables are theoretically grounded and empirically traceable.

Table 2. Definition and characteristics of variables used in the empirical analysis.

Variable	Definition	Unit of Measurement	Analytical Objective	Data Source	Variable Type
Y	Energy poverty measured as the share of households unable to keep their dwelling adequately warm	Percentage of total households (%)	Captures household-level energy deprivation as the main social outcome variable	Eurostat (EU-SILC)	Dependent
X1	Industrial energy intensity defined as final energy consumption per unit of industrial value added	Energy units per EUR of value added	Measures industrial energy efficiency and structural energy performance	Eurostat (Energy balances, National Accounts)	Independent (endogenous)
X2	Real GDP per capita at constant prices (2015 = 100)	EUR per capita	Controls for overall economic development and income capacity	Eurostat (National Accounts)	Independent (control)
X3	Expenditure on social benefits	Percentage of GDP (%)	Represents redistributive and social protection mechanisms	Eurostat (Social Protection Statistics)	Independent (control)
X4	Electricity prices for household consumers	EUR per kWh	Tests the price-based transmission mechanism affecting energy affordability	Eurostat (Electricity Price Statistics)	Independent (mediator candidate)
X5	Nominal unit labour costs in industry	Index (2015 = 100)	Captures industrial cost pressures with potential spillover effects	Eurostat (Labour Productivity and Costs)	Independent (control)
X6	Real labour productivity per person employed in industry	Index (2015 = 100)	Instrument capturing technological progress and productivity-driven efficiency gains	Eurostat (Labour Productivity Statistics)	Instrumental variable

The conceptual model used in the study is that labour productivity in industry (X6), i.e., technological innovations, better production organisation and modernisation of machinery, contribute to a decrease in energy intensity in industry (X1), i.e., lower energy consumption per unit of value added in industry, and thus to an improvement in energy efficiency in industry (1/X1). In this way, X6 indirectly affects Y through X1. On the other hand, a decrease in energy intensity in industry, i.e., an improvement in the energy efficiency of industrial production, means lower energy costs across the economy, less pressure on energy prices, higher competitiveness and higher incomes, which determines the level of energy poverty in households (Y). The logic of the model is that energy poverty is a function of both macroeconomic factors (represented by variables X2-X5) and energy

intensity parameters on the industrial side. Among the control variables, macroeconomic factors are expected to increase the ability of households to finance energy expenditure and encourage investment in energy efficiency (buildings, appliances, etc.) and a decrease in the level of energy poverty (Y). Higher social expenditure (X3) is expected to mean stronger redistribution and social protection mechanisms, which may compensate for high energy costs for the most vulnerable households and a decrease in Y. Electricity prices for household consumers (X4), meanwhile, are a direct determinant of energy costs in household budgets. Therefore, higher X4 is expected to contribute to higher Y. The last variable is nominal unit labour cost in industry (X5), where higher unit labour costs in industry are expected to drive up production costs, contribute to higher prices of goods and indirectly to the cost of living, including energy, and ultimately have a positive impact on Y.

Taking all these assumptions into account, we used two models for analysis in our work: (1) the Fixed Effects (FE) model controlling for country and year effects, and (2) the Instrumental Variables (IV) approach using Two-Stage Least Squares (2SLS) to address potential endogeneity of labour productivity in industry. The FE model was chosen to control for country and year heterogeneity, and this was performed on the basis of the Hausman test [87–89]. The IV model, on the other hand, is an econometric technique designed to address endogeneity issues in regression analysis [90,91]. The estimation of this model was performed using the two-stage least squares (2SLS) method [92–94]. To ensure methodological correctness, robustness checks were additionally performed, which included heteroskedasticity and autocorrelation tests, followed by HAC correction. This approach is consistent with the assumptions of fixed effects regression and increases the robustness of statistical inference [6,95,96].

Description of parameters in the IV (2SLS) model

- Y—household energy poverty indicator; dependent variable measuring the share of households unable to keep their dwelling adequately warm.
- X1—industrial energy intensity; endogenous explanatory variable representing energy efficiency in industry.
- $\hat{X1}$ (predicted X1)—fitted value of industrial energy intensity obtained from the first-stage regression; captures exogenous variation in X1 driven by labour productivity.
- X6—real labour productivity in industry; instrumental variable reflecting technological progress and production efficiency, assumed to affect energy poverty only indirectly through X1.
- X2—real GDP per capita; control variable capturing overall income level and economic development.
- X3—expenditure on social benefits; control variable representing redistributive and social protection mechanisms.
- X4—electricity prices for household consumers; control variable testing the price-related transmission channel affecting energy affordability.
- X5—nominal unit labour costs in industry; control variable capturing production cost conditions and structural economic characteristics.
- μ_i (country fixed effects)—unobserved, time-invariant national characteristics such as housing stock quality, climate, institutional framework, and industrial structure.
- γ_t (time fixed effects)—common temporal shocks affecting all countries, including energy crises, macroeconomic disturbances, and policy changes.
- ε_{it} (error term)—idiosyncratic, time-varying disturbances not explained by the model.

The Fixed Effects (FE) model was chosen to account for unobserved, time-invariant characteristics of countries that could bias the estimates if ignored. By including country and year dummies, the FE model controls for these constant factors; it ‘removes’ the

influence of these constant characteristics in order to focus on variability over time, thus isolating the effect of X1 on Y within each country over time. This approach is appropriate when the primary concern is heterogeneity across entities that does not change over time. This prevents the erroneous attribution of the impact of variables when differences between countries are significant but not measured in the data. In contrast, the Instrumental Variables (IV) model is a method used when we suspect endogeneity, i.e., a situation where the explanatory variable is correlated with the model error, which could lead to erroneous conclusions. To address this, we use labour productivity as an instrument for energy efficiency in industry. The instrument satisfies two key conditions: firstly, relevance, i.e., in our model, labour productivity in industry is strongly correlated with energy efficiency in industry, and second, exogeneity, namely, labour productivity does not directly affect the dependent variable (energy poverty level), but allows us to obtain the 'purified' effect of X1 on Y, free from the problem of endogeneity.

This paper analyses the impact of energy efficiency in industrial processes on energy poverty levels using a panel data set covering all 27 European Union countries over the years 2003–2023. The research period is limited by the availability of statistical data but covers the entire period of the new Member States' presence in the EU structures. Each observation represents a country-year pair, including the dependent variable (Y), the main explanatory variable (X1), macroeconomic controls (X2–X5), and an instrumental variable (X6). Panel data allows us to capture both cross-sectional and time-series variation, which is essential for understanding dynamic relationships and controlling for unobserved heterogeneity.

The Two-Stage Least Squares (2SLS) method is applied: Stage 1 predicts X1 using X6 and controls; Stage 2 regresses Y on the predicted X1 and controls. This approach provides consistent estimates of the causal effect of X1 on Y.

Thus, six stages of the research model used can be distinguished in the study (see Figure 1).

According to this research procedure, the basic fixed effects (FE) panel model for the country and year will be estimated according to the following equation (second stage—Y regressed):

$$Y_{it} = \beta_0 + \beta_1 X_{1it} + \beta_2 X_{2it} + \beta_3 X_{3it} + \beta_4 X_{4it} + \beta_5 X_{5it} + \mu_i + \gamma_t + \varepsilon_{it} \quad (1)$$

where

i—country, i = 1, . . ., 27;

t—year;

μi—fixed effects, unobservable country-specific effects (country fixed effects);

γt—time dummy (dummy for the year), controls for time dummies common to all countries, which allows for the elimination of unobservable structural differences and common shocks (e.g., COVID-19, the 2022 energy crisis, the 2008–2009 financial crisis);

ε_{it}—random component;

Y_{it}—dependent variable,

X_{1it}, . . ., X_{5it}—independent variables, where X_{1it} is the main independent variable, and X_{2it}-X_{5it} are macroeconomic control variables.

The selection of the FE model will be verified using Hausman's test comparing fixed (FE) and random effects (RE) estimators. Student's t-statistics will be used to assess the significance of the parameters.

