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The Green Divide: How sustainable solutions can close the energy poverty gap

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Highlights

- The government's investment in infrastructure is the strongest economic factor that continuously and significantly reduces energy poverty in the context of income inequality, measured by both the Gini and Palma coefficients.
- Especially if income disparities are not adequately addressed, it has been determined that urbanisation significantly worsens energy poverty and leads to the deepening of the problem.
- The unstable (both positive and negative) impact of renewable energy adoption on energy poverty suggests that such investments initially create potential distribution issues in terms of income distribution.
- The analysis surprisingly shows that the reduction of overall energy poverty is associated with higher income inequality, indicating that the benefits of infrastructure investments may initially be concentrated in wealthier households.
- Using robust econometric models such as Panel Corrected Standard Errors (PCSE) and Feasible Generalised Least Squares (FGLS), comprehensive policy reforms prioritising technological innovation and sustainable energy infrastructure are being promoted.

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ABSTRACT

This study examines energy poverty, a worldwide issue that hinders socioeconomic advancement and disproportionately impacts marginalised groups by restricting their access to opportunities. Economic inequality is a major contributing element, as income disparities have a direct impact on the availability, affordability, and dependability of energy, especially in emerging and developing nations. We also see that environmental deterioration caused by unsustainable energy usage exacerbates the issue. Our study examines energy poverty and income inequality data using a regression model that incorporates Panel-Corrected Standard Errors (PCSE) and Feasible Generalised Least Squares (FGLS) approaches, highlighting the crucial role that sustainable energy access plays in accomplishing the UN Sustainable Development Goals (SDGs). Our quantitative results (where coefficients represent the point change in inequality indices per unit change in independent variables) indicate that government investment in infrastructure considerably reduces energy poverty; for instance, FGLS government spending coefficients were -0.014 for Gini and -0.063 for Palma. Adoption of renewable energy has a mixed effect; the FGLS-Palma model indicates a significant negative effect (-1.155), while other models show positive coefficients (e.g., FGLS-Gini: 0.059), suggesting possible regressive distributional issues or high initial technology transfer costs during the early stages of transition. Importantly, energy poverty is made worse by urbanisation (PCSE-Palma urbanisation coefficient: 0.420), and if rising income gaps are not adequately addressed, the problem will only get worse. To guarantee widespread access and promote long-term global fairness, this research promotes comprehensive policy reforms that give priority to technical innovation, international cooperation, and investments in sustainable energy infrastructure.

Keywords: Energy poverty, Income inequality, Panel data analysis (PCSE/FGLS), Sustainable development goals (SDGs), Urbanisation

1. AN INTEGRATED ECONOMETRIC ANALYSIS OF ENERGY POVERTY

Energy poverty is one impediment to socioeconomic development worldwide, affecting millions of people. While earlier research has amply investigated this matter, there remains a void in the literature: an encompassing, integrated econometric study of its joint economic, infrastructural, and ecological causations. This paper fills this gap by synthesising these dimensions under the auspices of one theoretical framework. Our uniqueness lies in trying not only an integrated approach but also a focus on the economic consequences of interdependencies with income inequalities via the Palma ratio, a distribution-sensitive index more often neglected by Gini coefficient-based studies. Two interrelated insufficiencies of the current debate necessitate this study. One derives from the fragmented nature of the analysis that has considered economic, infrastructural, and ecological factors in isolation, rather than as a complex system. Fragmentation constrains the possibility of identifying interactions at the system's level or codifying into policy recommendations, undertakings that work in tandem.

Utilising systems thinking, we draw on the capabilities approach to conceptualise the varying ways in which energy deprivation impinges on well-being in the various domains of human life. Second, the literature usually lacks specific, econometrically informed intervention pathways, even while it generally supports policy improvements. We address typical econometric issues, like as heteroscedasticity and autocorrelation, that are ubiquitous in macroeconomic panel data by carefully using Panel-Corrected Standard Errors (PCSE) and Feasible Generalised Least Squares (FGLS). By going beyond descriptive correlations to create strong links between sustainable development indicators, income inequality, and green economy characteristics, this methodological rigour improves the accuracy and efficiency of our estimations. Developing focused, evidence-based policy interventions requires such a thorough econometric analysis over a wide range of developing nations. The ultimate goal of this research is to offer a data-driven roadmap for utilising integrated economic policies and sustainable energy to promote equitable development and lessen deprivations associated with energy. Our research will shed light on the statistical effects of certain investments in efficiency-related fields or enhancements to environmental quality (as part of the Global Green Economy Index) on GDP per capita and unemployment rates. We also look into how these elements, coupled with the use of renewable energy, help to reduce economic disparity.

Strong economic justifications for giving green transitions top priority are provided by the clear correlation between environmental and economic factors and observable socioeconomic results. Thus, the study goes beyond simply drawing attention to the issue of energy poverty and provides policymakers with useful information. Implementing progressive energy pricing policies to guarantee affordability for vulnerable people, encouraging localised renewable energy solutions like solar mini-grids in rural areas, and investing in smart grid technologies to increase reliability are a few examples. The global conversation on attaining the Sustainable Development Goals through a fair energy transition needs to be informed by this unique contribution.

