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AUTHORS

Liliana Smiech
Tetiana Kurbatova
Oleksandra Kubatko
Iryna Sotnyk
Galyna Trypolska
Tetiana Perederii

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Liliana Śmiech (Hungary), **Tetiana Kurbatova** (Ukraine), **Oleksandra Kubatko** (Ukraine), **Iryna Sotnyk** (Switzerland, Ukraine), **Galyna Trypolska** (Ukraine), **Tetiana Perederii** (Ukraine)

ASSESSING THE IMPACT OF HOUSEHOLD ENERGY EFFICIENCY AND RENEWABLE ENERGY DEVELOPMENTS ON ENERGY POVERTY REDUCTION

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Liliana Śmiech, Ph.D. Candidate, Faculty of Economics and Business, Széchenyi István University, Hungary. (Corresponding author)

Tetiana Kurbatova, Ph.D. in Economics, Associate Professor, Department of International Economic Relations, Sumy State University, Ukraine.

Oleksandra Kubatko, Ph.D. in Economics, Associate Professor, Department of Economics, Entrepreneurship and Business Administration, Sumy State University, Ukraine.

Iryna Sotnyk, D.Sc. in Economics, Professor, Renewable Energy Systems group, University of Geneva, Switzerland; Department of Economics, Entrepreneurship, and Business Administration, Sumy State University, Ukraine.

Galyna Trypolska, Ph.D. in Economics, Senior Research Fellow, State Organization "Institute for Economics and Forecasting of the National Academy of Sciences of Ukraine", Ukraine.

Tetiana Perederii, Ph.D. Student, Sumy State University, Ukraine.

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Abstract

The paper aims to develop and adapt an econometric model for assessing and forecasting the impact of household energy efficiency and renewable energy deployment on reducing energy poverty in Ukraine. Due to the lack of updated statistical data after 2022 caused by the war, the adapted model was tested using pre-war data from the State Statistics Service of Ukraine and the World Bank for 2002–2021. As access to some pre-war datasets was also restricted for security reasons in Ukraine, proxy indicators were applied, allowing adaptation to limited information conditions. The modeling results showed that a 1,000 USD increase in GDP per capita reduces the share of the population living below the national poverty line and, accordingly, the energy-poor population, by 3%. Conversely, a 1% increase in gross capital formation raises the energy poverty level by 0.5%, indicating no direct impact of investment in physical capital, including expenses on energy-efficiency measures, on household welfare. Household expenditures on utilities and the share of renewable energy in total energy consumption were found to be statistically insignificant. The study confirms that household income remains the dominant determinant of energy poverty, while improvements in energy efficiency and renewable energy development play supportive but not yet decisive roles. These findings highlight the need to integrate social and energy policies to raise household incomes, improve access to renewable technologies, and promote energy efficiency measures. The developed model offers a tool for enhancing state policies to alleviate energy poverty under wartime constraints and in post-war recovery.

Keywords renewable energy, energy efficiency, energy poverty, households, Ukraine

JEL Classification Q42, Q48, Q58, C51

INTRODUCTION

Energy poverty is among the major socio-economic challenges, and addressing it is essential for ensuring social stability, the well-being of the population, and sustainable development. The depletion of non-renewable energy resources and rising energy prices drive governments to develop new approaches to energy policy that guarantee affordable access to energy for households. This problem is especially relevant for developing countries and transition economies, Ukraine in particular, where the low income level of the population is combined with the high energy intensity of the housing stock and the insufficient development of energy-efficient technologies and renewable power systems (Pysmenna & Trypolska, 2020).

The private household sector plays one of the key roles in the process of the green energy transition (Sotnyk et al., 2022). On the one hand,

households can reduce their energy costs by implementing energy-saving measures. On the other hand, they are highly vulnerable to fluctuations in energy prices, which makes the issue of energy poverty and social inequality even more pressing. Therefore, the formation of an effective energy policy in this sector requires a comprehensive consideration of both economic and behavioral factors that influence the level of energy consumption.

The implementation of measures for energy efficiency and the development of renewable power in the residential sector can significantly reduce household energy costs in the medium and long term (Ameli & Brandt, 2015). This contributes to strengthening energy security and reducing the social vulnerability of the population. However, the green energy transition in households in developing countries and transition economies often faces a number of challenges related to the high cost of implementing innovative energy technologies, limited access to financial resources and credit programs, as well as insufficient public awareness of the benefits of such technologies (Kurbatova et al., 2024). For Ukraine, an additional serious challenge became the Russian military invasion, which led to large-scale destruction of energy infrastructure, instability of power supply, and increased risks for investments in energy-efficient technologies and renewable energy.

