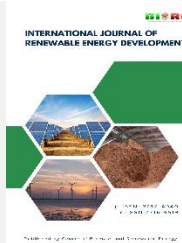




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Research Article

Harnessing renewable energy and technological innovation to alleviate energy poverty in least developed countries: A pathway toward low-carbon and sustainable development

Ramisa Rutbata Hossain[✉], Md Qamruzzaman[✉], Piana Monsur Mindia*[✉]

School of Business and Economics, United International University, Dhaka, Bangladesh

Abstract. Energy poverty remains a critical developmental challenge in Least Developed Countries (LDCs). However, existing literature tends to examine renewable energy, technological innovation, and carbon emissions separately, often overlooking their interconnected impact on energy poverty. Addressing this significant research gap, the present study investigates the combined roles of renewable energy consumption (REC), technological innovation (TI), and CO₂ emissions in alleviating energy poverty in LDCs from 2000 to 2020. Specifically, the study explores: (1) how renewable energy consumption influences energy poverty reduction; (2) the extent to which technological innovation improves energy accessibility and affordability; and (3) the impact of carbon emissions on pathways to reducing energy poverty. Utilizing advanced econometric methods on an extensive panel dataset, the findings reveal that a 10% increase in REC reduces energy poverty by approximately 0.814% to 1.105%, underscoring renewable energy's vital role in providing sustainable and affordable energy access. Similarly, technological innovation significantly mitigates energy poverty; a 10% improvement in TI results in a 1.215% to 1.564% decrease in energy deprivation, highlighting innovation's potential to overcome infrastructural barriers in energy delivery. Furthermore, a 10% reduction in CO₂ emissions correlates with a 0.914% to 1.399% decline in energy poverty, reinforcing that low-carbon strategies effectively promote both environmental sustainability and equitable energy access. This study uniquely integrates these factors, offering novel empirical insights into their collective influence on energy poverty in low-income contexts—an area previously underexplored. The findings emphasize the urgent need for coordinated policy frameworks and targeted investments in renewable energy infrastructure and technological innovation. Such integrated strategies are essential to simultaneously address energy poverty and environmental challenges, fostering sustainable, low-carbon growth trajectories aligned with the global Sustainable Development Goals (SDGs).

Keywords: Renewable energy; Technological Innovation; Energy Poverty; Least Developed Countries; CO₂ Emission



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1. Introduction

The impact of energy poverty, a lack of access to affordable, reliable energy sources, is profound and multifaceted across the globe at the economic and environmental levels. The studies of Amin *et al.* (2020), Ullah *et al.* (2021) and Chevalier and Ouédraogo (2009), found that energy poverty is a negative factor in economic growth in the long run and the short run. Energy poverty is an obstacle to the economy, as it affects both productivity and economic growth and worsens poverty cycles (González-Eguino, 2015). Lacking access to modern energy services, people and communities are compelled to rely on inefficient and frequently hazardous alternatives such as traditional biomass fuels for cooking and heating, which not only pose health risks but also take up valuable time and resources (González-Eguino, 2015). This reliance continues to constrain economic activities, restrict income-generating opportunities, and perpetuate a cycle of poverty by hindering access to education and healthcare services (Sovacool & Dworkin, 2015). Furthermore, energy poverty exacerbates urban-rural disparities, principally through

the amplification of the inequality between urban and rural areas, where rural populations are disproportionately affected by limited infrastructure development and higher costs associated with extending energy access. These economic implications thus impede economic development, competitiveness, and vulnerability to external shocks, thus preventing progress toward achieving sustainable development goals (González-Eguino, 2015). However, in addition to its economic consequences, energy poverty has a high environmental cost, contributing to environmental degradation and accelerating climate change. It relies not only on traditional energy sources such as solid biomass and kerosene—which contribute to indoor and outdoor air pollution, deforestation, and habitat destruction—but also plays a role in biodiversity loss and ecosystem degradation. Environmental consequences beyond local ecosystems are global warming's greenhouse gases from burning fossil fuels for energy release into the atmosphere, including resulting extreme events, sea level rise, and disruptions to agricultural systems.