2. THEORETICAL FRAMEWORK: A MULTIDIMENSIONAL APPROACH TO ENERGY POVERTY

Energy poverty adversely affects millions of people, with socioeconomic processes being hampered by complex systemic elements (Imelda, 2020). While many skeleton points have been spelt out by previous works, a proper theoretical framework that binds ecology, economics, and infrastructure issues is still lacking for any matter of comprehensive study. It expels all theoretical explanations relating to the origin, consequence, and module for a sustainable solution of energy poverty in the multidimensional poverty framework, principally from Sen's (1981) capabilities approach and a systems thinking perspective (Sterman, 2000). This paradigm prohibits oversimplification of deprivations felt throughout one or more life spheres due to the consumption by way of deficiency or inconsistency or cost from one side of energy and simply being without access on the other ([Churchill and Smyth, 2020](#)). Reducing energy shortage requires strengthening energy supply networks and filling up these basic infrastructure deficiencies.

The ecological effects of energy poverty are just as important as the socioeconomic ones. To secure future prosperity and preserve ecological balance, this study examines these environmental effects and promotes sustainable energy options ([Feeny et al., 2021](#)). Addressing energy poverty necessitates a comprehensive strategy; this study explores how sustainable energy might serve as a driving force behind the UN Sustainable Development Goals. Countries may address environmental sustainability, boost educational opportunities, improve health outcomes, and reduce poverty all at once by encouraging inexpensive and clean energy.

It is essential to comprehend the revolutionary potential of sustainable energy to promote just and productive societies. This thorough investigation ultimately aims to respond to the following research question: How can the adoption of sustainable energy solutions, backed by integrated

economic, infrastructure, and ecological policies, effectively help to reduce energy poverty and achieve the Sustainable Development Goals on a global scale? What are the main causes of energy poverty? To answer this broad issue, we will look for trends that can change the dynamics of energy shortage, investigate novel ideas, and pinpoint patterns that emerge from the energy poverty paradigm. To guarantee the effectiveness, durability, and inclusivity of initiatives meant to alleviate global energy poverty for a sustainable and just future, this paper acts as a call to action, promoting coordinated, all-encompassing strategies that include astute policymaking and grassroots interventions (Rieskamp and Hoffrage, 2008). Finally, this comprehensive study is a call to action, encouraging coordinated efforts to identify, understand and solve the complex problem of global energy poverty.

Millions of people are affected by the dynamics of energy poverty, which impedes socioeconomic advancement due to a complex interaction of systemic elements (Imelda, 2020). Numerous aspects of this problem have been clarified by earlier research, but a thorough theoretical framework is required to combine the ecological, economic, and infrastructure aspects while critically examining their interdependencies. This study critically examines the origins, effects, and avenues for sustainable solutions of energy poverty using a multifaceted framework for poverty, particularly using the capabilities approach and a systems thinking viewpoint. This method makes it possible to have a more complex knowledge of the deprivations that occur in different areas of life as a result of inadequate, unstable, or expensive energy, going beyond simply not having access to it.

2.1. Failures in Entitlement and Economic Inequality

Our theoretical approach is based on the substantial correlation between economic inequality and energy poverty. We argue that economic differences are a key cause of what Sen's (1981) entitlement model would refer to as "entitlement failures" in energy access, rather than just a correlation with energy poverty. Due to their limited resources, vulnerable groups are less able to obtain essential energy resources, which exacerbates already-existing socioeconomic inequalities and impedes their overall development (Nussbaumer et al., 2012; Oum, 2019; Nguyen and Su, 2022). Economic precarity limits opportunities for economic growth, makes it harder to access basic services (including healthcare and education), and highlights how brittle the current infrastructure is.

Principles of ecological economics, which highlight how human economies are interwoven with natural ecosystems, are consistent with this (Daly, 1996). Gaining an understanding of this mutual link is essential to creating solutions that effectively address the global energy shortfall, going beyond just economic measures to take environmental sustainability into account as a vital aspect of well-being.

2.2. Systemic Vulnerabilities and Infrastructure Deficits

Widespread economic, social, and environmental problems are caused by deficiencies in energy supply and infrastructure, which are a crucial structural component of energy poverty. By using a systems thinking approach, we see energy infrastructure as a complex adaptive system whose failures spread to other industries (Sterman, 2000).

By raising prices and causing delays in the flow of people and commodities, outdated and unreliable electricity grids and ageing transportation networks significantly harm economic competitiveness (Gouveia et al., 2021). Foreign investment, which is essential for economic progress, is discouraged by this inadequate infrastructure. Additionally, the use of antiquated energy sources because of inadequate infrastructure leads to air and water pollution, which has a direct negative influence on public health and impedes the achievement of sustainable development goals (Bouzarovski & Petrova, 2015). These structural failures disproportionately impact vulnerable populations, who face increased social inequality as a result of limited access to basic amenities like power and transportation, which restricts their access to jobs, healthcare, and educational opportunities. This makes it harder to participate in the knowledge-based global economy and maintains the digital divide.