1. THEORETICAL FRAMEWORK

Most modern studies consider energy poverty as the result of the interaction of three key factors: low energy efficiency of the housing stock, limited income levels of the population, and high energy prices (Scarpellini et al., 2015; Stojilovska et al., 2022; Thomson et al., 2017; Naumenkova et al., 2024). The above factors form the so-called "vicious circle of poverty", where insufficient household income renders investment in energy-saving measures unaffordable, while the absence of such measures results in low energy efficiency in housing. Therefore, the level of energy consumption increases, leading to higher household energy costs and, consequently, a further decrease in real income. Table 1 presents national approaches to defining energy poverty of the population.

Table 1. National definitions and issues of energy poverty among the population in selected European countries

Source: EU (2016), Pye et al. (2015a).

Country	Definition
Cyprus	Energy poverty may affect consumers who find themselves in a difficult situation due to a low income level (as evidenced by tax returns), combined with their professional status, family circumstances, or health condition. Consequently, they are unable to cover their electricity (or energy) costs, as these expenses constitute a significant portion of their budget
France	Energy poverty is defined as a condition in which a person faces significant difficulties in ensuring an adequate level of energy supply in his/her home to meet basic needs, which is primarily due to the insufficiency of financial resources
Ireland	Energy poverty is viewed as a situation where households are unable to sufficiently cover their level of energy consumption due to limited access to utility services (heating, lighting, etc.) at affordable prices, and where expenditures for energy bills exceed 10% of available income
Italy	A household is considered to be in energy poverty if its electricity payment expenses exceed 5% of available income, and expenses for consumed natural gas exceed 10%
The United Kingdom	A household is considered to be in energy poverty if: 1) its income is lower than the poverty line (considering energy expenditures); 2) its energy expenditures are higher than the typical level for this type of household. The "low income – high costs" indicator is based on two criteria: 1) energy expenditures exceed the average level; 2) residual income after paying for energy is lower than the official poverty line. Meanwhile, in England, the 10% threshold continues to be used, according to which, "a household is in a state of fuel poverty if it is forced to spend more than 10% of its income on energy required to heat the dwelling to an appropriate temperature (21°C in the main living area and 18°C in other rooms)"
Slovakia	Energy poverty is defined as a state in which a household's average monthly expenditures on electricity, gas, and heat supply constitute a significant share of its average monthly income. A household is considered energy poor if its monthly disposable income is lower than the established minimum household income threshold. The corresponding threshold values are published on the website of the Ministry of Labor, Social Affairs and Family of the Slovak Republic, as well as on platforms related to labor issues, social protection, municipalities, and local self-government bodies

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It is worth noting that the scientific literature also includes studies with a broader interpretation of the concept of energy poverty, considering not only financial aspects but also social and environmental conditions. Thus, Bouzarovski (2018) states that energy poverty manifests differently depending on the specifics of the energy market, state policy, and climatic conditions. He argues that in Eastern European countries, where the housing stock has a significant level of deterioration and low energy efficiency, energy poverty is significantly more acute than in Western Europe.

Some studies examine the impact of energy-efficient modernization programs on reducing energy poverty. Thus, Pye et al. (2015b) show that investments in improving residential energy efficiency lead to a decrease in the share of income spent on energy. Thus, energy modernization of the housing sector is considered one of the most effective tools for combating energy poverty in the context of transitioning to a low-carbon economy. At the same time, Cirman et al. (2013) and Tarasenko et al. (2024) note that countries with a low level of energy efficiency often struggle to increase it due to a lack of financial resources, experience, or access to modern technologies. To overcome this challenge, they propose using various economic instruments, including subsidies for energy-efficiency programs, preferential lending, and grants for private households. In this context, Ameli and Brandt (2015), targeting OECD countries, complement previous studies by identifying the key factors for household investments in energy efficiency improvement and renewable energy development, specifically:

1) socio-economic characteristics of households;

2) characteristics of their housing;

3) attitudes, knowledge, and behavior of households regarding the environment;

4) household awareness of their own energy costs.

Knowledge of these factors allows for a more effective adaptation of economic instruments and support programs, making them relevant to the needs and capabilities of specific groups of households.