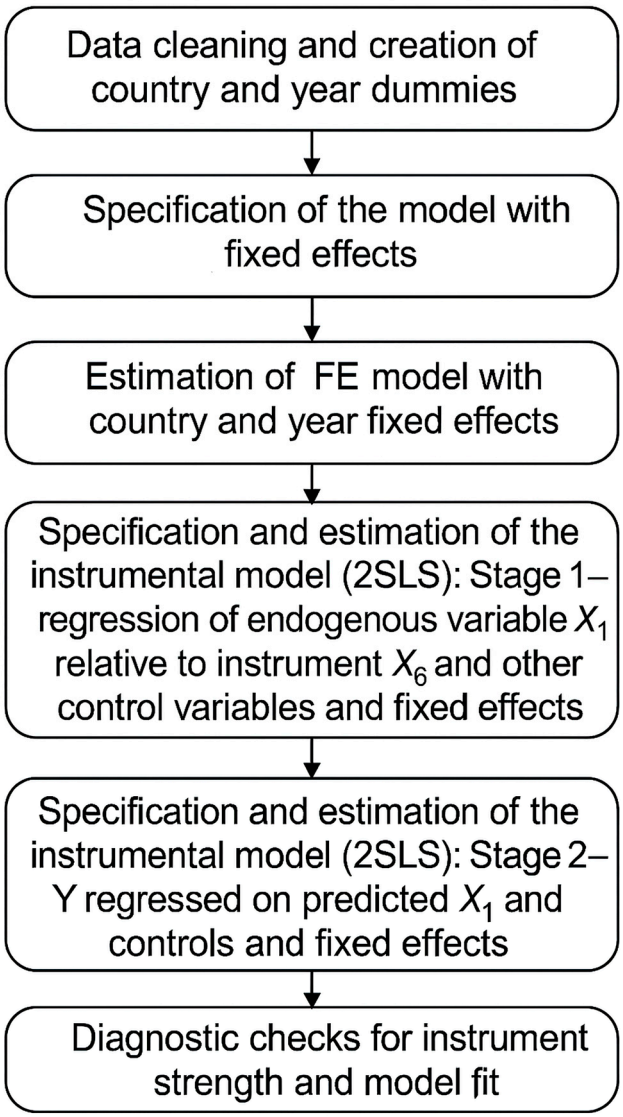


Figure 1. Stages of the research model.

The Instrumental Variables model (IV model), on the other hand, will be modelled according to the equation (first stage—regression of endogenous variable):

$$X_{1,it} = \propto_0 + \propto_1 X_{6it} + \propto_2 X_{2it} + \cdots + \propto_5 X_{5it} + v_{it} \quad (2)$$

The relevance of instrument X6 for energy intensity (X1) will be assessed on the basis of the instrument relevance test (F-statistic) and the coefficients of determination R-squared and adjusted R-squared for model fit evaluation. The Breusch-Pagan test will be used, robust standard errors (HC3) will be applied to account for heteroscedasticity, and autocorrelation and heteroscedasticity will be jointly corrected using the Newey-West HAC correction, which will allow for a comparison of the results obtained with different covariance matrix specifications.

Significance tests for coefficients (p-values) will also be calculated to confirm the statistical relevance of X1 and controls. FE estimation is performed using the least squares method with the use of the robust HC3 covariance matrix and the Newey-West HAC correction (HAC).

4. Results

4.1. Correlation Analysis

First, Hausman's statistic was calculated (for variables X1–X6): $\chi^2 = 28.077$, df = 6, $p = 0.0000878$. These results indicate that the use of a random effects (RE) model should be rejected and confirm that a fixed effects (FE) model is the correct choice, as the unobservable fixed characteristics of countries are correlated with the regressors (Table 3).

Table 3. The correlation matrix.

	Y	X1	X2	X3	X4	X5	X6
Y	1	0.54194	−0.47975	−0.39999	−0.36462	−0.17738	−0.18607
X1	0.54194	1	−0.2517	−0.33797	−0.4742	−0.38992	−0.39346
X2	−0.47975	−0.2517	1	0.400334	0.47535	0.021226	0.149421
X3	−0.39999	−0.33797	0.400334	1	0.51544	−0.07698	0.193875
X4	−0.36462	−0.4742	0.47535	0.51544	1	0.227438	0.308443
X5	−0.17738	−0.38992	0.021226	−0.07698	0.227438	1	−0.01219
X6	−0.18607	−0.39346	0.149421	0.193875	0.308443	−0.01219	1

Next, in order to identify the interdependencies, strength and direction of linear relationships between variables, including between energy intensity in industry sectors and real labour productivity in industry, the correlation matrix was used.

The correlation analysis indicates that higher energy intensity is strongly positively correlated with energy poverty (r = 0.54), and corr(X1, X6) = −0.393, which indicates a correlation between these variables, i.e., higher real labour productivity in industry leads to lower energy intensity of industry. In addition, the possibility of multicollinearity between independent variables was found.

4.2. Diagnostic Model

In the next stage, the authors proceeded to diagnose and evaluate the FE model. As part of this stage, the existence of heteroscedasticity, autocorrelation and collinearity was checked. The results of these tests are shown in Table 4.

Table 4. Diagnostics of FE model assumptions.

Statistical Test	Statistics	*p*-Value
Breusch-Pagan	LM statistic = 61.6937	2.0367×10^{-11}
	F statistic = 11.3952	4.8822×10^{-12}
Durbin-Watson	DW statistic = 0.4983	-
AR(1)	$\hat{\rho}$(AR1) = 0.8425	-
	t-statistic (AR1) = 33.8263	2.74×10^{-135}
Variance Inflation Factors (VIF)	VIF(X1) = 1.73 VIF(X2) = 1.36 VIF(X3) = 1.57 VIF(X4) = 1.88 VIF(X5) = 1.36 VIF(X6) = 1.27	- - - - - -
R-squared	0.8851	-
X1 coefficient	33.6052	7.26×10^{-7}

The results suggest the presence of strong heteroscedasticity, indicating the need to apply HAC correction, which indicates that cluster-robust standard errors are necessary or heteroscedasticity and autocorrelation consistent (HAC), which was performed in the

model. Additionally, it was found that there is no strong autocorrelation. The above results indicated the validity of using the FE-IV (2SLS) model with HAC correction.

Next, the FE–IV model was diagnosed, and first-stage diagnostics (IV model) tests were calculated to assess whether instrument X6 is relevant and predicts X1 well. The results of these calculations are shown in Table 5.

Table 5. Results of the relevance diagnosis of the first stage of regression.

X6 Coefficient	Standard Error	t-Statistic	*p*-Value	F-Statistic
−0.003532	0.000256	−13.773	3.7×10^{-37}	189.70

The results show that variable X6 is a very powerful and relevant instrument. Therefore, the FE–IV model diagnostics (second stage), i.e., heteroscedasticity and autocorrelation, were performed (Tables 6 and 7).

Table 6. Results of FE-IV model diagnostics.

Statistical Test	Statistics	*p*-Value
Breusch-Pagan	LM statistic = 124.6894	3.18×10^{-25}
	F statistic = 31.6297	2.09×10^{-28}
Durbin-Watson	DW statistic = 0.4684	n.d.
AR(1)	$\hat{\rho}$(AR1) = 0.8605	2.34×10^{-149}
	t-statistic (AR1) = 36.8691	
R-squared	0.8698	-

Table 7. Results of FE and FE-IV panel models for energy poverty as a dependent variable.

Independent Variable	FE Model	FE-IV Model
X1(FE)/X1_impl. (FE-IV)	33.61 ***	73.0776 ***
	(6.98)	(15.03)
X2	0.00015	0.000011
	(0.00017)	(0.00011)
X3	0.11	0.2018
	(0.19)	(0.21)
X4	21.34 *	20.3980 **
	(11.50)	(9.92)
X5	−0.08 **	−0.0112
	(0.034)	(0.03)
X6	−0.139 **	-
	(0.067)	

Significance level: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

These results indicate that there is a positive correlation between energy intensity in industry (X1) and energy poverty (Y). It can therefore be concluded that a decrease in energy intensity in industry has a statistically very significant impact on reducing the level of energy poverty among households and that this impact is very strong. It was also found that the effect, after controlling for endogeneity, is even stronger and still significant.

Answering the first hypothesis (H1), it was found that a reduction in the energy intensity of industry (X1) leads to a statistically significant reduction in the level of energy poverty (Y). In the FE model, the X1 coefficient is positive and highly significant (33.6; $p < 0.001$). In contrast, in the FE–IV model, the coefficient for the X1_impl. variable is even higher and indicates a statistically significant strong positive effect after endogeneity

correction (73.1; $p \approx 0.00005$). Thus, H1 is strongly confirmed positively (both in the FE model and after endogeneity correction in the FE–IV model), which means that a decrease in the energy intensity of industry significantly reduces energy poverty in the EU.

Next, we checked whether the fixed effects across EU countries are homogeneous or heterogeneous. The results of the country-level effects before and after endogeneity correction are shown in Figure 2.

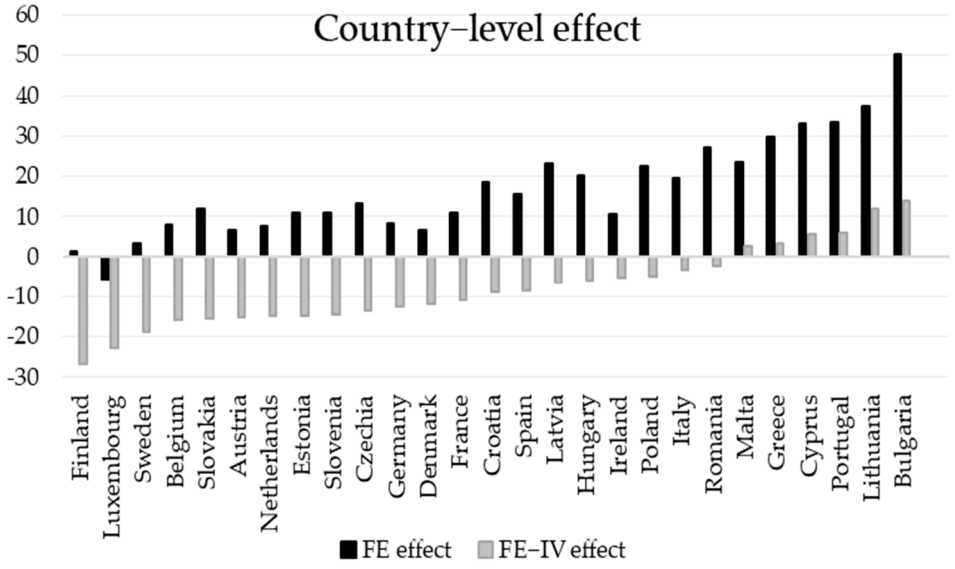


Figure 2. Country-level effects across the EU countries based on the FE model and the FE-IV model.