Importantly, these structural flaws can also result in environmental risks like spills and leaks from outdated buildings, which exacerbate climate change and highlight the pressing need for a switch to more sustainable and effective infrastructure (Munyanyi et al., 2021). According to our paradigm, to address these systemic vulnerabilities and create a more resilient and equitable energy environment, substantial investment and integrated planning—leveraging new technologies and renewable energy—are necessary (Deller et al., 2018; Simcock et al., 2021).

2.3. The Capabilities Approach, Sustainability, and Ecology

The third pillar of our theoretical framework, which is mostly influenced by the capacities approach, highlights the complex interrelationships among ecological, energy, and poverty (Nussbaum, 2011). According to this perspective, development should be evaluated based on people's actual chances to attain well-being rather than just economic output. For basic human requirements like heating, cooking, and lighting, energy access is a crucial competence (Heger et al., 2018; Masron & Subramaniam, 2019; Asghar et al., 2022; Raihan et al., 2022). When modern energy is scarce, disadvantaged groups—especially women and children—are disproportionately affected by the use of destructive environmental practices like burning biomass, which causes deforestation and extreme indoor air pollution. Their capacity to be healthy, educated, and lead productive lives is thus severely limited. Furthermore, the extraction and use of conventional energy resources frequently harm biodiversity and ecosystems, with poor communities bearing an unfair share of the environmental costs (Neaime & Gaysset, 2018; Shi & Qamruzzaman, 2022). By diminishing the natural resources that are essential to their livelihoods and increasing their vulnerability to the effects of climate change, this worsens their poverty. A significant change to sustainable energy solutions is required to meet the Sustainable Development Goals (SDGs), especially SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action) (Shyu, 2021; Rao et al., 2022; Zhao et al., 2022). By promoting energy independence and offering decentralised access to electricity, renewable energy sources such as hydroelectric, solar, and wind provide environmentally friendly substitutes (Bode, 2022).

3. METHODOLOGY

For this study, we have based the selection of our model on that of Sowadogo and Ouba (2024), who explore the relationships between natural resources and income inequality. Recognising the energy relationship as another resource that can impact income inequality, we adapt their model to our specific research interest, which can be observed in Equation 1.

$$I_{it} = \beta_1 EP_{it} + \beta_2 GOV_{it} + \beta_3 REN_{it} + \beta_4 X_{it} + \varepsilon_i \quad (\text{Eq 1})$$

The scope of our dataset covers a panel of 35 emerging and developing nations over the period 2000–2023. These countries were selected based on data availability and their significance in global energy poverty discussions, including nations such as Argentina, Brazil, Chile, China, Colombia, Egypt, India, Indonesia, Malaysia, Mexico, Morocco, Pakistan, Peru, Philippines,

South Africa, Thailand, Türkiye, and Vietnam, among others. The balanced panel structure allows for a comprehensive assessment of the long-term dynamics between energy access and income distribution across diverse geographic and economic contexts.

This model restricts the number of explanatory variables to prevent over-specification while permitting the adoption of a tried-and-true framework that fits our area of interest. Control variables: The World Bank Development Indicators (WDI) statistics for the years 2000–2023 are used to incorporate the following control variables, except the Financial Development Index, which comes from the International Monetary Fund (IMF):

GDP per capita (LGDP): To take into consideration the state of the economy as a whole.
Industrialisation (LIN): To quantify the degree of industrial activity that affects the supply and demand for energy.

Trade liberalisation (LTL): To evaluate how economic openness affects inequality and energy availability.

Foreign Direct Investment (FDI): To comprehend how external capital contributes to economic expansion and income distribution, as well as how it may impact poverty and energy availability.
Energy Intensity (LEI): Indicates how efficiently energy is used per unit of economic output; a greater number indicates less energy efficiency.

Urbanisation (LUR): To account for changes in the population and how they affect the need for energy and the construction of infrastructure in both urban and rural areas.

In our theoretical approach, these control variables provide a more accurate evaluation of the relationship between income disparity and energy poverty by reducing the possibility of confounding effects from other economic difficulties.

Since panel data sometimes contains autocorrelation and heteroscedasticity (changing error variances across nations), we choose Panel-Corrected Standard Errors (PCSE) and Feasible Generalised Least Squares (FGLS) for the analysis of income inequality. These are typical problems in macroeconomic research, and basic Ordinary Least Squares (OLS) regressions would produce biased standard errors and wasteful estimates if they were disregarded. These problems

are addressed by both PCSE and FGLS, which yield more trustworthy outcomes. Aiming for the Best Linear Unbiased Estimator (BLUE), FGLS is incredibly efficient at converting data to directly account for the error structure. This frequently results in estimations of the coefficients that are more accurate. In fact, FGLS found more statistically significant components in our analysis when the Palma ratio was used, indicating that it better captures the underlying link in the data. In contrast, PCSE uses a "sandwich" estimator to account for cross-sectional correlation and heteroscedasticity in order to provide robust standard errors.