Several studies emphasize the significant role of renewable power advancement in alleviating energy poverty. Specifically, the installation of generating capacities based on renewable energy sources in the residential sector can lower household energy supply costs and reduce their dependence on fossil fuel price fluctuations (Karatasou & Santamouris, 2019; Trypolska et al., 2023, 2024, 2025). Furthermore, the development of renewable energy at the community level ensures the creation of new jobs, which also has a positive social impact in the form of increased incomes, contributing to the alleviation of energy poverty (Trypolska et al., 2021; Zavrazhnyi et al., 2024).

Building upon these findings, it becomes essential to develop appropriate analytical tools that can quantitatively assess the influence of energy efficiency, renewable energy development, and other socio-economic factors on energy poverty levels. In the scientific literature, two main approaches to modeling energy poverty among the population are distinguished. The first is based on the construction of composite indices, while the second relies on the application of economic and mathematical models.

Within the framework of the first approach, Bouzarovski and Herrero (2015) propose a two-level assessment of energy poverty. At the first level, the "risk of poverty" is calculated, defined as the share of the population with incomes below 60% of the national median value after social transfers. At the second level, the Energy Poverty Index is formed, reflecting the share of households that reported:

1) the inability to adequately heat their homes (*Inability*);

2) the presence of arrears on utility bills (*Arrears*);

3) living in a dwelling with a leaking roof or the presence of dampness and rot (*Housing Defects*).

Thus, the composite *Energy Poverty Index* is as follows:

$$Energy\ Poverty\ Index = 0.5 \cdot Inability + 0.25 \cdot Arrears + 0.25 \cdot Housing\ Defects. \quad (1)$$

In the index structure, the "*Inability*" indicator carries a higher weight, as the authors believe that households' self-reported instances of thermal discomfort are a more significant indicator of energy poverty than the presence of utility arrears. The "*Arrears*" indicator reflects the share of households with overdue payments for energy and other utility services. The "*Housing Defects*" indicator has a substantial link to energy poverty, but does not always serve as its direct criterion.

The definition of energy poverty proposed by Maxim et al. (2016) underlines the close connection of this phenomenon with energy efficiency problems. Within the scope of our study, the Bouzarovski and Herrero (2015) index was modified by replacing the "*Inability*" indicator with three other indicators, also based on self-assessment and directly related to energy poverty. Thus, we propose the *Compound Energy Poverty Indicator (CEPI)*:

$$CEPI = (0.3 \cdot Not\,Warm + 0.2 \cdot Not\,Cool + 0.1 \cdot Dark + 0.2 \cdot Arrears + 0.2 \cdot Housing\ Defects), \quad (2)$$

where *Not Warm* – indicator of perceived temperature comfort in winter; *Not Cool* – indicator of perceived temperature comfort in summer; *Dark* – indicator of perceived room lighting; *Arrears* – indicator of unpaid utility bills; *Housing Defects* – indicator of perceived damage or leakage in the dwelling.

One of the disadvantages of the CEPI indicator is that its weighting coefficients do not account for the cost differences in addressing problems related to lighting, heating, and cooling. It is important to note that ensuring adequate household heating requires significantly greater financial expenditure than resolving issues with poor lighting. Maxim et al. (2016) propose an approach to address this issue by increasing the weights for the "*Not Warm*" and "*Not Cool*" indicators relative to the "*Dark*" indicator.

In empirical studies employing the second approach, which relies on economic-mathematical modeling methods, quantitative indicators of energy poverty are also utilized. Specifically, according to Romero et al. (2018), a household is considered energy poor if its expenditures on energy resources exceed the national average level, and its residual income (after paying energy costs) is less than 60% of the national average household income minus the average energy costs. Other key variables used for assessing the level of household energy poverty are presented in Table 2.