Additionally, energy poverty leads to a vicious cycle in which environmental degradation challenges disproportionately

* Corresponding author
Email: piana@bus.uiu.ac.bd (P.M.Mindia)

disadvantaged populations, intensifying their socioeconomic challenges, creating a cycle of poverty, and triggering the cycle of energy poverty. Energy poverty thus becomes not only a necessary condition to expand economic development and social equity but also an essential aspect of global actions to reduce anthropogenic climate change and protect the environment for future generations (Zhao *et al.*, 2021), (González-Eguino, 2015), (Chevalier & Ouédraogo, 2009). Regions endowed with more natural resources like solar, wind, or biomass are better able to use these for the production of energy to reduce the reliance on expensive fossil fuels and access to energy (Sharma *et al.*, 2019). In this aspect, technological innovations play a significant role. Improved renewable energy technologies such as solar panels and cookstoves offer a sustainable, affordable solution, especially in geographically challenged and remote or off-grid locations (Taltavull de La Paz *et al.*, 2022). Supportive government policies that encourage energy efficiency and the utilisation of renewable energy, along with social safety nets, are crucial for increasing the accessibility, affordability, and reliability of energy among vulnerable populations. (Sharma *et al.*, 2019).

On the other hand, there are many negative drivers of energy poverty. In this regard, the first critical problem is that of infrastructure deficiency: Unreliable electricity grids and limited access to clean cooking facilities are significant obstacles to the availability of modern energy services for many regions, followed by the fact that such services are impossible to provide economically (Zang *et al.*, 2021). Similarly, economic restraints include high energy costs compared to incomes and decreased purchasing power that hinder the amount of a household's income that can be spent on purchasing essential energy services and appliances. (Sharma *et al.*, 2019). Social vulnerability, as determined by income inequality, unemployment, or lack of education, further raises vulnerability to energy poverty, and marginalised groups face additional barriers to accessing affordable energy services (Ismail & Khembo, 2015). The study of *Certomà et al.* (2023) advocated that environmental degradation through generally inefficient and polluting fuel sources, such as solid biomass and kerosene, includes the cost of enormous health problems and environmental damage, especially for the low-income population

Energy poverty has a significant and interconnected impact on developing nations, affecting both environmental sustainability and economic development. This complex issue involves varying degrees of access to electricity, the implementation of renewable energy sources, and carbon dioxide emissions. For example, in 1999, Albania and Argentina had very high rates of electricity access (100% and 95.13%, respectively), while Algeria and Angola had data gaps suggesting the possibility of very low access rates. Notably, the urban-rural electricity access gap further complicates the situation, as seen in Argentina's urban-rural divide in the same year. However, the extent to which countries have adopted renewable energy—crucial for sustainable development—varies widely. In 1999, Angola had a high renewable energy consumption rate of 72.42%, primarily from hydropower and biomass. In contrast, Algeria's rate was only 0.51%, reflecting its heavy dependence on fossil fuels. The adoption of renewable energy sources by nations often differs due to the availability of natural resources and the economic and political environments shaping their energy sectors. CO₂ emissions serve as a key indicator of industrialization levels and environmental impact. Argentina's industrialized economy and broader industrial base resulted in substantial CO₂ emissions, totalling 134,502 kilotons

in 1999. Albania..., on the other hand, emitted only 2,985.35 kilotons because its industrial sector was so much smaller. The persistence of this gap reflects an ongoing challenge that developing nations strive to overcome—specifically, balancing economic growth with environmental considerations. Energy poverty remains a critical issue in Least Developed Countries (LDCs), where millions lack access to affordable and reliable energy. This limitation hinders productivity, restricts access to essential services, and perpetuates economic hardship. Addressing energy poverty is not only a development imperative but also central to climate action and technological equity. The motivation for this study arises from the need to understand how renewable energy consumption, technological innovation, and carbon emissions interact to influence energy poverty in LDCs. Although these themes are often examined separately, their interrelationships remain poorly understood in low-income contexts. This research is significant because it bridges an urgent policy gap. By exploring how cleaner energy, technological progress, and emissions mitigation can work synergistically, it offers integrated solutions to reduce energy poverty. These insights are timely as countries pursue the dual objectives of expanding energy access and minimizing environmental risks. The guiding research question is: How do renewable energy use, technological innovation, and carbon emissions influence energy poverty in Least Developed Countries? Answering this question can support more effective energy policies, inform international aid strategies, and accelerate sustainable development outcomes in vulnerable regions. This study addresses critical gaps in the existing literature by providing new empirical insights into the drivers of energy poverty in LDCs. Specifically, the research advances knowledge by establishing the direct association between carbon dioxide emissions and energy poverty

Prior literature has predominantly focused on the environmental and economic dimensions of CO₂ emissions, leaving their social consequences underexplored. This study addresses that gap by demonstrating how high emissions can indirectly perpetuate energy poverty by limiting access to clean, affordable energy systems. Second, the study contributes to understanding technological innovation as a key factor in reducing energy poverty. Existing research often treats innovation primarily as a means for emission control or productivity enhancement. This study broadens that perspective by quantifying how technological innovation improves energy accessibility, reduces system costs, and addresses infrastructural deficiencies in least developed countries (LDCs). Third, it introduces a novel integrated framework that combines renewable energy consumption, technological innovation, and CO₂ emissions to evaluate their collective impact on energy poverty. These elements are typically studied in isolation or within high-income economies. This study extends the analysis to a low-income context and highlights their interdependencies. Fourth, the study employs recent panel econometric techniques to provide robust evidence on both short-run and long-run dynamics. This methodological rigor enables more precise policy implications, particularly relevant for contexts characterized by data constraints and structural volatility. Finally, the study offers a region-specific perspective by focusing on LDCs, where energy poverty is deeply intertwined with socioeconomic vulnerability. The insights provide actionable pathways to support sustainable energy transitions in settings most affected by underdevelopment and environmental fragility.