Although it may not always be as effective as FGLS, its strength is in guaranteeing the accuracy of our statistical conclusions, especially in cases where the precise error structure is complicated. Our confidence in these estimators was further reinforced by the Durbin-Wu-Hausman endogeneity test, which verified that endogeneity is not a problem. In the end, the consistent indications between the PCSE and FGLS models, as well as their agreement with the Gini index findings, support the validity of our conclusions about the dynamics of income inequality, with FGLS offering the most thorough insights for our particular dataset.

Panel data analysis often encounters issues like heteroskedasticity, serial correlation, and cross-sectional dependence, which can lead to inefficient OLS estimates and biased standard errors, undermining inference. To address these challenges, econometric techniques such as Panel-Corrected Standard Errors (PCSE) and Feasible Generalised Least Squares (FGLS) are employed. PCSE is particularly effective when the number of cross-sectional units (N) is small relative to the periods (T), providing robust standard errors that are less prone to the "overconfidence" sometimes seen with other methods. Its strength lies in correcting standard errors for heteroskedasticity and cross-sectional dependence, and it can also incorporate AR (1) serial correlation through transformations, making it suitable for studies where reliable inference is paramount and detailed error structure modelling is not strictly necessary.

On the other hand, when all three problems—cross-sectional dependence, serial correlation, and heteroskedasticity—occur and need to be explicitly modelled for optimal effectiveness, FGLS is recommended. It attempts to generate asymptotically efficient coefficient estimates by transforming the data according to an estimated error covariance matrix. Because it can more precisely estimate the intricate error structure, FGLS performs exceptionally well in "long" panels where the number of periods (T) greatly outnumbers the cross-sectional units (N). FGLS provides

a thorough correction and, provided its assumptions are met, can produce the most accurate estimates, making it excellent when efficiency is the main research goal, despite being more computationally demanding and sensitive to the proper specification of the error structure

Table 1: Brief Comparison of PCSE and FGLS

	PCSE (Panel-Corrected Standard Errors)	FGLS (Feasible Generalised Least Squares)
Primary Focus	Robust standard errors for OLS coefficients in the presence of heteroskedasticity and cross-sectional dependence (and often AR(1) serial correlation via Prais-Winsten).	Efficient coefficient estimates by transforming data to account for full error covariance structure.
Handling of Errors	Corrects standard errors after OLS (or Prais-Winsten) estimation. Does not re-estimate coefficients for efficiency gains directly (though the Prais-Winsten part does).	Directly transforms the data to achieve efficient coefficient estimates.
Efficiency	Generally less efficient than FGLS if FGLS's error model is correctly specified, but provides more reliable standard errors.	More efficient if the assumed error structure is correct.
Robustness	More robust to misspecification of the exact error structure, as it focuses on correcting standard errors.	Less robust to misspecification of the error structure; incorrect specification can lead to biased coefficients.
Computational Complexity	Relatively less computationally intensive for standard error calculation.	It can be more computationally intensive, especially with many cross-sectional units, due to the need to invert a large covariance matrix.
Risk of Overconfidence	Less prone to "overconfident" (underestimated) standard errors compared to FGLS in some scenarios.	Can produce "overconfident" standard errors if the underlying assumptions are not fully met, particularly with small T.

In conclusion, the main research goal (e.g., obtaining robust standard errors for inference vs. obtaining the most efficient coefficient estimates) and the particulars of the panel data (N and T dimensions) frequently influence the decision between PCSE and FGLS. It's always a good idea to use both as a robustness check to make sure the results are consistent.

4. RESULTS

We explore the intricate connection between income inequality, as shown by the Palma and Gini indices, and energy poverty. Feasible Generalised Least Squares (FGLS) and Panel-Corrected Standard Errors (PCSE) are robust econometric techniques that we used to overcome important statistical problems in our panel data models. These techniques are essential because preliminary diagnostic tests showed that autocorrelation and heteroscedasticity were widespread in our models, as shown by the extremely significant p-values from the Wooldridge and Modified Wald tests (Table 2).

Table 2: Autocorrelation and heteroscedasticity

Test	Test statistic	P value	Presence
<i>Palma_{it} = β₁EP_{it} + β₂GOV_{it} + β₃REN_{it} + β₄X_{it} + ε_i</i>			
Modified Wald test for GroupWise heteroscedasticity	$\chi^2 = 172.48^a$	0.00	Yes
Wooldridge test for autocorrelation in panel data	F-statistic = 23.71 ^a	0.00	Yes
<i>Gini_{it} = β₁EP_{it} + β₂GOV_{it} + β₃REN_{it} + β₄X_{it} + ε_i</i>			
Modified Wald test for GroupWise heteroscedasticity	$\chi^2 = 131.52^a$	0.00	Yes
Wooldridge test for autocorrelation in panel data	F-statistic = 21.09 ^a	0.00	Yes

The χ^2 statistic of 172.48 (Palma) and 131.52 (Gini), both with p-values of 0.00, confirms heteroscedasticity, which suggests that the variability of income inequality varies by nation. This implies that, depending on certain economic situations, structural features, or regulatory frameworks, the factors driving income disparity may have different effects. For example, some economies may be more vulnerable to external shocks or changes in policy, which could result in more unstable inequality results.