Adapting the above-mentioned approaches, the econometric model reflecting the influence of factors on the dependent variable (the energy poverty indicator in the private household sector) can be presented as:

$$\begin{aligned}&\left(Pr\ (Y_i = 1 \mid X)\right) = \varphi\left(\beta_0 + \beta_i X_i + \varepsilon_i\right) = \\ &\varphi(\beta_0 + \beta_1 Nemp + \beta_2 Educ + \beta_3 Gend + \\ &+ \beta_4 Age + \beta_5 Child + \beta_6 Income + \beta_7 Owner \\ &+ \beta_8 Dwell + \beta_9 Insulation + \beta_{10} Ren + \\ &+ \beta_{11} Eefic + \beta_{12} GasPrice + \beta_{13} BAge \\ &+ \beta_{14} Rur + \varepsilon_i,\end{aligned} \quad (3)$$

where *Pr* – probability of falling into an energy poverty situation in the private household sector; Y_i – individual household indicators corresponding to the level of energy consumption; X – vector of the model's explanatory variables; X_i – individual characteristics of households (explanatory variables); φ – logit statistical model for analyzing dependencies when the dependent variable is binary; $\beta_0, \beta_1, ..., \beta_{13}$ – logit statistical model for analyzing dependencies when the dependent variable is binary; ε_i – stochastic (random) component of the model.

The impact of the factors included in model (3) should be interpreted as follows. It is expected that in cases where all household members are unemployed, the probability of such a household falling into the energy-poor category significantly increases due to limited income. At the same time, if the main earner has a higher education, the material well-being of such a household is assumed to

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Table 2. Definition of variables used in the assessment of household energy poverty

Source: Larbi Cherif et al. (2024), Burguillo et al. (2025).

Variable	Definition
Dependent Variable	
Energy Poverty Indicator (Binary)	1 – if the household has a low level of energy consumption; 0 – otherwise
Explanatory Variables	
Employment of household members (*Nemp*)	1 – if no household member is working; 0 – if there is at least one working member in the household
Education of the main earner (*Educ*)	1 – if he/she has a higher education; 0 – otherwise
Gender of the main earner (*Gen*)	1 – if male; 0 – if female
Age of the main earner (*Age*)	1 – if he/she is over 60 years old; 0 – otherwise
Children (*Childs*)	1 – if there are dependent children in the household; 0 – otherwise
Number of income recipients (*Income*)	1 – if only one household member receives income; 0 – if two or more members receive income
Ownership (*Owner*)	1 – if the dwelling is rented; 0 – if it is owned
Type of dwelling (*Dwell*)	1 – if it is a detached house (stand–alone dwelling); 0 – if it is an apartment building
Insulation (*Insulation*)	1 – if the house is insulated; 0 – if it is not insulated
Renewable Energy (*Ren*)	1 – if there are solar panels or a wind turbine; 0 – if not
Energy Efficiency (*Eefic*)	The ratio of household income to total energy consumption per year (USD / kg of oil equivalent)
Natural Gas Price (*GasPrice*)	Cost of natural gas for the current year in comparative prices.
Building Age (*BAge*)	1 – if the building is less than 25 years old; 0 – if it is more than 25 years old
Rural Area (*Rur*)	1 – if the household is located in a rural area; 0 – if it is located in an urban area

be higher, which reduces the risk of energy poverty. Furthermore, households with more educated members generally demonstrate a higher level of energy efficiency. This is explained not only by the potentially higher incomes associated with higher education but also by a greater propensity to adopt new technologies and a motivation to implement energy-efficient measures (Kurbatova et al., 2025). If the head of the household is male, the probability of the household falling into the energy poor category is lower, as men, on average, receive higher incomes than women. Conversely, households with a head aged 60 or older have a higher risk of energy poverty. This is because most older adults live on pension payments, which are usually lower than earned income. If the family has dependent children, household maintenance costs increase while incomes remain the same, which also increases the probability of energy poverty. When only one household member receives income, the family's well-being decreases, thereby increasing the risk of falling into the energy-poor category. Households living in rented accommodation have a higher probability of ending up in the energy poor category. This is explained by the fact that tenants are generally not motivated to improve the energy efficiency of the dwelling since they do not own it. At the same time, owners may pass on the cost of energy resources to tenants, thereby increasing households' total energy expenditures. It is also expected that residents of detached (individual) houses face a higher risk of energy poverty because such houses usually have greater heat loss and, consequently, higher energy consumption. The presence of dwelling insulation and the installation of energy-saving windows are among the key elements that determine the energy characteristics of a building. Specifically, factors that improve the daylight coefficient and, accordingly, reduce energy consumption include: the area of window openings, the reflection coefficients of internal surfaces, a lower sill height, and a reduction in room depth (Das & Paul, 2015). The presence of renewable energy installations (specifically, solar

panels or wind turbines) reduces the probability of a household falling into the energy-poor category, as they provide savings on energy costs. Similarly, the higher the ratio of household income to annual energy consumption (USD/kg of oil equivalent) – i.e., the higher the energy efficiency – the less likely the household is to be classified as energy vulnerable.