2. Literature review and research gap

2.1 Renewable energy consumption and Energy poverty

The link between renewable energy use and energy poverty is an increasingly important area of study; as countries seek to fulfil Sustainable Development Goals (SDGs) while combating climate change, governments must examine how to implement new energy frameworks that address both SDG 1: No Poverty and SDG 7: Affordable and Clean Energy. Energy poverty, which refers to the absence of access to modern energy services, impacts millions around the world, with developing countries being particularly affected. Databases were systematically reviewed based on the two key search terms of energy poverty and renewable energy consumption, with the main studies then synthesised within this literature review. Solar, wind, and biomass (renewable energy sources) have been presented as potential solutions to help end energy poverty. Studies show that low-income households have much to gain from the implementation of renewable energy technologies. For instance, Xia, Yu, *et al.* (2022) discovered that the rise of disposable income among residents in rural areas of China has a positive correlation with lower levels of energy poverty, indicating that investments made in renewable energy can develop local economies and then help with access to energy. Moreover, Adusah-Poku and Takeuchi (2019) said that the adoption of distributed renewable energy sources, including solar home systems, has proven to offer continuous per-user electricity access in off-grid energy communities, thus decreasing dependency on conventional biofuels, which further perpetuates energy deprivation. Furthermore, there is also the importance of renewable energy for energy security. Research has shown that by transitioning to renewable energy, we can shield ourselves from energy price volatility that hits the least fortunate hardest. For instance, Ogwumike and Ozughalu (2015) noted that access to modern energy sources such as renewables is crucial to sustainable development because energy poverty remains a top challenge for Nigeria. The study by Okushima (2017) and Yudiartono *et al.* (2023) concluded that renewable energy can offer vulnerable populations a more stable and affordable energy supply through diversification of energy and less reliance on fossil fuels. Additionally, the economic impact of renewable energy usage is not only restricted to energy access. Research by Šoavá *et al.* (2018) suggested a unidirectional causal relationship running from renewable energy consumption to economic growth in European nations, implying that renewable energy investments lead to job creation and, thus, economic growth. This economic growth, in turn, can help reduce poverty and raise living standards — and it does so by addressing the root causes of energy poverty. This highlights the synergy between renewable energy consumption and economic advancement. Xiao *et al.* (2021) suggested a need to align energy policies with more comprehensive socio-economic frameworks. Policy frameworks are critical for designing pathways for the transition to renewables and overcoming energy poverty. These policies should focus on investments in renewable energy infrastructure, especially for low-income and rural areas facing energy poverty. For example, Taušová (2024a) study in Poland, that government measures designed to stimulate renewable energy investments significantly reduced energy poverty levels. Likewise, the Multidimensional Energy Poverty Index (MEPI) constructed by Nussbaumer *et al.* (2012) highlights the importance of integrated policy responses that address multiple dimensions of energy poverty, such as access, affordability, and reliability of energy services. Successful renewable energy projects, all in one way

or the other, include some community engagement and education. Jones (2023) found evidence that indicates that the acceptance and sustainability of renewable energy projects can be improved when local communities are involved in the planning and implementation of such projects. For instance, the study of Brown and Vera-Toscano (2021) emphasised the need to tackle the health-related impacts of energy poverty and proposes that renewables can not only increase access to energy but also public health outcomes. Involving communities in the shift to renewable energy not only empowers them but also ensures that energy solutions are customised to local needs and wants. A shift to clean energy is also going to have to address equity and access issues. Indeed, alleviation of energy poverty is possible with renewable energy technologies, but if access to renewable energy technologies is not equally distributed, marginalized communities may be deprived. Adusah-Poku *et al.* (2021) also stress the need to remove systemic barriers to energy access, including access to affordable and financial options for renewable energy technologies. So, according to the study of Litaaba-Akila (2023) this means that renewable energy solutions should not only meet the needs of the wealthy but also implement interventions and policies that improve accessibility and equity for vulnerable populations. The relationship between renewable energy consumption and energy poverty changes based on regional and contextual reasons. Local infrastructure, economic conditions, and cultural attitudes toward energy use are among several variables that can dictate how effective renewable energy interventions are in any given context. Based on studies, like Cyrek and Cyrek (2022), solar photovoltaic systems, and wind and biogas systems are indeed widely discussed in rural areas of developing countries that have limited infrastructure to overcome energy crises. The findings of the study of Taušová (2024b) also said ensuring that renewable energy solutions are tailored to the specific context of each community is key to addressing energy poverty. To sum up, improving access to affordable and sustainable energy through renewable energy consumption can play a significant role in combating energy poverty. However, unleashing this potential requires a comprehensive strategy involving technology improvements, structural policies, community engagement in equity and access, and more. Further studies could investigate the dynamic interrelation of these issues and provide effective strategies for integrating renewables into efforts to combat energy poverty (Juszczak *et al.*, 2022; Ntanos *et al.*, 2018; Pombo-Romero *et al.*, 2023).