The results indicate strongly differentiated country fixed effects (FE model) and even stronger differentiation after correction for endogeneity X1 (FE-IV model). The results showed that the minimum FEs are for Luxembourg (−5.64) and the maximum for Bulgaria (50.64), which means that the spread between countries is as high as 55.98 points. After endogeneity correction (FE-IV effects), these spreads still exist, with the minimum value for Finland (−26.63) and the maximum for Bulgaria (13.79), which means a spread of 40.42 points. This indicates that EU countries differ structurally in terms of energy poverty levels and have persistent determinants that are not observed in the model. The reasons for these differences may lie in differences in housing policies, varying building infrastructure efficiency, climatic differences or different electricity prices. After X1 instrumentation, national effects shift by as much as several to several dozen points, which means that in different countries the impact of the decline in energy intensity in industry on the decline in energy poverty varies in strength. This confirms that there is causal heterogeneity, which is direct empirical evidence to support hypothesis H2.

4.3. Correlation Analysis

The differences between countries are also confirmed by the varying correlation between energy intensity (X1) and energy poverty (Y) among EU countries (see Figure 3).

As the analysis data show (Figure 3), the correlation for the EU as a whole is positive and strong, indicating that the higher the energy intensity of industry, the greater the risk of energy poverty in society. However, across countries, this correlation varies greatly.

These results also reinforce the conclusions on the significance of hypotheses H3 and H4. In the context of H3, this confirms that countries with lower energy intensity of industry show lower levels of energy poverty. The correlation between the mean X1 and the mean Y across countries is strong, at 0.52. The value of $p = 0.0054$ (<0.01) indicates high statistical significance.

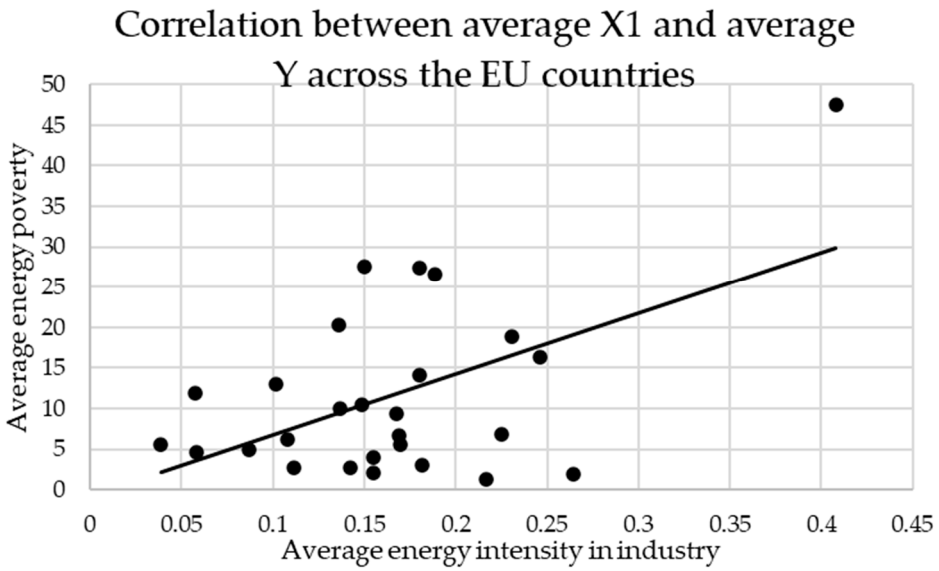


Figure 3. Correlation between energy intensity and energy poverty across the EU countries.

In the next step, verifying hypothesis H4, it was checked whether the decrease in energy intensity in industry (X1) reduces energy poverty (Y) indirectly through the stabilisation of electricity prices (X4). For this purpose, an indirect effect analysis (X1 → X4 → Y) was verified, i.e., four regression equations:

- first model, where

$$X4 \sim X1: X4 = \alpha_1 + \beta_1 X1 + \varepsilon_1 \quad (3)$$

- second model, where

$$Y \sim X4: Y = \alpha_2 + \beta_2 X4 + \varepsilon_2 \quad (4)$$

- third model for fixed effects:

$$Y = \alpha_i + \beta_3 X1 + \beta_4 X4 + Controls + \mu_i \quad (5)$$

- and, fourth model for FE-IV/2SLS:

$$Y = \alpha_i + \beta_5 X1_impl + \beta_6 X4 + Controls + \mu_i. \quad (6)$$

The results of this analysis are presented in Table 8.

Table 8. Regression results for H4.

Variable	Model 1: X4 ~ X1	Model 2: Y ~ X4	Model 3: FE	Model 4: FE-IV
X1	0.0129 (p = 0.231)	-	33.6052 *** (p < 0.001)	-
X1_hat	-	-	-	73.0776 *** (p = 0.0001)
X4	-	0.1184 (p = 0.214)	18.9921 (p = 0.147)	20.3980 ** (p = 0.0499)
X2	-	-	0.000014 (p = 0.911)	0.000011 (p = 0.9232)
X3	-	-	0.2193 (p = 0.322)	0.2018 (p = 0.3477)
X5	-	-	−0.0087 (p = 0.801)	−0.0112 (p = 0.7195)

Significance level: * p < 0.10, ** p < 0.05, *** p < 0.01.

Analysis of the first model indicates that the variable describing the energy intensity of industry (X1) does not have a statistically significant impact on electricity prices (X4).

This means that in the panel data set under study, fluctuations in energy intensity do not translate into noticeable price dynamics for households. In the second model, a positive but still insignificant relationship was observed between X4 and the scale of energy poverty (Y), suggesting that energy prices, although theoretically capable of affecting the level of energy deprivation, are not in themselves a sufficient predictor of its intensity in panel terms.

Estimates within the fixed effects model (Model 3) confirm a clear and statistically significant strong relationship between X1 and Y, emphasising the dominance of the direct channel. At the same time, the lack of significance of the coefficient at X4 suggests that the indirect mechanism based on the impact of energy prices does not play a relevant role in this context. After applying a two-stage estimation (Model FE-IV), which corrects the endogeneity of X1 using an instrument based on labour productivity (X6), the strength of the impact of X1 on Y is further reinforced. However, in this case, the impact of X4 on energy poverty is statistically significant. After adjusting for the endogeneity of X1 (instrument X6) and controlling for X2–X5 and country fixed effects, X4 has a positive, marginally significant relationship with Y. However, it was found that X1 does not affect X4. Thus, hypothesis 4 cannot be confirmed. As a result, it can be concluded that the indirect mechanism assumed in hypothesis H4, although theoretically justified and consistent with economic intuition, is not clearly confirmed empirically in the analysed panel data for EU countries.

The hypothesis that energy prices might serve as a mediating variable on the relationship between industrial energy intensity and energy poverty was based on traditional energy-economic theory, implying that enhancements in energy efficiency upstream would result in a decrease in aggregate energy consumption and correspondingly lead to declines in wholesale and retail energy prices due to market forces. According to traditional energy-economic reasoning, it is assumed that enhancements in energy efficiency within energy-intensive industrial segments would help reduce stress on generation capacities and energy sources as well as on consumptions via networks. As a result, it would reduce stress on energy prices, impacting end-use sectors, including households. The highly regulated structure of electricity markets within the European Union and the various associated cost components and considerations make it somewhat difficult for any enhancements due to industrial energy efficiency gains to be transmitted directly within wholesale and retail energy sector price signals. The empirical findings contained within the current study, therefore, do not refute but instead highlight institutional factors leading to industrial efficiency gains and the subsequent impact on retail factors within the current EU institutional framework, effectively saying that institutional factors have led to a decoupling effect on retail energy prices.

To verify hypothesis H5, we examined whether the strength of the impact of industry energy intensity (X1) on energy poverty (Y) may vary depending on selected macroeconomic characteristics of countries, such as GDP per capita (X2), expenditure on social benefits (X3) or labour costs in the industrial sector (X5). In order to assess the validity of this assumption, the moderation tests were conducted for potential differentiating variables, namely X2, X3 and X5. For this purpose, for each moderating variable Z (Z∈{X2,X3,X5}), the following was estimated:

$$Y = \beta_1 X1 + \beta_2 Z + \beta_3 (X1 \times Z) + \beta_4 X_4 + \mu_i \quad (7)$$

First, three separate moderation tests were performed in the FE model (which acts as a diagnostic model) to check whether the moderation mechanism exists at all. The results of the analysis are shown in Table 9.