In more in-depth empirical studies, it is proposed to measure the household energy efficiency indicator (EEH_{it}) as the ratio of the annual volume of energy consumed to the dwelling area and the number of its inhabitants (Kurbatova et al., 2025). The lower the amount of energy consumption per person and per unit of area, the more energy-saving the household is considered to be:

$$EEH_{it} = \frac{EC_{it}}{HS_{it} \cdot SH_{it}}, \quad (4)$$

where EC_{it} – is the volume of energy consumed by an individual household i in year t; HS_{it} – is the area of the dwelling of an individual household i in year t; SH_{it} – is the number of members of an individual household i in year t.

The increase in the cost of natural gas in the current year (in comparative prices) raises the probability that a household will fall into the energy-poor category, as prices for this key energy resource for heating and cooking directly increase energy expenditures. Conversely, if the residential building is less than 25 years old, the probability of classifying the household as energy vulnerable decreases, as newer buildings are typically characterized by a higher level of energy efficiency (due to modern building standards and a lower level of wear and tear). For rural households, the risk of falling into the energy poverty category is also lower, which can be explained by a more pragmatic approach to energy consumption, wider implementation of energy-efficient technologies and renewable energy projects (in private houses), and the availability of subsidiary farming, which can increase family income. The practical application of the proposed model (3) requires conducting empirical research, which involves carrying out periodic representative sociological surveys of households that would cover all regions of the country.

Thus, the developed theoretical framework demonstrates that energy poverty is a multifactorial and interconnected phenomenon whose formation is influenced by a wide range of socio-economic, technical, and institutional factors. Their manifestations differ significantly depending on national conditions: the level of population income, the state of the housing stock, the structure of the energy market and utility sector, the dynamics of energy prices, the specifics of industrial development, and the priorities of state energy policy, especially in terms of encouraging energy efficiency improvements and green energy deployment. Such multidimensionality supports the development of advanced, flexible, and adaptable mathematical models that can serve as a scientific basis for assessing and improving government strategies, regulatory mechanisms, and support instruments aimed at reducing energy poverty and accelerating the green energy transition.

The purpose of this study is to develop and test an econometric model for the comprehensive assessment and forecasting of the impact of enhancing energy efficiency measures and developing renewable power in the household sector on energy poverty reduction. In addition, the model takes into account a range of factors influencing the energy poverty indicator, including socio-economic, demographic, housing, and energy-related characteristics.

The initial hypotheses of the study are as follows:

H1: With an increase in gross capital formation (% of GDP), including investments in energy efficiency, the number of people below the national poverty line and, accordingly, the energy-poor population, decreases.

H2: With an increase in household expenditures on utilities (% of total household expenditures), the level of energy poverty increases.

H3: With an increase in GDP per capita, the number of people living below the national poverty line and, accordingly, the energy-poor population, decreases.

H4: With an increase in the share of electricity generation from renewable power sourc-

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es (excluding hydropower), the number of people below the national poverty line and, accordingly, the energy-poor population, decreases.

The analysis is based on pre-war statistical data covering the period up to 2021. The choice of this timeframe is due to the full-scale Russian invasion of Ukraine in 2022, which disrupted regular statistical observations, leading to the loss and restriction of access to parts of the datasets. Therefore, the analysis relies on pre-war data, while the developed model is designed to be adaptable for future use under post-war data availability.

The formation and application of such a mathematical model makes it possible to scientifically substantiate the effectiveness of sectoral policies, identify priority areas for household support, and optimize the instruments of state regulation and financial incentives. This, in turn, constitutes an essential prerequisite for achieving Sustainable Development Goal No. 7, Affordable and Clean Energy, as well as for building a more resilient and equitable energy system focused on long-term socio-economic benefits.

2. RESULTS AND DISCUSSION

The assessment of energy poverty in Ukraine through the application of the developed econometric model (3) is significantly constrained by the conditions of the ongoing full-scale war. Direct statistical data collection is hindered by threats to energy security, large-scale destruction of housing, and significant numbers of internally displaced persons. At the same time, the use of adapted approaches is necessary to develop an effective energy policy in the residential sector to contribute to reducing energy poverty of the population, which has increased significantly over the last 10 years and has worsened during the war (2022–2025). Specifically, according to the State Statistics Service of Ukraine, the share of Ukrainian households' expenditures on housing, water, electricity, gas, and other types of fuel increased from 9–10% in 2010–2013 to 15–17% in 2016–2021. This growth is driven by a combination of low household incomes, high energy intensity of the housing stock, and rising energy prices, further exacerbated by the waves of Russian aggression in 2014 and 2022 (State Statistics Service of Ukraine, n.d.).