2.2 Carbon emissions and Energy poverty

In an era of continuous global efforts to combat climate change, the relationship between carbon emissions and energy poverty is a vital area of study. Inadequate access to modern energy services is widely recognised as energy poverty, which, unfortunately, is most prevalent among low-income populations and contributes to poor health and economic stagnation. This literature review aims to summarise the existing published studies on the influence of carbon emissions on energy poverty and to draw attention to new people across the globe who do not have access to energy, and the potential benefits of energy. The main worry about carbon emissions is the correlation to climate change, further aggravating energy poverty. The frequency and magnitude of climate-related disasters come with rising carbon emissions, which disproportionately harm vulnerable populations. Studies, for instance, Haoyan (2023), have shown that climate change results in higher demand for energy, which is increasingly needed for heating and cooling,

putting additional pressure on low-income households already grappling with energy affordability. As a result, the study of Xu *et al.* (2022) implied that any actions to cut down carbon emissions should be implemented with caution while compensating with solutions for energy poverty, as the neglect of one will ultimately deter the eradication of the other. The situation is all the more deplorable as carbon emissions have economic effects in the face of energy poverty. Duong and Flaherty (2022) formed a theory suggesting that carbon emissions correlate positively with industrial expansion, which can increase energy demand, leading to higher energy prices for users. In economic terms, this causes a "double-edged sword." While economic growth and prosperity reduce poverty, they also increase carbon emissions and energy poverty if not kept sustainable. The objective is to foster growth that is both zero-carbon and inclusive, ensuring it does not lead to further environmental degradation according to the Ampatzidis (2023) study. Technology is also critical both in reducing our carbon emissions as well as alleviating energy poverty. Palma *et al.* (2022) said that renewable energy technologies could provide affordable energy solutions for low-income households, decreasing the reliance on fossil fuels and offsetting carbon emissions. As an example, Cheng *et al.* (2021) noted that the use of solar energy systems in rural areas leads to energy accessibility, infrastructural improvement, and carbon footprint reduction. However, low-income households may be unable to afford the upfront costs of these technologies. Chen (2021) highlighted the need for supportive policies and financial instruments to make these technologies accessible. Policy interventions, therefore, help to mediate the relationship between carbon emissions and energy poverty. To avoid counterproductive impacts, effective climate policies need to take the socio-economic setting of energy poverty into account. Hu *et al.* (2020) stressed that a concrete example is carbon taxation, which can encourage cuts to emissions yet could unjustly overburden low-income households if not implemented from an equity perspective. The study Barbier (2014) highlighted that the revenue from carbon taxes can also be recycled to support energy efficiency programs and provide subsidies for low-income households in order to mitigate the financial burden of carbon taxes. In addition, the relationship between carbon emissions and energy poverty is mediated by wider socio-economic variables such as income inequality and educational attainment. The research by Yahong *et al.* (2022) indicated that energy is more available in highly unequal regions, but people with low incomes have limited access because the high income should be used for other purposes rather than energy. Also, Dzator and Acheampong (2020) stated that designing targeted social programs addressing income inequality can thus be an effective way to reduce energy poverty while simultaneously contributing to carbon emissions mitigation. Energy poverty has important health implications and is also related to carbon emissions. Wollburg (2023) stressed that the use of traditional biomass fuels for cooking and heating in low-income households presents serious health risks due to poor indoor air quality, particularly for women and children. Bousnina and Gabssi (2023) proved that not only does transitioning to cleaner energy sources reduce carbon emissions, but it also leads to better health outcomes, illustrating the co-benefits of tackling energy poverty and climate change together. To summarise, exploring the relationship between carbon emissions and energy poverty ultimately suggests the need for a holistic solution incorporating economic, environmental, and social drivers. As such, successful responses should focus on sustainable economic development, innovation

in technologies, and fair policy measures, ensuring that measures to decarbonise the economy do not further entrench energy poverty. Future studies should carry on this examination, concentrating on developing integrated solutions that simultaneously solve climate change and energy access issues (Baniya & Giurco, 2021; Heffron, 2022).