Table 9. Regression Results for H5: Moderation Analysis.

Variables (Interaction)	Interaction Coefficient β_3	Standard Error	t-Statistic	*p*-Value
X1 × X2	0.0031	0.0025	1.2495	0.2226
X1 × X3	5.2046	2.4039	2.1651	0.0397 **
X1 × X5	0.2346	0.1472	1.5934	0.1232

Significance level: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

The results of the estimates indicate that only variable X3 (expenditure on social benefits) shows a statistically significant moderating effect in the relationship X1 → Y, i.e., the impact of energy intensity of industry on the level of energy poverty. Analogous interactions with variables X2 and X5 are not statistically significant and therefore do not meet the empirical criterion for moderation of this effect. Since this moderating effect was only found for variable X3, in the next stage the moderating effect for the FE-IV model was calculated only for this variable. Thus, the endogenous variables are X1 and X1 × X3, and the instruments are X6 and X6 × X3. The results of the moderation analysis with instrumentation X1 and X1 × X3 are shown in Table 10.

Table 10. Results of the analysis for the FE-IV model—IV moderation with X1 and X1 × X3 instrumentation.

Variable	Coefficient	Standard Error	t-Statistic	*p*-Value
X1 (IV)	77.4467	15.9891	4.8437	0.0001 ***
X1 × X3 (IV)	5.4098	2.7467	1.9696	0.0596 *
X3	0.1797	0.2073	0.8672	0.3938
X2	0.00001338	0.0001	0.1226	0.9033
X4	20.9854	9.8973	2.1203	0.0437 **
X5	−0.0054	0.0308	−0.1756	0.8619

Significance level: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

The results of the analysis indicated that the value of coefficient X1, and thus its impact on energy poverty, remains statistically significant even after adding X2 as a key variable (although the significance would decrease—the standard error would increase). GDP per capita, despite being included in the model as a key variable, does not provide structural information and remains statistically insignificant as a determinant of energy poverty. Thus, the impact of GDP per capita (X2) is statistically insignificant, and this variable does not play an independent role in determining energy poverty (Y). The same applies to variable X3. Taking into account all the results, it should be concluded that hypothesis H5 is negatively verified. The results show that in the FE-IV model, the impact of energy intensity (X1) on energy poverty (Y) is stronger (which we already know from previous analyses), which is consistent with the endogeneity correction of X1. It was also found that the moderating effect of expenditure on social benefits (X3) is marginal (p = 0.0596), but weakens after instrumentation (in the FE model p = 0.0397). At the same time, the Fe model confirmed that variables X2 and X5 do not moderate the impact of X1 on Y (the *p*-value is high, which means that both variables are consistently statistically insignificant). The conclusion from hypothesis H4 that variable X4 affects Y (but independently of X1) was also confirmed. Therefore, the final conclusion is that only variable X3 shows an empirically justified role as a moderator of the X1–Y relationship, although this effect decreases after correcting for the endogeneity of X1 in the FE-IV model. Hypothesis H5 is therefore only partially confirmed, as variables X2 and X5 do not show moderating effects of energy intensity on energy poverty.

Hypothesis H6 assumed that an increase in real labour productivity in the industrial sector (X6) may indirectly reduce energy poverty (Y), primarily by reducing the energy intensity of industry (X1). To verify this mechanism, the relationships between X6 and X1 were analysed in the first stage of instrumental estimation, and in the second stage, in which X1 was replaced by forecast values (X1_hat), the results of which are presented in Tables 4–7. Table 11 presents the summary results for hypothesis H6.

Table 11. Regression results for H6 with indirect effect X6 → X1 → Y.

Model/Variable	Coefficient	*p*-Value	Interpretation
First stage: X1 ~ X6	−0.003532	0.000000	Labour productivity reduces energy intensity in the industrial sector
Second stage: Y ~ X1_hat	73.077569	0.000000	Cleansed of endogeneity, energy intensity strongly influences energy poverty.

In the first stage of model IV, in which the energy intensity of industry was explained by a set of economic variables and fixed effects for countries, labour productivity in industry (X6) shows a clearly negative and statistically strong relationship with energy intensity. This result means that economies with higher labour productivity are typically characterised by lower energy consumption per unit of value produced, which is confirmed both by energy economics theories and by many sectoral analyses.

In the second stage of estimation, which examined the impact of energy intensity adjusted for endogeneity on energy poverty, a positive and highly significant coefficient was obtained. This result suggests that the indirect channel of X6's impact on Y through a decrease in X1 is not only consistent with theoretical intuition but also clearly present in the data. Thus, an increase in productivity translates into a reduction in energy intensity, which in turn correlates with a decrease in energy poverty. This hypothesis has therefore been positively confirmed.

5. Discussion

The empirical results obtained in this study provide strong support for theoretical frameworks describing the relationship between technological efficiency, macroeconomic structure, and household energy deprivation. The robust negative association between industrial energy intensity and energy poverty is consistent with the foundational logic of the energy–economy nexus theory, which posits that improvements in system-wide energy efficiency reduce per-unit energy demand and thereby stabilise aggregate energy expenditures. In classical formulations of this framework, lower primary energy requirements translate into reduced cost pressures for downstream consumers, especially in economies where industrial sectors remain central to national energy balances. The FE and FE-IV estimates indicate that these theoretical expectations hold systematically across European Union Member States and that the mechanism is not merely correlational but reflects a causally meaningful relationship rooted in production-side technological change [97].

The results further align with the theory of endogenous growth, which emphasises the role of productivity and innovation in shaping long-term economic outcomes. In the present analysis, labour productivity in industry functions as an exogenous driver of improved energy efficiency [98–102]. The confirmed X6 → X1 → Y pathway demonstrates that productivity-induced efficiency gains diffuse beyond the industrial sector and help reduce the vulnerability of households to energy deprivation. This is consistent with the argument that technological upgrading within firms produces spillover effects in the broader economy by promoting resource optimisation and reducing structural inefficiencies. The strong significance of the instrumental variable reinforces the proposition, found in earlier theoretical work, that efficient production systems integrate labour-capital complementarities conducive to lower energy intensity.

At the same time, the heterogeneity observed in fixed effects supports socio-technical transition theories, particularly the multilevel perspective. This framework argues that energy systems evolve through interactions between technological regimes, institutional structures and consumer practices [103–106]. The wide divergence in baseline energy poverty levels across countries, despite similar directional effects of efficiency gains, confirms that structural features of national housing stock, climatic conditions, welfare institutions or market regulation shape the local manifestation of energy vulnerability. In this context, the study's finding that macroeconomic variables (income, social benefits and labour costs) do not significantly moderate the primary mechanism suggests that energy poverty is embedded in long-term structural determinants rather than short-term economic fluctuations. This is consistent with theories emphasising path dependency in energy and housing systems.

The absence of a statistically significant indirect effect through electricity prices appears to contradict classical energy price transmission models, which assume that efficiency gains reduce market prices for end-users [107–110]. However, this divergence can be explained by institutional price-setting mechanisms, regulated tariffs and the high share of non-energy components in retail electricity bills (taxes and network charges). The results therefore support theoretical approaches that treat energy poverty as a multidimensional socio-economic condition influenced not only by market forces but also by institutional and regulatory constraints. In line with energy justice theory, the study underscores that improving efficiency alone cannot guarantee affordability unless supported by equitable pricing structures and redistributive mechanisms.

Statistically insignificant, the coefficient associated with the labour costs in industry, X5, in Table 9. It suggests that higher unit labour costs do not go along with high levels of energy poverty. This effect is likely to reflect a structural correlation in which higher labour costs are characteristic of more advanced, high-productivity economies with better technological standards, stronger labour-market institutions, and higher average household incomes. In such contexts, high labour costs tend to go hand in hand with lower industrial energy intensity, greater stability in employment, and fiscal capacity for social and energy-related policies, all factors contributing indirectly to energy poverty being low.

More importantly, this X5 significance does not imply that there is any moderating influence of the correlates on the relationship between industrial energy intensity and energy poverty. This is supported by (a) the fact that its interaction effects are not significant and (b) the stability of the X1 coefficient across specifications, documenting that labour costs do not change the magnitude of the energy-intensity channel but capture broader structural features absorbed by country fixed effects. Therefore, X5 shall be understood as a contextual control reflecting the level of economic development and production structure, rather than an independent policy handle to reduce energy poverty. By clarifying this, the statistical significance of X5 is made consistent with the theoretical framework of this study, eliminating ambiguity in its interpretation.