Autocorrelation also shows a persistent temporal dependence in income inequality, with p-values of 0.00 and F-statistics of 23.71 (Palma) and 21.09 (Gini). This indicates that historically high levels of inequality have a substantial impact on current levels, indicating that the economy has deeply ingrained structural components and feedback loops that make quick changes to the distribution of income difficult.

Also, "Yes" results in table 2 above indicate that both heteroskedasticity and autocorrelation are statistically significantly present. This means that the basic OLS assumptions are violated.

Therefore, uncorrected standard errors and statistics are unreliable and can lead to misleading conclusions. Therefore, it is essential to use robust estimation techniques such as panel-corrected standard errors (PCSE).

Ignoring these econometric problems could result in ineffective Ordinary Least Squares (OLS) estimations and biased standard errors, making hypothesis testing incorrect and possibly producing false policy recommendations. Thus, we must use FGLS and PCSE. Panel models with both spatial and serial correlation are the focus of the FGLS (Parks' methodology), which addresses heteroscedastic errors by modifying the model in two steps. A strong substitute is offered by PCSE, which uses a sandwich estimator to account for panel dependency and Prais-Winsten weighting for autocorrelation. Our literature review and robustness checks indicate that FGLS is the more reliable estimator for our data, showing more consistent and significant components, which leads to a more economically sound interpretation of the factors influencing income inequality, even though both approaches provide notable improvements over OLS.

We are more confident in the selected estimators because the Durbin-Wu-Hausman test further demonstrated that endogeneity is not an issue. Our thorough examination of the variables affecting energy poverty and income inequality using the FGLS and PCSE models (Table 2) yields several important conclusions:

1. Energy Poverty's (EP) Complicated Connection

The negative coefficients for Energy Poverty (EP) in both the Palma and Gini models, which are found in both FGLS and PCSE estimations, surprisingly imply that reduced energy poverty is associated with higher income inequality. In the FGLS model, for instance, there is a noteworthy inverse relationship between EP and the Gini (-0.012) and Palma ratio (-0.145). This surprising result may suggest that, as income is concentrated among wealthier households, more money may be invested in energy infrastructure, which would benefit a larger population and somewhat lessen overall energy poverty. But more thorough research is needed on this.

2. The Mixed Effects of Renewable Energy (REN)

Depending on the inequality indicator applied, the effect of REN on energy poverty differs. Adoption of renewable energy can successfully reduce energy poverty when income disparity is substantial, as evidenced by the fact that REN greatly lowers energy poverty for Palma (-1.155) in the FGLS model. Nonetheless, it demonstrates a positive influence on Gini (0.059), and in the

PCSE model, both Palma (0.247) and Gini (0.061) exhibit a positive relationship. This contradictory finding would suggest that early investments in renewable energy could raise prices or have distributional consequences that, at least temporarily, favour higher-income groups more than others, influencing the degree of energy poverty in different ways across income levels.

3. Government Spending (GOV)

A Potent Mitigator. In all models, government spending (GOV) continually and considerably lowers energy poverty. By suggesting that greater government spending on welfare and public services enhances energy access and affordability for vulnerable populations, this emphasises its critical role in alleviating inequality. Regardless of the income inequality metric, government action effectively reduces energy poverty, as evidenced by the FGLS model's GOV coefficients of -0.014 for Gini and -0.063 for Palma.

4. The Diverse Impact of Income Levels and GDP

In the FGLS Palma model, the log of GDP per capita (LGDP) and energy poverty have a significant negative association (-1.130), indicating that economic expansion can successfully lower energy poverty in situations when income disparity is strong. On the other hand, a modest positive correlation (0.009) is indicated by the Gini model. Palma (0.197) and Gini (0.002) had less noticeable but still positive correlations in the PCSE model, suggesting that the relationship between economic growth and The Gini coefficient and the Palma ratio have different sensitivity points in measuring income inequality; while the Gini coefficient is more sensitive to changes in the middle part of the income distribution, the Palma ratio focuses on the ratio of the top 10% of income to the bottom 40%, providing a clearer analysis of inequality at the extremes (tails) of the distribution. This technical distinction explains why renewable energy investments have different effects on the Gini and Palma indices in our study: While the transition to renewable energy can create a temporary increase in costs and inequality in the overall distribution (Gini), which includes the middle-income group, it can also improve energy access for the poorest segment, reducing inequality at the extremes (Palma).