2.3 Technological innovation and Energy poverty

Exploring the relationship between technological innovation and energy poverty is a crucial link in understanding broader challenges of sustainable development and equitable access to energy in today's world. The absence of access to modern energy facilities, i.e., formally known as energy poverty, impacts millions worldwide both economically and socially, leading to further distortions. Inviting New Solutions: Renewable energy and energy efficiency advancements could reduce energy poverty through accessible, durable options. Given that, this literature review aims to synthesise several key research findings that studied the role of technological progress in renewable energy sources, namely solar, wind, and biomass, in solving energy poverty. For example, the cost of solar energy technologies has decreased dramatically, allowing households in remote areas to produce their electricity. Studies, for instance, Alshehhi *et al.* (2018), showed that decentralised solar systems can enable people in remote areas not connected to the national grid to access energy, reducing energy poverty. Moreover, Landrum and Ohsowski (2017) found that the advancement of energy storage technologies, like batteries, improves the reliability of renewable energy systems, making energy utilisation possible in times of low generation. This enhances access to energy and ensures environmental sustainability, assisting in reducing co-emissions through polluting fossil fuels. Furthermore, energy efficiency technologies make a significant contribution to alleviating energy poverty. Reducing energy consumption by innovating energy-efficient appliances and building designs can increase the energy affordability of low-income households. The research Ehnert *et al.* (2015) found that adopting energy-efficient technologies brings huge cost savings to consumers, alleviating the financial stress of energy expenses. Moreover, Baumgartner and Ebner (2010) noted that energy efficiency measures can be adopted on current infrastructure, serving as a cheap solution for enhancing energy access without the necessity of large additional spending on energy-generating plants. Policy has a seminal role to play in enabling the uptake of these technologies. Governments and international organisations play a crucial role in establishing a conducive environment for technological innovation with respect to the energy field. According to the Akhtar (2023), such policies included those that encourage research and development in renewable energy technologies, incentivise energy efficiency and help decentralise energy systems, addressing energy poverty. In addition, Bansal and DesJardine (2014) reported that public-private partnerships can harness resources and expertise that can significantly streamline the implementation of innovative energy solutions where they are needed most. Apart from technological and policy considerations, the success of innovations in fighting energy poverty also depends on social factors. Promoting awareness, adoption, and empowerment of the people, as well as allowing solutions to become self-sustaining, is a key. Study of Wynsberghe (2021) showed that

Table 1
Summary of literature survey

Author	Country	Methodology	Findings
Xia, Yu, <i>et al.</i> (2022)	China	Empirical analysis	Rising rural income correlates with reduced energy poverty via renewable energy.
Adusah-Poku and Takeuchi (2019)	Ghana	Case study	Distributed solar systems reduce reliance on biofuels and enhance energy access.
Ogwumike and Ozughalu (2015)	Nigeria	Qualitative analysis	Renewables offer stability and sustainable development potential.
Okushima (2017)	Japan	Quantitative modeling	Renewables ensure affordable, stable supply for the vulnerable.
Xiao et al. (2021)	Global	Bibliometric analysis	Calls for aligning renewable policies with socio-economic goals.
Taušová (2024a)	Poland	Case study	Policy incentives lower energy poverty through renewable investment.
Nussbaumer <i>et al.</i> (2012)	Global	Index development	The Multidimensional Energy Poverty Index emphasizes integrated policy response.
Jones (2023)	US	Thematic analysis	Community involvement enhances the acceptance of renewable projects.
Brown and Vera-Toscano (2021)	Australia	Longitudinal survey	Links renewable use to improved public health outcomes.
Adusah-Poku <i>et al.</i> (2021)	Ghana	Survey-based	Highlights financial and systemic barriers to energy access.
Litaaba-Akila (2023)	Togo	Survey analysis	Equitable policies were critical for poor household access to renewables.
Cyrek and Cyrek (2022)	EU	Comparative study	Renewables in rural areas help overcome infrastructure gaps.
Taušová (2024a)	Slovakia	Policy analysis	Tailored renewable solutions are required for effective outcomes.
Haoyan (2023)	China	Empirical	Rising emissions exacerbate energy poverty.
Duong and Flaherty (2022)	Vietnam	Structural equation modeling	Growth increases emissions and costs for poor households.
Ampatzidis (2023)	Greece	Spatial analysis	Zero-carbon growth was necessary to avoid marginalizing people experiencing poverty.
Cheng et al. (2021)	China	Panel data	Solar systems enhance access and reduce emissions.
Chen (2021)	China	Econometric model	Carbon taxes can hurt people with low incomes without equitable design.
Hu et al. (2020)	China	Market simulation	Carbon pricing must consider socio-economic settings.
Barbier (2014)	Global	Policy review	Recycling carbon tax revenue helps low-income energy users.
Yahong et al. (2022)	Developing countries	Panel data	Energy inequality persists despite high regional availability.
Wollburg (2023)	Global	Modeling	Emissions from traditional fuels worsen health and energy poverty.
Alshehhi et al. (2018)	Global	Financial analysis	Sustainability practices improve energy affordability.
Landrum and Ohsowski (2017)	Global	Content analysis	Decentralized innovation expands access.
Rusch <i>et al.</i> (2022)	Global	Strategic framework	Efficiency upgrades lower costs and improve access.
Palma <i>et al.</i> (2022)	Portugal	Efficiency study	Energy-efficient heating reduces emissions and costs.
Xiong <i>et al.</i> (2025)	China	Regional analysis	Innovation reduces structural distortions in energy access.
Anais <i>et al.</i> (2022)	EU	Case synthesis	Governance and innovation are needed together.
Batool <i>et al.</i> (2022)	OECD	Empirical modeling	Innovation bridges sustainability and access.
Dong <i>et al.</i> (2025)	China	Econometric	Tech innovation helps low-income energy affordability.