It was also found that GDP per capita (X2) does not moderate the impact of energy intensity (X1) on energy poverty (Y), but such a moderating effect occurs in the case of social benefits expenditure (X3). The economic rationale for X3 moderating the impact of X1 on Y is that social benefits increase disposable income and thus reduce extreme poverty, as confirmed by the literature [50,73]. However, social benefits can simultaneously sustain high levels of energy consumption in households (no pressure to reduce energy consumption) and thus maintain energy demand across the economy during periods of price increases. If X1 increases, i.e., industry consumes more energy per unit of production, cost pressure in the energy sector increases, and with it prices, including energy prices. Households in high-transfer systems maintain their energy consumption for longer, which

makes them more exposed to cost increases, which in the long term causes energy poverty to increase across the economy as a whole. This is a classic mechanism from economic theory, whereby transfers stabilise consumption but increase exposure to energy price increases.

The results above can be related to both behavioural and socio-cognitive models of understanding consumption patterns with respect to energy in households [111–114]. It has been found that awareness about energy, value for the environment, and energy consumer segments can significantly impact the perception of energy-related forces by households. Thus, the structural parameter estimated in the panel models may be reinforced or moderated by behaviour-driven heterogeneity among the Member States, in line with theoretical frameworks establishing an interplay between economic drivers of energy poverty and household-level awareness and adaptation capabilities. This research can be helpful in creating structures for collaborative cooperation between governments and local institutions during energy transformation. Collaborative models of energy transformation are today the basis for a smooth transition from black energy to green energy at individual levels of society, provided they take into account integrated tools to mitigate the problems of the ongoing transformation [115].

The results imply that an active industrial policy addressing energy poverty needs to focus on structural changes regarding industrial energy efficiency, with a focus on technological progress in energy-intensive industries, instead of solely addressing price. From a policy perspective, there would be a focus on promoting technological advances and digital transformation in energy-intensive industries and on spreading energy-efficient technologies. Policies would include actions like investment tax credits for energy-saving capital, privileged loans for energy renovation and energy-intensive industries, as well as conditional state aid targeted at energy intensities. Importantly, it will be seen that these measures should be formulated on a structural and longitudinal timetable because these impacts on energy poverty are driven more by productivity and cost stabilisation effects than price.

The large degree of heterogeneity among Member States implies a territorially differentiated and institutionally coordinated approach to industrial policy and related social and energy policies. Within Member States with a large share of households with persistent energy poverty, there should be a consistency between industrial efficiency measures and labour market policies that improve skills and productivity, thus strengthening the indirect link from modernised industries to better welfare for households. Furthermore, because cost savings from energy efficiency do not automatically and necessarily lead to lower energy prices for households within the existing EU regulatory framework, additional policy tools are needed for mutual reinforcement. These additional tools include, inter alia, reinvesting a certain share of fiscal savings within energy systems related to industrial efficiency efforts into targeted support for households, renovation plans, or energy poverty alleviation actions. By taking an integrated policy approach, energy efficiency can be seen as an instrument not merely promoting a low-carbon society but having an intrinsic link with a just energy transition.

A proper limitation of the research would be that it still lacks a considerable amount of empirical analysis on the income mechanism, despite it being understood as the most realistic methodological explanation for changes caused in energy poverty given changes in industrial energy efficiency. As it stands, because it already probes into productivity changes via labour productivity and country characteristics, it does not address changes within income and changes within income distribution due to changes in industrial efficiency. However, as it stands, as a limitation and pertaining to the research methods and data available, there are no consistent sources available within the Member States of the EU regarding changes within disposable household income stratified per energy

vulnerability. However, as it stands, it should be determined that the impact of income would be associated with slow-moving structural changes within and due to productivity changes and associated changes within employment and fiscal adjustment, which would be absorbed within and shown within country fixed effects as opposed to marginal structural effects. A subsequent research stream would be applicable with regard to incorporating microdata on income.

6. Conclusions

The aim of the study was to assess, using panel data models, the impact of improving energy efficiency (using the energy intensity decline measure) in industry on the level of energy poverty in European Union countries, taking into account the macroeconomic environment (income, social, energy and labour market) in EU economies. To this end, panel data models were used for all 27 countries for the period 2003–2023. In pursuit of this objective, six research hypotheses were tested, analysing the impact of the decline in energy intensity, and thus the increase in energy efficiency, on the level of energy poverty measured as the percentage of households unable to keep their homes adequately warm. The testing of these hypotheses provided certain findings which also constitute the added value of this work.

The analysis indicated that:

- The energy intensity of industry is one of the key factors influencing energy poverty. The FE-IV result confirms that this relationship is not an artefact of endogeneity; on the contrary, after its removal, the impact of X1 becomes even stronger.
- High energy prices significantly worsen the situation of households. The stability of the X4 coefficient between models proves that energy pricing policy and amortisation mechanisms are of paramount importance for reducing energy poverty.
- Increased labour productivity indirectly reduces energy poverty. X6→X1→Y is an empirically confirmed channel: countries with higher industrial productivity are characterised by lower energy intensity and thus lower levels of energy poverty.

The article also provides recommendations for energy and economic policy. The results suggest that effective reduction in energy poverty should focus on increasing the energy efficiency of industry, supporting technological modernisation (increased labour productivity), stabilising energy prices for households, and investing in energy infrastructure. The variability between countries contained in the FEs indicates that this policy must be adapted to local structural conditions.

The first hypothesis (H1) indicated that a reduction in the energy intensity of industry leads to a statistically significant reduction in the level of energy poverty, which was positively verified. In both models, FE(HAC) and FE-IV, the coefficient of energy intensity is positive and highly statistically significant, showing that improving the energy efficiency of industry can significantly reduce energy poverty in the EU. Similarly, the second hypothesis (H2) was clearly confirmed. The impact of reducing the energy intensity of industry (X1) on energy poverty (Y) varies greatly between EU countries, although it exists in all countries. These differences persist in both the FE and FE-IV models, indicating deep structural national conditions. The endogeneity correction further highlights that the X1 → Y mechanism has different intensities depending on the country. It was also found that the macro variables X2–X5 are not directly significant in the FE–IV models (p-values: 0.94, 0.35, 0.12, 0.79), while their impact appears through fixed differences between countries (FE) and varying levels of energy intensity of industry in EU countries. The impact of energy intensity is modulated by structural national differences, although not directly by significant macroeconomic and social parameters (X2–X5). Another hypothesis (H3) was also positively verified. This is confirmed by the value of the X1 coefficient of 33.61 ($p < 0.001$)

in the FE model and 73.08 (p = 0.003) in the FE-IV model (cleaned of endogeneity). The fourth hypothesis (H4) was only partially confirmed. It was found that the indirect effect of the decline in energy intensity in industry on the reduction in energy poverty indirectly through the stabilisation of electricity prices exists and is economically meaningful but lacks statistical significance in the FE-IV model, even though the direction of the effect is correct. Changes in energy intensity do not translate into a statistically significant effect on electricity prices (after controlling for other factors and country fixed effects), even though the price of electricity has a positive, partially significant impact on energy poverty. There is therefore no confirmation that a decrease in energy intensity in industry reduces energy poverty indirectly through the stabilisation of energy prices. Hypothesis 5 (H5) found that the analysed data does not confirm that differences in the impact of energy intensity in industry on energy poverty are determined by changes in income levels or labour costs but can only be modified by social support. Therefore, they rather result from the social policy pursued by the state and deeper structural conditions specific to individual countries. Finally, hypothesis H6 was empirically confirmed. It was found that high labour productivity contributes to improving the energy efficiency of industry, which, by reducing energy costs and increasing the stability of the energy system, contributes to reducing the scale of energy poverty in the analysed countries.

In summary, it should be noted that improving energy efficiency in industrial sectors by reducing energy intensity may be an effective way to reduce energy poverty among households across the European Union. At the same time, it was found that the macroeconomic and social environment is a factor that differentiates this impact in individual countries, while on a community-wide scale, no statistically significant direct impact was found.

Undoubtedly, due to existing research limitations, there is room for further in-depth research on the subject. It was found that the chosen methodology was appropriate to address research issues and assess the significance of the topics discussed. The FE model controls for unobserved country-specific and time-specific effects, while the IV approach mitigates bias from endogenous regressors. The combination of these methods ensures robust and credible estimates of the impact of energy efficiency on energy poverty in the EU. However, future research could extend this analysis using dynamic panel models or additional instruments for robustness checks.

Various methodological and conceptual constraints apply to the study, which must be borne in mind when analysing the findings. The data used is a panel dataset covering the period 2003–2023, subject to limitations imposed by the Eurostat datasets available, which may fail to reflect the minute fluctuations in energy demand, resilience, and sectoral shock effects on energy intensity for industry.