The Russian full-scale invasion of Ukraine in 2022 created critical risks for the collection and updating of official statistics. Many regions found themselves in the combat zone, where the statistical observation infrastructure was damaged or destroyed, part of the data was lost, and delays in reporting by enterprises and households increased. As a result, access to detailed and reliable statistical information became extremely limited. Regular household surveys were suspended, and it became impossible to obtain consistent, regionally disaggregated data on such key indicators as household income, energy consumption, and renewable power and energy efficiency parameters.

In addition, access to many statistical data sources that were publicly available before 2022 has been significantly restricted or closed for security reasons. At present, part of this information is deliberately withheld from open access in order not to disclose data about critical energy facilities, regional consumption patterns, electricity production volumes, the locations of power plants, key substations, main transmission networks, and other critical infrastructure. These restrictions are linked to the deliberate and massive shelling of energy infrastructure facilities by the Russian Federation, as open access to such data could be used to plan further attacks. As a result, even pre-war datasets are fragmented, making it impossible to conduct a detailed regional analysis of energy poverty.

The above-mentioned limitations, caused by the wartime conditions, necessitate the use of so-called proxy indicators in research – approximate measures that help compensate for the lack of direct statistical data and ensure the analytical reliability of results even under restricted access to official information. Such indicators may include the poverty headcount ratio (% of the population) as a proxy for the energy poverty, GDP per capita (as an indicator of household income), GDP per unit of energy (as an indicator of energy efficiency), gross capital formation (as a proxy for investments in energy efficiency), and the share of household expenditures on utility services in income.

Additional difficulties arise in determining price indicators. In the absence of official data on consumer prices for utilities, it is feasible to use average world prices for crude oil as an approximate indicator of energy carrier costs. Although this approach does not ensure absolute accuracy, it allows for maintaining the comparability of dynamic series and constructing models that reflect the main trends.

This situation represents a significant limitation of the study, as the absence of direct and up-to-date data reduces the accuracy and granularity of the results. Nevertheless, under the conditions of war and limited access to "ideal" statistical indicators, the application of the adapted, proxy-based modeling approach remains a scientifically grounded and practically relevant solution (Li et al., 2022). This makes it possible to assess the impact of increased energy efficiency and the development of renewable energy in the private household sector on reducing energy poverty even under military challenges.

The proxy indicators described above reflect the main factors of energy poverty and can be included in model (5):

$$PR_t = \beta_0 + \beta_1 GDP\_pc_t + \beta_2 GFCF_t + \beta_3 EXU_t + \beta_4 REN_t + u_t, \quad (5)$$

where PR_t – poverty headcount ratio below the national poverty line (% of the population) in year t; GDP_pc_t – GDP per capita (in USD) in year t; $GFCF_t$ – gross fixed capital formation (% of GDP) in year t; EXU_t – expenditures on utility services (% of total household expenditures) in year t; REN_t – share of renewable energy in the structure of total electricity generation (%) in year t; β_0 – constant term (cons) of the regression; β_1, …, β_4 – regression coefficients of the model; u_t – regression disturbance.

The input data for further modeling were obtained from official sources, including the State Statistics Service of Ukraine (n.d.) and the open data of the World Bank (World Bank Group, n.d.). The dataset covers the period 2002–2021 (Kubatko et al., 2025). The econometric estimation of the developed adaptive model of energy poverty was carried out using the Ordinary Least Squares (OLS) method in Stata 18.0. The model was tested for the statistical significance of its parameters, for multicollinearity and residual autocorrelation, and for its stability and adequacy.

The results of the estimation of energy poverty among the population of Ukraine for the years 2002–2021 are presented in Figure 1.

The modeling results revealed the following patterns.

First, with a 1,000-unit increase in GDP per capita (USD), the population headcount below the national poverty line (% of the population) decreases by 3%. This result confirms *H3*: an increase in household income reduces both absolute and energy poverty. The decrease in energy poverty occurs due to an increased capacity of households to pay for energy carriers and invest in improving residential energy efficiency.