energy projects can have a higher acceptance and sustainability when the local community is involved in the planning and implementation. Moreover, Demastus and Landrum (2023) reported that combined with knowing the particular energy demands of specific communities, can guide the development of customized solutions that are more likely to succeed in reducing energy poverty. There is also an equity and access question at the intersection of technological innovation and energy poverty. The risks of technological innovations can be avoided only when all communities are equally able to access them, as otherwise, the benefits will not be evenly distributed, and marginalised communities may continue to be left behind. Hizarci-Payne (2020) stresses that the success of innovative energy solutions in reaching vulnerable populations depends on addressing specific systemic barriers to energy access through targeted interventions and policies. Emanuel and Adams (2011)

supported that this criterion can help with concerns like affordability and availability of financing options and provide technical assistance for new technology adoption. Moreover, the role of technological innovation in energy poverty is not homogeneous in regions and contexts. For example, local infrastructure, economic conditions, and cultural attitudes toward energy use can affect how well technological interventions work. However, Suciu (2023) highlighted that in areas where infrastructure is either non-existent or insufficient to support a project/development, the implementation of decentralized renewable energy systems may be limited by logistical challenges that can impact successful implementation. Similarly, Tiwary (2023) concluded that cultural perception of technology and energy consumption can affect the adoption of new energy solutions in communities. In summary, we have a technology-based opportunity to combat energy poverty

through affordable and sustainable energy access. However, unlocking this potential must be a holistic endeavour grounded in technology, policy, community, equity, and access. The ongoing study of the interplay between these elements is essential for creating successful tools to use technological innovation to solve energy poverty. Table 1 reports the summarised literature survey of the study

2.4 Literature Gap

There is much research on renewable energy consumption and its ability to mitigate energy poverty, but minimal research on how technological innovation and CO2 emissions are involved in this context, especially in Least Developed Countries (LDCs). Firstly, the extant literature, however, deals primarily with CO2 emissions and their relationship with climate change, environmental degradation, and economic growth. However, little is known about the relationship between CO2 emissions and energy poverty. Still, few studies have looked at the environmental costs of high emissions while ignoring how rising emissions can compound energy poverty by limiting access to cheap, clean energy. This gap is particularly pressing because, in LDCs, energy poverty and environmental degradation are closely intertwined. Surprisingly, no studies have related CO2 emissions to energy poverty, particularly since there is a worldwide commitment to the Sustainable Development Goals (SDGs) that underline the reduction of poverty and environmental sustainability.

Secondly, there is very little literature on how technological innovation can reduce energy poverty. Nevertheless, technological progress is considered a pillar of economic growth and energy efficiency, but there are only a few studies examining the direct effect of innovation on energy poverty. However, the existing literature mostly views clean energy technologies as a means to reduce emissions rather than enhance energy access and affordability in LDCs. It is an important gap, as technological innovation is needed to fill infrastructural barriers and enable the use of renewable energy solutions in regions of high poverty.

There is no intersectional analysis of the interaction between renewable energy consumption, technological innovation, and CO2 emissions in LDCs. These factors are often studied in isolation or developed countries and emerging economies. This paper seeks to fill these gaps by investigating the relationship between CO2 emissions, technological innovation, and energy poverty in LDCs. The study aims to

extract new knowledge of how such elements may contribute to environmental sustainability and the achievement of the SDGs.