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References

1. Rios-Ocampo, M.A.; Romero, J.C.; Centeno, E.; Mora, S. A just energy transition is not just a transition: Framing energy justice for a quantitative assessment. *Energy Res. Soc. Sci.* **2025**, *119*, 103900. [CrossRef]
2. Simionescu, M.; Radulescu, M.; Cifuentes-Faura, J.; Balsalobre-Lorente, D. The role of renewable energy policies in TACKLING energy poverty in the European UNION. *Energy Policy* **2023**, *183*, 113826. [CrossRef]
3. Carfora, A.; Minervini, L.F.; Scandurra, G. Fiscal incentives for energy poverty in Italy: Bridging the gap or missing the mark? *Energy Res. Soc. Sci.* **2025**, *126*, 104161. [CrossRef]
4. Stojilovska, A.; Guyet, R.; Mahoney, K.; Gouveia, J.P.; Castaño-Rosa, R.; Živčič, L.; Barbosa, R.; Tkalec, T. Energy poverty and emerging debates: Beyond the traditional triangle of energy poverty drivers. *Energy Policy* **2022**, *169*, 113181. [CrossRef]
5. Tang, J.; Zhao, P.; Gao, Y. Can smart energy alleviate energy poverty in China?–Empirical evidence using synthetic control methods. *J. Clean. Prod.* **2024**, *449*, 141821. [CrossRef]
6. Zhang, L.; Xiong, G.; Ni, R.; Chiu, Y.; Pang, Q.; Shi, Z.; Wang, X. Improving energy-related efficiency towards SDG7 in China: What role does energy poverty play? *J. Environ. Manag.* **2024**, *369*, 122289. [CrossRef] [PubMed]
7. Nordensvärd, J.; Björklund, M.; von Malmborg, F.; La Fleur, L.; Skogsmo, E.; Gamez, D.H.B. Reviewing the EU policy nexus of energy efficiency and social policy. *Renew. Sustain. Energy Rev.* **2025**, *224*, 116128. [CrossRef]
8. Pillai, A.; Reaños, M.T.; Curtis, J. An examination of energy efficiency retrofit scheme applications by low-income households in Ireland. *Heliyon* **2021**, *7*, e08205. [CrossRef]
9. Osuma, G.; Oyetayo, O.; Martins, B.O.; Ohonba, A. Does financial inclusion grease or sand the wheels of energy poverty in Africa? The role of governance and infrastructure. *Sustain. Futures* **2025**, *10*, 101161. [CrossRef]
10. Mucedero, G.; Monteiro, R. An integrated regional prioritisation framework for seismic and energy-efficiency performance upgrading of residential buildings. *Int. J. Disaster Risk Reduct.* **2024**, *103*, 104341. [CrossRef]
11. Barroco Fontes Cunha, F.; Carani, C.; Nucci, C.A.; Castro, C.; Santana Silva, M.; Andrade Torres, E. Transitioning to a low carbon society through energy communities: Lessons learned from Brazil and Italy. *Energy Res. Soc. Sci.* **2021**, *75*, 101994. [CrossRef]
12. Nagaj, R.; Vasilev, J.; Žuromskaitė-Nagaj, B. Hierarchical modelling of sustainable energy consumption profiles for developed and developing countries. *Intellect. Econ.* **2025**, *19*, 234–259. [CrossRef]
13. Halkos, G.; Moll de Alba, J.; Todorov, V. Analyzing manufacturing sector and selected development challenges: A panel data analysis. *Energy* **2021**, *235*, 121253. [CrossRef]
14. Li, R.; Li, L.; Wang, Q. The impact of energy efficiency on carbon emissions: Evidence from the transportation sector in Chinese 30 provinces. *Sustain. Cities Soc.* **2022**, *82*, 103880. [CrossRef]
15. Gajdzik, B.; Wolniak, R.; Nagaj, R.; Žuromskaitė-Nagaj, B.; Grebski, W.W. The Influence of the Global Energy Crisis on Energy Efficiency: A Comprehensive Analysis. *Energies* **2024**, *17*, 947. [CrossRef]
16. Dong, K.; Jiang, Q.; Shahbaz, M.; Zhao, J. Does low-carbon energy transition mitigate energy poverty? The case of natural gas for China. *Energy Econ.* **2021**, *99*, 105324. [CrossRef]
17. Cao, Y.; Guo, L.; Qu, Y. Evaluating the dynamic effects of mitigation instruments on CO_2 emissions in China's nonferrous metal industry: A vector autoregression analysis. *Sci. Total Environ.* **2022**, *853*, 158409. [CrossRef] [PubMed]
18. Shehzadi, A. Energy efficiency and productivity in emerging and developing Asian countries: A firm level analysis. *J. Asian Econ.* **2023**, *88*, 101653. [CrossRef]
19. Ai, M.; Zhang, W.; Du, S.; Yu, X.; Bu, Y. The impact of digitalization on the green transformation of China's industrial sectors: The mediating role of green technology innovation and technological transformation. *Int. Rev. Econ. Financ.* **2024**, *96*, 103736. [CrossRef]
20. Gajdzik, B.; Wolniak, R.; Grebski, W.W. Structural Drivers of Poland's Renewable Energy Transition (2010–2023): Empirical Insights from Regression and Cluster Analysis. *Energies* **2025**, *18*, 4754. [CrossRef]
21. Orshansky, M. Counting the Poor: Another Look at the Poverty Profil. *Soc. Secur. Bull.* **1965**, *28*, 3–29.
22. Orshansky, M. How poverty is measured. *Mon. Labor Rev.* **1969**, *92*, 44–49.
23. Boardman, B. Fuel poverty is different. *Policy Stud.* **1991**, *12*, 30–41. [CrossRef]
24. Abdoulaye Sy, S.; Mokaddem, L. Energy poverty in developing countries: A review of the concept and its measurements. *Energy Res. Soc. Sci.* **2022**, *89*, 102562. [CrossRef]
25. Winkler, H.; Simões, A.F.; de la Rovere, E.L.; Alam, M.; Rahman, A.; Mwakasonda, S. Access and affordability of electricity in developing countries. *World Dev.* **2011**, *39*, 1037–1050. [CrossRef]
26. United Nations, Department of Economic and Social Affairs. *Sustainable Development Goal 7: Ensure Access to Affordable, Reliable, Sustainable and Modern Energy for All*; United Nations: New York, NY, USA, 2015. Available online: https://sdgs.un.org/goals/goal7 (accessed on 10 November 2025).
27. United Nations. *The Sustainable Development Goals Report 2025*; United Nations: New York, NY, USA, 2020. Available online: https://unstats.un.org/sdgs/report/2025/ (accessed on 10 November 2025).