The correlation between energy poverty and income level (LIN) is consistently negative across all models. For example, LIN's coefficients under FGLS are -0.097 for Gini and -0.145 for Palma. This is consistent with economic theory: as income levels rise, energy becomes more affordable,

hence lowering energy poverty. Across all income inequality measures, this steady negative association demonstrates that income growth is a viable approach to reducing energy poverty.

5. Foreign Direct Investment (FDI) and Trade Liberalisation (LTL)

Across all models, trade liberalisation (LTL) consistently shows a negative correlation with energy poverty, suggesting that trade can reduce energy poverty by, for instance, redistributing wealth or funding public services. When there is high income disparity, trade policies can be an effective instrument for reducing energy poverty, according to LTL's significant coefficients (-0.703 for Palma and -0.371 for Gini under FGLS). Similar to this, most models consistently demonstrate that foreign direct investment (FDI) has a negative impact on energy poverty, with both the Gini (-0.002) and FGLS Palma (-0.044) being negative. This effect is more pronounced for Palma in the PCSE model (-1.169), suggesting that FDI can successfully reduce energy poverty by funding infrastructure projects that increase access to energy, create jobs, or ease the transfer of knowledge.

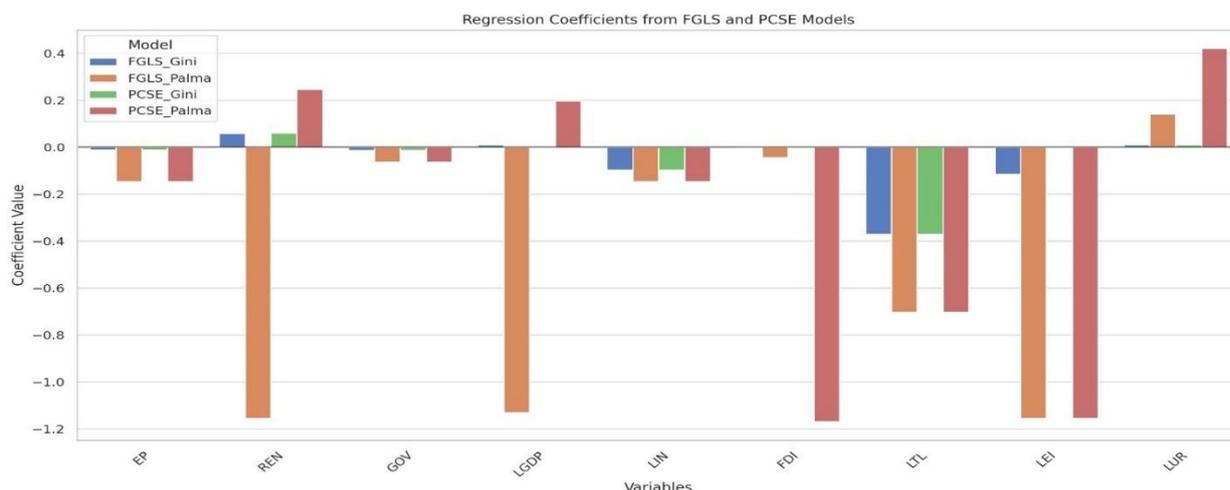
6. Urbanisation (LUR) and Energy Infrastructure (LEI)

The results of energy infrastructure (LEI) investments vary. In the PCSE Gini model, LEI turns positive (0.002), despite having a significant negative impact in the FGLS Palma model (-1.155) and a lower negative impact in the Gini model (-0.115). This implies that although investments in energy infrastructure are usually advantageous, they might have varying distributional effects across different measures of inequality, thereby favouring some groups over others. In every model, there is a persistent and noteworthy positive association between energy poverty and the urbanisation rate (LUR). The LUR coefficients for Palma and Gini in the FGLS model are 0.141 and 0.009, respectively. This implies that low-income households may find it more difficult to obtain reasonably priced energy as a result of expanding urbanisation, which brings with it problems like congested cities, poor infrastructure, and growing living costs. When income inequality is high, the impact of urbanisation on energy poverty is more noticeable, according to the Palma model's higher coefficient (0.420 in PCSE). This could be because the advantages of urbanisation are not distributed fairly, making it difficult for low-income urban dwellers to access energy.