3. Data and methodology of the study

3.1 Theoretical and conceptual development of the study:

Addressing energy poverty is not a simple task that can be resolved through a single approach, and the theoretical and conceptual framework of the research presented here further suggests that relationships among energy demand, carbon, and technology are part of the broader solution. Energy Ladder theory, van der Kroon *et al.* (2013), is among the theoretical foundations on which the present study is grounded. According to this theory, households switch from traditional biomass fuels to more modern and efficient energy sources as they get richer. Such a transition is a key element in the dynamics of energy poverty reduction and, thus, needs to be better understood, especially in diverse regions such as South Asia, characterised by strong socioeconomic and geographical disparities. Such inequalities are some of the most important determinants of access to modern energy services and energy use trends, rendering the theories of the Energy Ladder reasonably necessary to study the decomposition of energy poverty through the quantitative assessment of potential energy supply-demand developments as income levels increase.

Along with the Energy Ladder theory, this study includes the impacts of the Trade-off Theory. The idea from this theory is that attempts to eradicate poverty can come at the cost of more energy usage with environmental footprints. This paradigm is critical for acknowledging the imperatives of sustainable development strategies that ensure economic growth with environmental sustainability. The recognition of this trade-off in this study points to the importance of policies that do not sacrifice environmental health when seeking to alleviate energy poverty. In addition, by implementing the Solow Growth Model (SGM) (Stein, 2007), this work points out the importance of generating technological productivity for economic efficiency and sustainable growth. The SGM highlights that technological change is an important driver of economic growth and can play a major role in mitigating energy poverty.

The conceptual framework of this study, see Figure 1, is based on recognising that energy poverty goes beyond the restriction of access to modern energy services and has a wider context covering living conditions and economic development. Access to power is fundamental to a country's advancement; it

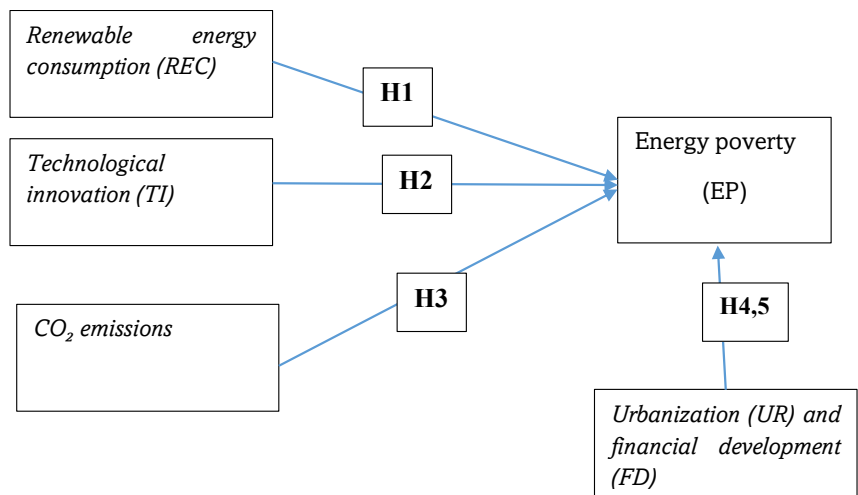


Fig 1 Conceptual framework with the hypothesis

influences everything from well-being to training and financial freedoms. This framework integrates theoretical foundations (Energy Ladder Theory, Trade-Off Theory, and Solow Growth Model) with empirical constructs—renewable energy consumption (REC), technological innovation (TI), and CO₂ emissions—analysing their combined impact on energy poverty (EP) in LDCs, see Fig 1.

H1: *Renewable energy consumption (REC) has a significant negative relationship with energy poverty (EP) in LDCs.*

H2: *Technological innovation (TI) significantly reduces energy poverty (EP) in LDCs by enhancing access and efficiency.*

H3: *Reduced CO₂ emissions are associated with a decline in energy poverty (EP), as low-carbon strategies support cleaner, more accessible energy.*

H4: *Urbanisation (UR) contributes to reducing energy poverty (EP) by improving infrastructure and energy access.*

H5: *Financial development (FD) alleviates energy poverty (EP) by enabling investments in renewable and efficient energy infrastructure.*

The theoretical development of the study depends on a blend of econometric models and regression analysis to explore the relationships between renewable energy consumption, CO₂ emissions, technological innovation, and energy poverty. Quantitative methods also provide empirical evidence of how these factors influence energy poverty levels.

$$EP | REC, TI, CO_2 \quad (1)$$

$$EP_{it} = \alpha_{it} + \beta_1 REC_{it} + \beta_2 TI_{it} + \beta_3 CO2_{it} \quad (2)$$