28. United Nations Framework Convention on Climate Change (UNFCCC). *Paris Agreement*; FCCC/CP/2015/L.9/Rev.1; United Nations: Paris, France, 2015.
29. European Commission. *The European Green Deal*; European Union: Brussels, Belgium, 2019. Available online: https://ec.europa.eu/info/sites/default/files/european-green-deal-communication_en.pdf (accessed on 10 November 2025).
30. European Commission. *A Clean Industrial Deal for the EU*; European Union: Brussels, Belgium, 2023. Available online: https://commission.europa.eu/ (accessed on 10 November 2025).
31. European Commission. *Energy Poverty*; European Union: Brussels, Belgium, 2018. Available online: https://energy.ec.europa.eu/topics/markets-and-consumers/energy-consumers-and-prosumers/energy-poverty_en (accessed on 20 November 2025).
32. Nagaj, R. Green Deal as one of the determinants of energy poverty. *Sci. Pap. Silesian Univ. Technology. Organ. Manag. Ser.* **2024**, *208*, 420–434. [CrossRef]
33. Ghosh, A. Decoding energy poverty: Rural-urban disparities and structural barriers in BRICS countries. *Front. Environ. Econ.* **2025**, *4*, 1552502. [CrossRef]
34. Ben Cheikh, N.; Ben Zaied, Y.; Nguyen, D.K. Understanding energy poverty drivers in Europe. *Energy Policy* **2023**, *183*, 113818. [CrossRef]
35. Slabe-Erker, R.; Zabavnik, D.; Dominko, M.; Primc, K. Can Macroeconomic Projections Predict Energy Poverty? Available online: https://ssrn.com/abstract=4926347 (accessed on 10 November 2025).
36. Primc, K.; Slabe-Erker, R.; Majcen, B. Energy poverty: A macrolevel perspective. *Sustain. Dev.* **2019**, *27*, 982–989. [CrossRef]
37. Touray, A.; Hao, Y. Bridging the energy gap: Macro-drivers of access-based energy poverty in West Africa. *Energy Econ.* **2025**, *148*, 108707. [CrossRef]
38. Lisicki, J.; Miazga, A.; Owczarek, M. Impact of the macroeconomic factors on the level of energy poverty—Case of the Czech Republic, Poland and Slovakia. *Econ. Environ.* **2024**, *90*, 836. [CrossRef]
39. Wolde-Rufael, Y. Electricity consumption and economic growth: A time series experience for 17 African countries. *Energy Policy* **2006**, *34*, 1106–1114. [CrossRef]
40. Rancilio, G.; Campagna, L.; Ricci, M.; Sdringola, P.; Merlo, M. Geospatial energy poverty assessment and clustering for policy prioritization. *Energy Policy* **2026**, *210*, 115047. [CrossRef]
41. Gajdzik, B.; Sroka, W.; Vveinhardt, J. Energy Intensity of Steel Manufactured Utilising EAF Technology as a Function of Investments Made: The Case of the Steel Industry in Poland. *Energies* **2021**, *14*, 5152. [CrossRef]
42. Qi, X.; Chen, J.; Wang, J.; Liu, H.; Ding, B. The impact of urbanization on the alleviation of energy poverty: Evidence from China. *Cities* **2024**, *151*, 105130. [CrossRef]
43. Ali, M. Urbanization and energy consumption in sub-Saharan Africa. *Electr. J.* **2021**, *34*, 107045. [CrossRef]
44. Dokupilová, D.; Stojilovska, A.; Palma, P.; Gouveia, J.P.; Paschalidou, E.G.; Barrella, R.; Feenstra, M.; Horta, A.; Sánchez-Guevara, C.; Kádár, J.; et al. Exploring Energy Poverty in Urban and Rural Contexts in the Era of Climate Change: A Comparative Analysis of European Countries and Israel. *Energies* **2024**, *17*, 2939. [CrossRef]
45. Marcoje, B.M.; Hallack, M.; Schiavon, L.D.C.; Machado, D.C.; Abreu, M.W.D. Energy poverty in Brazil: A look at access to energy services. *Dev. Sustain. Econ. Financ.* **2026**, *9*, 100103. [CrossRef]
46. Acharya, R.H.; Sadath, A.C. Energy poverty and economic development: Household-level evidence from India. *Energy Build.* **2019**, *183*, 785–791. [CrossRef]
47. Djeunankan, R.; Tadadjeu, S.; Kamguia, B. Linking energy poverty and industrialization: Empirical evidence from African countries. *Energy* **2024**, *292*, 130374. [CrossRef]
48. Tamasiga, P.; Onyeaka, H.; Altaghlibi, M.; Bakwena, M.; Ouassou, E. Empowering communities beyond wires: Renewable energy microgrids and the impacts on energy poverty and socio-economic outcomes. *Energy Rep.* **2024**, *12*, 4475–4488. [CrossRef]
49. Lehtonen, O.; Hiltunen, A.P.; Okkonen, L.; Blomqvist, K. Emerging spatial clusters of energy poverty vulnerability in rural Finland—Byproducts of accumulated regional development. *Energy Res. Soc. Sci.* **2024**, *109*, 103418. [CrossRef]
50. García-Vaquero, M.; Daumann, F.; Sánchez-Bayón, A. European Green Deal, Energy Transition and Greenflation Paradox under Austrian Economics Analysis. *Energies* **2024**, *17*, 3783. [CrossRef]
51. Abel, P.; Münchmeyer, M. Energy Solidarity: Channelling and Restraining Legal Power in the Transition of the Energy Sector for a Successful European Green Deal. *Rev. Eur. Adm. Law* **2025**, *18*, 73–99. [CrossRef]
52. Jayalath, A.; Vaz-Serra, P.; Hui, F.K.P.; Aye, L. Thermally comfortable energy efficient affordable houses: A review. *Build. Environ.* **2024**, *256*, 111495. [CrossRef]
53. Bollino, C.A.; Botti, F. Energy poverty in Europe: A multidimensional approach. *PSL Quarterly Review. Econ. Civ.* **2017**, *70*, 473–507. [CrossRef]
54. Bouzarovski, S. Energy poverty in the European Union: Landscapes of vulnerability. *Wiley Interdiscip. Rev. Energy Environ.* **2014**, *3*, 276–289. [CrossRef]
55. Nagaj, R.; Gajdzik, B.; Wolniak, R.; Grebski, W.W. The Impact of Deep Decarbonization Policy on the Level of Greenhouse Gas Emissions in the European Union. *Energies* **2024**, *17*, 1245. [CrossRef]

56. Lu, S.; Ren, J. A comprehensive review on energy poverty: Definition, measurement, socioeconomic impact and its alleviation for carbon neutrality. *Environ. Dev. Sustain.* **2025**, *27*, 23889–23907. [CrossRef]
57. Awdziej, M.; Dudek, D.; Gajdzik, B.; Jaciow, M.; Lipowska, I.; Lipowski, M.; Tkaczyk, J.; Wolniak, R.; Wolny, R. Energy Efficiency Starts in the Mind: How Green Values and Awareness Drive Citizens' Energy Transformation. *Energies* **2025**, *18*, 4331. [CrossRef]
58. Gajdzik, B.; Nagaj, R.; Wolniak, R.; Bałaga, D.; Žuromskaitė, B.; Grebski, W.W. Renewable Energy Share in European Industry: Analysis and Extrapolation of Trends in EU Countries. *Energies* **2024**, *17*, 2476. [CrossRef]
59. Halkos, G.E.; Aslanidis, P.-S.C. Green Energy Pathways Towards Carbon Neutrality. *Environ. Resour. Econ.* **2024**, *87*, 1473–1496. [CrossRef]
60. Wysokińska, Z. Energy Policy in the European Union within the European Green Deal Strategy. *Comp. Econ. Res.* **2024**, *27*, 73–91. [CrossRef]
61. Certomà, C.; Corsini, F.; Di Giacomo, M.; Guerrazzi, M. Beyond Income and inequality: The Role of Socio-Political Factors for Alleviating Energy Poverty in Europe. *Soc. Indic. Res.* **2023**, *169*, 167–208. [CrossRef]
62. Gielen, D.; Wagner, N.; Johnson, L. The role of renewable energy in the global energy transformation. *Energy Strategy Rev.* **2019**, *24*, 38–50. [CrossRef]
63. Ozturk, I.; Aslan, A.; Kalyoncu, H. Energy consumption and economic growth relationship: Evidence from panel data for low and middle income countries. *Energy Policy* **2010**, *38*, 4422–4428. [CrossRef]
64. Environmental and Energy Study Institute (EESI). *Energy Efficiency*; Environmental and Energy Study Institute: Washington, DC, USA, 2001. Available online: https://www.eesi.org/ (accessed on 20 November 2025).
65. Li, R.; Xin, Y.; Sotnyk, I.; Kubatko, O.; Almashaqbeh, I.; Fedyna, S.; Prokopenko, O. Energy poverty and energy efficiency in emerging economies. *Int. J. Energy Environ. Policy* **2022**, *69*, 1–21. [CrossRef]
66. Zhang, J.; Liu, Y.; Zhang, W.; Lin, X. Study on the Impact of Energy Poverty on Energy Efficiency of Construction Industry: Mediating Role of Energy Consumption Structure. *Front. Energy Res.* **2021**, *9*, 760895. [CrossRef]
67. Janikowska, O.J. Energy transition versus energy poverty in post-mining regions: Case study Poland, Greece, and Bulgaria. *Miner. Resour. Manag.* **2024**, *40*, 185–206. [CrossRef]
68. Streimikiene, D.; Kyriakopoulos, G.L.; Lekavicius, V.; Siksnelyte-Butkiene, I. Energy poverty and low-carbon just energy transition: Comparative study in Lithuania and Greece. *Soc. Indic. Res.* **2021**, *158*, 319–371. [CrossRef]
69. Nagaj, R. Macroeconomic Policy Versus Fuel Poverty in Poland—Support or Barrier. *Energies* **2022**, *15*, 4710. [CrossRef]
70. Etensa, T.; Alemu, T.; Yayo, M.; Negash, T. Toward sustainable solutions: Green energy poverty, energy justice, and environmental degradation in Ethiopia with moderating effects and countershock simulations. *Sustain. Futures* **2026**, *11*, 101587. [CrossRef]
71. Onwe, J.C.; Dhayal, K.S.; Ogwu, S.O.; Joseph, T.E. Striking the balance: Climate change, energy poverty, and inclusive growth in developing countries. In *Encyclopedia of Monetary Policy, Financial Markets and Banking*, 1st ed.; Apergis, N., Ed.; Academic Press: London, UK, 2025; pp. 479–486. [CrossRef]
72. Rodriguez-Alvarez, A.; Llorca, M.; Jamasb, T. Alleviating energy poverty in Europe: Front-runners and laggards. *Energy Econ.* **2021**, *103*, 105575. [CrossRef]
73. Nagaj, R. Climate and energy policies and its impact on energy poverty in Poland [Polityka klimatyczno-energetyczna a ubóstwo energetyczne w Polsce]. *Rynek Energii* **2020**, *146*, 3–10.
74. Wen, J.; Liu, M.; He, L. The driving factors of CO_2 emissions in China's resource processing industry: Evidence from an income-based accounting perspective. *Environ. Impact Assess. Rev.* **2026**, *118*, 108277. [CrossRef]
75. Zhang, M.; Tan, S.; Pan, Z.; Hao, D.; Zhang, X.; Chen, Z. The spatial spillover effect and nonlinear relationship analysis between land resource misallocation and environmental pollution: Evidence from China. *J. Environ. Manag.* **2022**, *321*, 115873. [CrossRef]
76. Wang, C.-N.; Nhieu, N.-L.; Ye, Y.-C. A Regret-Enhanced DEA Approach to Mapping Renewable Energy Efficiency in Asia's Growth Economies. *Algorithms* **2025**, *18*, 297. [CrossRef]
77. Liao, N.; He, Y. Exploring the effects of influencing factors on energy efficiency in industrial sector using cluster analysis and panel regression model. *Energy* **2018**, *158*, 782–795. [CrossRef]
78. Macharia, K.K.; Gathiaka, J.K.; Ngui, D. Energy efficiency in the Kenyan manufacturing sector. *Energy Policy* **2022**, *161*, 112715. [CrossRef]
79. Eurostat. *Inability to Keep Home Adequately Warm*; Eurostat: Luxembourg, 2022. Available online: https://ec.europa.eu/eurostat/databrowser/view/ILC_MDES01__custom_18806689/default/table (accessed on 8 November 2025). [CrossRef]
80. Eurostat. *Simplified Energy Balances*; Eurostat: Luxembourg, 2021. [CrossRef]
81. Eurostat. *Gross Value Added and Income by Detailed Industry (NACE Rev.2)*; Eurostat: Luxembourg, 2018.
82. Eurostat. *Real GDP per Capita*; Eurostat: Luxembourg, 2008. [CrossRef]
83. Eurostat. *Expenditure on Social Benefits by Function*; Eurostat: Luxembourg, 2023. [CrossRef]
84. Eurostat. *Electricity Prices for Domestic Consumers—Bi-Annual Data (Until 2007)*; Eurostat: Luxembourg, 2007. [CrossRef]
85. Eurostat. *Electricity Prices for Household Consumers—Bi-Annual Data (from 2007 Onwards)*; Eurostat: Luxembourg, 2007. [CrossRef]
86. Eurostat. *Labour Productivity and Unit Labour Costs by Industry (NACE Rev.2)*; Eurostat: Luxembourg, 2022. [CrossRef]