Second, with a 1% increase in gross fixed capital formation (% of GDP), the population headcount

```
      Source |       SS           df       MS      Number of obs   =        20
-------------+----------------------------------   F(4, 15)        =     40.23
       Model |  327.928731         4  81.9821827   Prob > F        =    0.0000
    Residual |  30.5692732        15  2.03795155   R-squared       =    0.9147
-------------+----------------------------------   Adj R-squared   =    0.8920
       Total |  358.498004        19   18.868316   Root MSE        =    1.4276

------------------------------------------------------------------------------
povertyheadcou~p | Coefficient  Std. err.      t    P>|t|     [95% conf. interval]
-----------------+------------------------------------------------------------
gdppercapitacu~s |  -.0033941    .000358    -9.48   0.000    -.0041572   -.0026309
grossfixedcapi~p |   .4979173   .1044994     4.76   0.000     .2751821    .7206524
expensesonutil~h |   -.283586   .1695436    -1.67   0.115    -.6449596    .0777875
electricitypro~b |   .4845739   .2668451     1.82   0.089     -.084193    1.053341
           _cons |   16.49907    3.17247     5.20   0.000     9.737108    23.26103
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Figure 1. Estimation of energy poverty among the population of Ukraine (2002–2021)

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below the national poverty line (energy poor, % of the population) increases by 0.498%. This indicates that investments in physical capital do not directly translate into higher household incomes, especially if investments are concentrated in large industrial or financial projects that are not aimed at improving the living conditions of the population and may increase energy poverty. Therefore, *H1* was not confirmed.

Third, household expenditures on utilities (% of total expenditures) and the share of electricity generation from renewable power sources, excluding hydroelectric power plants (% of total generation), proved to be statistically insignificant factors, i.e., *H2* and *H4* were not confirmed. This indicates that the level of energy poverty (within the framework of the selected proxy indicators) is influenced to a greater extent by income and general macroeconomic indicators than by the share of renewable energy or household expenditures on utilities.

Thus, the modeling results demonstrated that reducing energy poverty in Ukraine primarily depends on the level of population income, while gross fixed capital formation, household utility expenditures, and the share of renewable energy have a contradictory or indirect effect.

It is worth noting that the obtained results are consistent with the conclusions of Thomson et al. (2017), who emphasize that the level of household income is the main determinant of energy poverty even in EU countries with well-developed social protection systems. Similar to our study, they demonstrate that energy poverty is primarily caused by overall economic inequality rather than solely by high energy prices or low energy efficiency of the housing stock. This highlights the importance of combining income-raising policies with energy efficiency measures to achieve a long-term reduction in energy poverty.

The obtained results are also consistent with the findings of Middlemiss and Gillard (2015), who argue that energy poverty is a complex phenomenon that depends not only on economic but also on technical and behavioral factors. The obtained results emphasize that economic indicators alone are insufficient to fully assess the scale of energy poverty. The lack of data on the social and behavioral characteristics of households limits the model's ability to reflect the real situation.

Furthermore, the obtained results complement the conclusions of Maxim et al. (2016), who emphasize the importance of a comprehensive measurement of energy poverty that includes both quantitative and qualitative indicators. Similar to our study, they highlight that an effective assessment of the level of energy vulnerability is possible only when macroeconomic statistics are combined with data on consumer behavior, the technical condition of the housing stock, and climatic factors.

At the same time, our results differ partially from those of Heindl and Schüßler (2015), Romero et al. (2018), and Karatasou and Santamouris (2019), who identified a significant impact of price factors and tariff policies on the level of energy poverty. In our model, these factors did not have a statistically significant effect. This can be explained by the fact that in Ukraine, the government subsidizes energy prices for households; therefore, their actual impact on the population's welfare is difficult to accurately assess, as prices remain partially artificially lowered due to state regulation.

Overall, the results of this study are consistent with most contemporary research that considers energy poverty as a multifactorial problem, the solution to which requires the integration of economic, social, and energy policies. At the same time, the differences with certain studies reflect the specific features of the Ukrainian context, indicating the need to develop a methodology and policy framework for addressing energy poverty that is adapted to national realities.