Table 3: FGLS and PCSE estimation

	FGLS		PCSE	
	Palma	Gini	Palma	Gini
EP	-0.145*** (0.025)	-0.012** (0.004)	-0.157 (0.041)	-0.005 (0.001)
REN	-1.155** (0.418)	0.059*** (0.013)	0.247*** (0.081)	0.061*** (0.008)
GOV	-0.063*** (0.018)	-0.014*** (0.007)	-0.760 (0.145)	-0.067 (0.167)
LGDP	-1.130*** (0.127)	0.009*** (0.001)	0.197* (0.042)	0.002 (0.000)
LIN	-0.145*** (0.012)	-0.097*** (0.051)	-0.082*** (0.017)	-0.060*** (0.002)
LTL	-0.703*** (0.116)	-0.371*** (0.028)	-0.342 (0.187)	-0.032*** (0.005)
LFDI	-0.044*** (0.006)	-0.002*** (0.000)	-1.169* (0.532)	-0.006*** (0.001)
LEI	-1.155** (0.072)	-0.115** (0.014)	-0.007*** (0.000)	0.002 (0.003)
LUR	0.141*** (0.009)	0.009*** (0.001)	0.420*** (0.043)	0.019* (0.014)
Adj. R2	0.83	0.82	0.83	0.82

Figure 1. The regression coefficients from both FGLS and PCSE models



A comparison of regression coefficients for variables influencing energy poverty between the FGLS and the PCSE method. For each variable, there are four different coefficients: FGLS_Gini, FGLS_Palma, PCSE_Gini, and PCSE_Palma. Such four coefficients make it easier to observe how changes in the model or inequality index alter the results.

General Statement on Important Variables

Energy Poverty (EP): The negative coefficients obtained for the energy poverty (EP) variable in all models indicate that an increase in income inequality is associated with a decrease in energy poverty, which at first glance seems paradoxical and counterintuitive. This paradoxical situation can be explained by the fact that in the early stages of energy infrastructure construction, efforts to reduce overall energy poverty primarily benefit high-income groups in the short term; wealthy groups tend to be the first to benefit from infrastructure investments and network expansions. For policymakers, this result shows that energy access projects should not focus solely on total poverty figures, as this could lead to new inequalities across social strata even if energy access increases; therefore, supporting investments with progressive tariffs and region-based subsidies that directly target low-income households is a critical necessity for inclusive growth.

Renewable Energy (REN): Renewable energy (RE) investments exhibit complex and sometimes contradictory effects on income inequality indicators; for instance, the significant negative coefficient of the Palma ratio in the FGLS model (-1.155) suggests that these investments can reduce energy poverty under conditions of high income inequality. In contrast, the positive coefficients obtained for the Gini index in both the FGLS and PCSE models indicate that the transition to renewable energy may temporarily increase inequality by creating a "regressive" effect that favours certain income groups in the initial stages. This situation may arise from the high initial costs associated with the installation of renewable energy technologies, placing a burden on low-income groups, or from technology transfer processes being dominated primarily by advantaged groups with access to technological infrastructure.

Government Spending (GOV): The persistent negative coefficients for Government Spending (GOV) in all models degrade any doubts about higher public spending reducing energy poverty. This emphasises the strong role of social and public services for equitable energy access.

Log of GDP per capita (LGDP): The strong negative coefficient for LGDP under the Palma-FGLS (-1.130) proposes a condition where economic growth lowers energy poverty, particularly with high inequality. Whereas its effect is weaker or even positive for the Gini index, it may mean that economic growth is not always translating into benefits bestowed on all income levels equally.

Income Level (LIN): The consistently negative coefficients for Income Level(LIN) in all models conform to the economic theory that higher income levels decrease energy poverty. Its significance does not vary with either Gini or Palma usage, again underscoring the importance of this variable.

Foreign Direct Investment (FDI): The greatly negative coefficient for FDI in the PCSE_Palma

model, inter alia, (-1.169), implies the role of Foreign Direct Investment in reducing energy poverty. This impact is probably related to infrastructure development and job creation.

Trade Liberalisation (LTL): Negative coefficients of LTL across all models bear the implication that trade liberalisation helps reduce energy poverty. The stronger negative effect in the Palma (FGLS) model (-0.703) suggests that the relationship could be an additional consideration in highly unequal environments.

Energy Infrastructure (LEI): The negative sign of the coefficient in the Palma (FGLS) model (-1.155) and the positive sign in the Gini (PCSE) model imply that the effect of energy infrastructure might vary across income groups and increase inequality in some cases.

Urbanisation (LUR): Contrary to being a solution for energy poverty, positive coefficients of LUR among all models, especially on the high end of Palma (PCSE) at 0.420, suggest urbanisation may aggravate energy poverty. This could be because growing demand and poor infrastructure make it more difficult for low-income groups to get electricity in urbanising areas.

According to this comparative study, energy poverty is a complex issue that is intricately linked to income inequality. The estimate model (FGLS vs. PCSE) and inequality metric (Gini vs. Palma) selection have a big impact on suggested policies. Notably, trade liberalisation, rising incomes, government spending, and foreign direct investment are all successful strategies for reducing energy poverty. Income disparity could, however, momentarily rise as a result of urbanisation and some investments in renewable energy. A fair and inclusive energy transition must thus be ensured by carefully crafting energy policies with a strong emphasis on social fairness.

5. CONCLUSION

Energy poverty is a complicated and widespread issue that has a big influence on environmental sustainability, social development, and inequality. Our analysis demonstrates how differences in wealth and income directly impact access to vital energy resources, impeding overall progress and confirming the substantial correlation between economic inequality and energy poverty. We've also highlighted the essential significance of structural variables, such as poor infrastructure and disparities in government investment, which disproportionately affect energy access for different socioeconomic groups. This analysis emphasises how crucial sustainable energy solutions are to solving these complex issues.