87. Bajrami, R.; Tafa, S.; Gashi, A.; Hashani, M. Analysing the impact of money supply on economic growth: A panel regression approach for Western Balkan countries (2000–2023). *Reg. Sci. Policy Pract.* **2025**, *17*, 100159. [CrossRef]
88. Ban, G.; Chankoson, T.; Wang, Y. The impact of public policy on enterprise innovation performance: Panel data on financial subsidy policy. *Heliyon* **2025**, *11*, e41230. [CrossRef] [PubMed]
89. Mai, S.; Qing, L.; Mehmood, U.; Almulhim, A.A.; Aljughaiman, A.A. From digital advancement to SDGs disruption: How artificial intelligence without inclusion threatens sustainable development in G7 economies. *J. Environ. Manag.* **2025**, *394*, 127411. [CrossRef] [PubMed]
90. Yang, Y.; Zhang, J.; Li, Y. The effects of environmental information disclosure on stock price synchronicity in China. *Heliyon* **2023**, *9*, e16271. [CrossRef]
91. Quiroga, S.; Suárez, C.; Santos-Arteaga, F.J.; Rodrigo, J.M. Do common agricultural policy subsidies matter for the market-environment trade off? An evaluation of R&D objectives and decisions across farmers. *J. Agric. Food Res.* **2024**, *15*, 101047. [CrossRef]
92. Ferilli, G.B.; Palmieri, E.; Miani, S.; Stefanelli, V. The impact of FinTech innovation on digital financial literacy in Europe: Insights from the banking industry. *Res. Int. Bus. Financ.* **2024**, *69*, 102218. [CrossRef]
93. Leung, C.K.; Ko, J.; Guo, C. Weathering the storm: Analyzing the impact of extreme climate events on energy consumption across 141 countries. *Innov. Green Dev.* **2025**, *4*, 100255. [CrossRef]
94. Xu, Q.; Ruan, C.; Jiang, C.; Zhao, Q. The impact of ESG performance on debt financing costs from the perspective of supply chain. *Q. Rev. Econ. Financ.* **2025**, *104*, 102064. [CrossRef]
95. McCulloch, J.H. Moment Ratio estimation of autoregressive/unit root parameters and autocorrelation-consistent standard errors. *Comput. Stat. Data Anal.* **2016**, *100*, 712–733. [CrossRef]
96. Zhao, X.; Du, D.; Xiong, J.; Springer, A.; Lopez, S.R.M.; Winkler, B.; Hubler, K. The impact of forest restoration on agriculture in the Verde River watershed, Arizona, USA. *For. Policy Econ.* **2019**, *109*, 101999. [CrossRef]
97. Gajdzik, B.; Jaciow, M.; Wolniak, R.; Wolny, R.; Grebski, W.W. Assessment of Energy and Heat Consumption Trends and Forecasting in the Small Consumer Sector in Poland Based on Historical Data. *Resources* **2023**, *12*, 111. [CrossRef]
98. Yuan, F.; Zhang, P. Are natural resources, sustainable growth and entrepreneurship matter endogenous growth theory? The strategic role of technical progress. *Resour. Policy* **2024**, *96*, 105189. [CrossRef]
99. Jiao, P.; Liu, Y.; Li, S. Exploring the impacts of technological innovation on industrial structural transformation: An analysis based on the Schumpeterian endogenous growth theory. *Contemp. Soc. Sci.* **2024**, *9*, 17–39.
100. Wang, X. Theory and model optimisation of rural creative economy development in less developed regions based on endogenous growth model. *Appl. Math. Nonlinear Sci.* **2024**, *9*, 1–16. [CrossRef]
101. Cozzi, G. Semi-endogenous or fully endogenous growth? A unified theory. *J. Econ. Theory* **2023**, *213*, 105732. [CrossRef]
102. Jianping, D. Mechanism and path of integrated development of industrial Internet and manufacturing from the perspective of endogenous growth theory. In Proceedings of the 14th International Conference on E-Education, E-Business, E-Management and E-Learning (IC4E 2023), ACM International Conference Proceeding Series, Shenzhen, China, 1–4 February 2023; pp. 251–255.
103. Konishi, T. Corrigendum to "Dynamic analysis of patent policy in an endogenous growth model". *J. Econ. Theory* **2022**, *204*, 105521. [CrossRef]
104. Klein, M.A. The reward and contract theories of patents in a model of endogenous growth. *Eur. Econ. Rev.* **2022**, *147*, 104178. [CrossRef]
105. Gajdzik, B.; Jaciow, M.; Wolny, R. Types of E-Consumers and Their Implications for Sustainable Consumption—A Study of the Behavior of Polish E-Consumers in the Second Decade of the 21st Century. *Sustainability* **2023**, *15*, 12647. [CrossRef]
106. Gajdzik, B.; Jaciow, M.; Hoffmann-Burdzińska, K.; Wolny, R.; Wolniak, R.; Grebski, W.W. Impact of Economic Awareness on Sustainable Energy Consumption: Results of Research in a Segment of Polish Households. *Energies* **2024**, *17*, 2483. [CrossRef]
107. Libertson, F. Misalignments of theory and practice: Exploring Swedish energy utilities' understandings of energy justice, flexibility capital, and just energy transitions. *Energy Res. Soc. Sci.* **2024**, *111*, 103471. [CrossRef]
108. Bombaerts, G.; Spahn, A.; Laes, E. Structuring values and normative frameworks using Schwartz's value theory to map the three tenets of energy justice. *Energy Res. Soc. Sci.* **2023**, *104*, 103244. [CrossRef]
109. Santos Ayllón, L.M.; Jenkins, K.E.H. Energy justice, Just Transitions and Scottish energy policy: A re-grounding of theory in policy practice. *Energy Res. Soc. Sci.* **2023**, *96*, 102922. [CrossRef]
110. Rezaei, N.; Fattahi Meyabadi, A.; Deihimi, M. A game theory based demand-side management in a smart microgrid considering price-responsive loads via a twofold sustainable energy justice portfolio. *Sustain. Energy Technol. Assess.* **2022**, *52*, 102273. [CrossRef]
111. Vogel, R.; Vogel, D.; Liegat, M.C.; Hensel, D. From social categorization to implicit citizenship theories: Advancing the socio-cognitive foundations of state–citizen interactions. *Public Adm. Rev.* **2025**, *85*, 402–418. [CrossRef]

112. Kumar, U.P.S.; Jaiswal, C.; Kumar, N.; Ahmad, M.; Suresh, S. Understanding cognitive pathways of unethical pro-organizational behaviour: Insights from socio-cognitive theories and counteractive interventions. In *Principles and Clinical Interventions in Social Cognition*; IGI Global: Hershey, PA, USA, 2024; pp. 325–343.
113. Rašković, M.; Haynes, K.T.; Vangeli, A. The emergence of populism as an institution and its recursive mechanisms: A socio-cognitive theory perspective. *J. Int. Bus. Policy* **2024**, *7*, 19–40. [CrossRef]
114. Matović, B.; Petrović, A.; Damjanović, M.; Bulajić, A.; Ilić, V. Socio-cognitive determinants of pedestrians' intention to cross on a red light signal: An application of the theory of planned behaviour. *Safety* **2024**, *10*, 33. [CrossRef]
115. Zhou, C.; Richardson-Barlow, C.; Fan, L.; Cai, H.; Zhang, W.; Zhang, Z. Towards organic collaborative governance for a more sustainable environment: Evolutionary game analysis within the policy implementation of China's net-zero emissions goals. *J. Environ. Manag.* **2025**, *373*, 123765. [CrossRef] [PubMed]

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