The obtained results can serve as a foundation for developing an integrated national policy aimed at reducing energy poverty in Ukraine under the green energy transition. Considering that household income remains a key determinant of energy vulnerability, the policy should focus on strengthening economic support for the low-income population through targeted energy subsidies. Equally important is the integration of energy efficiency and renewable energy policies into a unified strategy at both national and regional levels. The absence of a statistically significant relationship between the share of renewable energy and the level

of energy poverty, as revealed in the study, indicates the need to expand household access to renewable energy technologies. This can be achieved through preferential credit programs and incentives for establishing energy cooperatives, among other mechanisms. In addition, it is advisable to strengthen the system for collecting and monitoring data on energy poverty. The introduction of a national energy poverty index, which would take into account economic, technical, and social aspects of vulnerability, will enhance the accuracy of policy decisions.

It is worth noting that our study has several limitations. First, the use of proxy indicators due to limited access to Ukraine's statistical data during wartime reduces the accuracy of assessing the impact of energy efficiency and renewable energy on alleviating energy poverty. Using macroeconomic data does not allow for considering regional differences, particularly between urban and rural areas or between zones of active hostilities and relatively stable regions. Second, the model does not include the behavioral aspects of energy consumption at the level of individual households, energy awareness, willingness to invest in energy efficiency measures, and renewable energy technologies. Although these factors could have a significant influence on the results, they were not included due to data limitations. Third, the study's timeframe covers only up to 2021, meaning it does not account for changes in Ukraine's energy sector since the beginning of the full-scale war in 2022, including infrastructure destruction and shifts in energy consumption patterns.

In view of this, future research should aim to overcome the current limitations associated with data availability. Once the conditions for large-scale data collection are restored, it will be possible to conduct a comprehensive household survey across regions, including both quantitative and qualitative components. Such research will make it feasible to construct more detailed econometric and behavioral models that reflect regional disparities, levels of infrastructure damage, and the differentiated access of households to energy resources. Another important direction is to study the mutual impact of energy efficiency and renewable energy. It is necessary to check whether the joint implementation of both measures (increasing energy efficiency and developing renewable power) yields a better result in reducing energy poverty than either measure separately.

CONCLUSION

This study aimed to develop, adapt, and apply an econometric model for a comprehensive assessment and forecasting of the interrelationship between an increase in energy efficiency, the development of renewable energy in the household sector, and their impact on energy poverty in Ukraine. The results showed that the key factor in reducing energy poverty is growth in household income, as this directly increases households' purchasing power and enables them to invest in energy efficiency measures and renewable energy projects. At the same time, capital investments focused primarily on the industrial sector do not contribute to reducing energy poverty and may even exacerbate social disparities. The study confirmed that the development of renewable energy and improvements in household energy efficiency are important tools for lowering energy vulnerability.

However, the share of household expenditures on utilities and renewable energy indicators does not have a direct effect on the level of energy poverty. These findings highlight the necessity of developing a comprehensive energy policy that combines economic growth with targeted support for low-income households, enabling them to implement energy efficiency measures and renewable energy projects, which will reduce energy vulnerability and improve the social well-being of the population.

AUTHOR CONTRIBUTIONS

Author contributions
Conceptualization: Liliana Śmiech, Tetiana Kurbatova, Iryna Sotnyk.
Data curation: Oleksandra Kubatko, Iryna Sotnyk.

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Formal analysis: Tetiana Kurbatova, Oleksandra Kubatko, Iryna Sotnyk, Galyna Trypolska.
Funding acquisition: Tetiana Kurbatova, Oleksandra Kubatko, Iryna Sotnyk, Galyna Trypolska.
Investigation: Liliana Śmiech, Tetiana Kurbatova, Oleksandra Kubatko, Iryna Sotnyk, Galyna Trypolska.
Methodology: Liliana Śmiech, Tetiana Kurbatova, Oleksandra Kubatko, Iryna Sotnyk.
Project administration: Iryna Sotnyk, Tetiana Perederii.
Resources: Tetiana Kurbatova, Oleksandra Kubatko, Iryna Sotnyk.
Software: Oleksandra Kubatko.
Supervision: Tetiana Kurbatova, Oleksandra Kubatko, Iryna Sotnyk.
Validation: Liliana Śmiech.
Visualization: Tetiana Kurbatova, Oleksandra Kubatko, Iryna Sotnyk, Tetiana Perederii.
Writing – original draft: Tetiana Kurbatova, Oleksandra Kubatko, Iryna Sotnyk, Galyna Trypolska, Tetiana Perederii.
Writing – review & editing: Liliana Śmiech, Tetiana Kurbatova, Oleksandra Kubatko, Iryna Sotnyk, Galyna Trypolska, Tetiana Perederii.

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