It's important to recognise the transitional challenges that may initially benefit higher-income populations, even while using renewable energy offers cleaner, more affordable choices that could lessen energy poverty. Our results highlight how crucial government intervention and targeted policies are to closing these gaps and guaranteeing a fair transition, especially through financing for social assistance programs and strong energy infrastructure.

Additionally, we've found that while growing urbanisation might boost economic growth, it has a double-edged effect: because of growing demand and poor infrastructure, it frequently makes energy poverty worse in densely populated places. To effectively address energy poverty, inclusive and all-encompassing policy approaches that take socioeconomic, regional, and environmental aspects into account are required. Promoting equitable energy access, particularly for underserved groups in developing countries, requires that these policies prioritise international cooperation and information sharing.

Future Directions

While tackling the complex nature of energy poverty, it is vital to address these intertwined relationships through comprehensive methods and interdisciplinary research to produce practical solutions that support social justice, economic resilience and sustainable development. This study provides a framework for future research to examine in greater depth how the energy access landscape is changing and how it contributes to a more sustainable and equitable society. Future studies could examine the micro-level impacts of renewable energy, particularly by investigating how different renewable technologies (e.g., decentralised solar energy versus grid-connected wind energy) affect different income groups in urban and rural areas, thereby providing more precise information on equitable energy access. Additionally, a more in-depth analysis of specific government programmes and their long-term effectiveness in reducing energy poverty is necessary; this includes evaluating the impact of targeted subsidies, infrastructure investments, and regulatory frameworks across various national contexts to identify best practices. Further disaggregation of urban-rural energy poverty dynamics, taking into account factors such as migration, informal settlements, and access to traditional and modern energy sources, is also of great importance; this could lay the groundwork for specific urban planning policies to prevent the worsening of energy poverty in rapidly growing cities. Finally, researching how new energy technologies (such as smart grids and battery storage) and behavioural interventions can alleviate energy poverty, alongside understanding social acceptance and adoption barriers in different communities, will be invaluable. By following these paths, we can collectively advance our

understanding of the evolving energy access landscape and contribute to a more sustainable and equitable society for all.

Policy Recommendations: In the Direction of a Fair Energy Transition

For energy poverty and economic inequality to be effectively addressed, our findings highlight the necessity of focused and sophisticated policy measures. Governments should prioritise and strategically reallocate public funds towards direct energy affordability programs, such as subsidies for vulnerable households and investments in energy infrastructure that specifically target underserved communities, given the persistently negative impact of government spending on energy poverty. This means shifting from broad consumption-based spending to more targeted, effective programs.

Investment Plans for Renewable Energy: The conflicting outcomes for renewable energy underscore the need for well-thought-out renewable energy regulations. Although Palma notes that energy poverty is often reduced by renewable energy, policymakers must make sure that new renewable energy projects do not unintentionally increase energy bills or unfairly benefit higher-income people. This is especially true for environments with higher levels of inequality. Decentralised renewable energy solutions might be implemented in low-income urban and rural areas, and supportive regulatory frameworks that ensure fair access and reasonable rates for everyone could be developed.

Economic Growth for Inclusive Energy Access: Economic growth generally lowers energy poverty, but the extent to which it does so depends on the kind of inequality. It is essential to implement policies that support small and medium-sized businesses (SMEs) and vocational training to promote inclusive economic growth. Instead of just concentrating wealth, this makes sure that the advantages of economic growth are widely shared, improving energy affordability for people of all income levels.

Trade and FDI for Sustainable Infrastructure: Given the inverse relationship between trade liberalisation and FDI and energy poverty, policymakers ought to aggressively support measures that draw FDI to green technology trade and sustainable energy infrastructure. This can speed up advances in energy availability, provide employment, and ease the transfer of information, especially in developing nations.

Resolving the Issue of Energy Poverty in Urbanisation: Given the significant correlation between urbanisation and energy poverty, proactive urban planning that incorporates reliable infrastructure development and sustainable energy solutions is necessary. This entails creating structures that use less energy, extending public transit, and making sure that informal settlements have access to reasonably priced and dependable energy services. It is also important to make sure that low-income urban people do not experience higher energy expenses as a result of urbanisation. Policymakers may create more effective plans to combat energy poverty, advance sustainable development, and create greater income equality by implementing these concrete, doable suggestions.

DECLARATION OF ETHICAL STANDARDS

The authors of the paper declare that nothing necessary for achieving the paper requires ethical committee and/or legal-special permissions.

CONTRIBUTION OF THE AUTHORS

Ibrahim Horoz: performed the experiments and analysed the results, Review & Editing.

Meltem Ince Yenilmez: Wrote the manuscript, Review & Editing.

CONFLICT OF INTEREST

There is no conflict of interest in this study.

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