The coefficient of REC (β_1) is expected to be positive and statistically significant, that is $\beta_1 > 0$, indicating RE reduces EP, which can be found in the study of Wang *et al.* (2022), Biernat-Jarka *et al.* (2021), Karduri and Ananth (2023), Kocak *et al.* (2023), and Chien *et al.* (2022). Renewable energy consumption can reduce energy poverty through the provision of affordable and sustainable energy solutions that reduce energy costs, improve access to remote areas, and create jobs. Renewable energy investments make our energy more secure and less dependent on expensive imports of fuels. Further, renewable energy projects improve energy efficiency in ways that reduce local pollution from burning fossil fuels and improve health outcomes. Government policies and technological advancements make renewable energy an all-around and effective solution to combat energy poverty.

The coefficient of TI (β_2) is expected to be positive and statistically significant, that is $\beta_2 > 0$, indicating TI reduces EP, which can be found in the studies of Zhang and Yu (2024), Wang *et al.* (2023), Anais *et al.* (2022), Sun *et al.* (2023), Batool *et al.* (2022), and Dong *et al.* (2022). Many ways exist to reduce energy poverty through technological innovation. First, the development of renewable energy sources, like solar and wind power, allows for off-grid energy solutions, which expand the reach of reliable and affordable energy services to remote or underserved areas. Innovations in energy efficiency technologies across the spectrum reduce the amount of energy consumed per unit of output, lowering energy costs for households and businesses. Thirdly, smart grid technologies and energy management systems enhance energy distribution and usage by integrating renewable energy sources into the grid more effectively and more efficiently, reducing waste and helping those who are energy poor.

The coefficient of TI (β_3) is expected to be positive and statistically significant, that is, $\beta_3 > 0$, indicating that low CO₂ emission reduces EP; this can be found in the study of Dong, Ren, *et al.* (2021). Through its interconnected mechanisms, low CO₂ emissions reduce energy poverty. Low CO₂ emission technologies fight climate change and reduce local air pollution, which helps improve public health outcomes, particularly in communities disproportionately burdened with energy poverty. Second, the financial benefits of low CO₂ emission technologies, represented by the low cost of renewables relative to fossil fuels, translate into actual monetary benefits to households and businesses, easing energy expenditure pressure and contributing to poverty reduction. Thirdly, these technologies increase energy resilience and security through the diversification of sources, decoupling from centralised infrastructure, and improved access to secure energy in remote or underserved areas. Additionally, it also promotes job creation and economic growth by permitting investments in sustainable infrastructure and energy efficiency ventures via renewable infrastructure and energy efficiency projects.

3.2 Variable definition with proxy

Renewable energy consumption is energy from naturally replenishing sources, such as solar, wind, hydro, geothermal, and biomass. (Biernat-Jarka *et al.*, 2021), (Dong, Jiang, *et al.*, 2021). Renewable energy sources are helping to reduce fossil fuels. This greatly reduces greenhouse gas emissions and, hence, mitigates climate change. Renewable energy, by leveraging natural processes, diminishes the need for non-renewable energy and propels sustainable energy solutions.

The release of carbon dioxide into the atmosphere is called CO₂ emissions. Most of it is due to the combustion of fossil fuels, including oil, coal, and natural gas. This is also caused by deforestation and several industrial procedures, such as cement manufacturing. The artificial greenhouse gases (disturbances humans cause in the Earth's radiative balance) are dominated by CO₂. The causes of global warming, rising sea levels, extreme weather events, and loss of biodiversity are these characteristics. The realisation of reduced CO₂ emissions and the reduction of global warming is essential for climate change, and the protection of ecosystems and human health is what is called CO₂ reduction.

Creating and applying technological innovation involves new or improved technologies, tools, systems, and processes that produce significant advancements or breakthroughs in one or more fields. The process is one of harnessing knowledge, expertise, and resources to create innovative solutions to problems, increase efficiency, advance progress, and provide value supported by the studies (Coccia, 2021), (Ebadi & Utterback, 1984), and (Lundgren, 1991). Improving energy efficiency, developing clean energy technologies, and minimising carbon footprints for different industries are critically dependent on innovations in technology. According to (Grübler *et al.*, 1999), improvements in technology lead to the creation of more efficient renewable energy systems, electric vehicles, and smart grids, all of which lower CO₂ emissions and contribute to a lower (by implication) environmental impact.

Foreign Direct Investment (FDI) is a term for a firm or individual of one country investing in business interests in another country. Acquisitions may be acquired by the whole or by a lasting management interest, joint ventures, or by transferring technology and expertise. FDI can have both positive and negative environmental impacts. FDI can bring forward advanced management practices that promote environmental efficiency on the positive side. However, if not

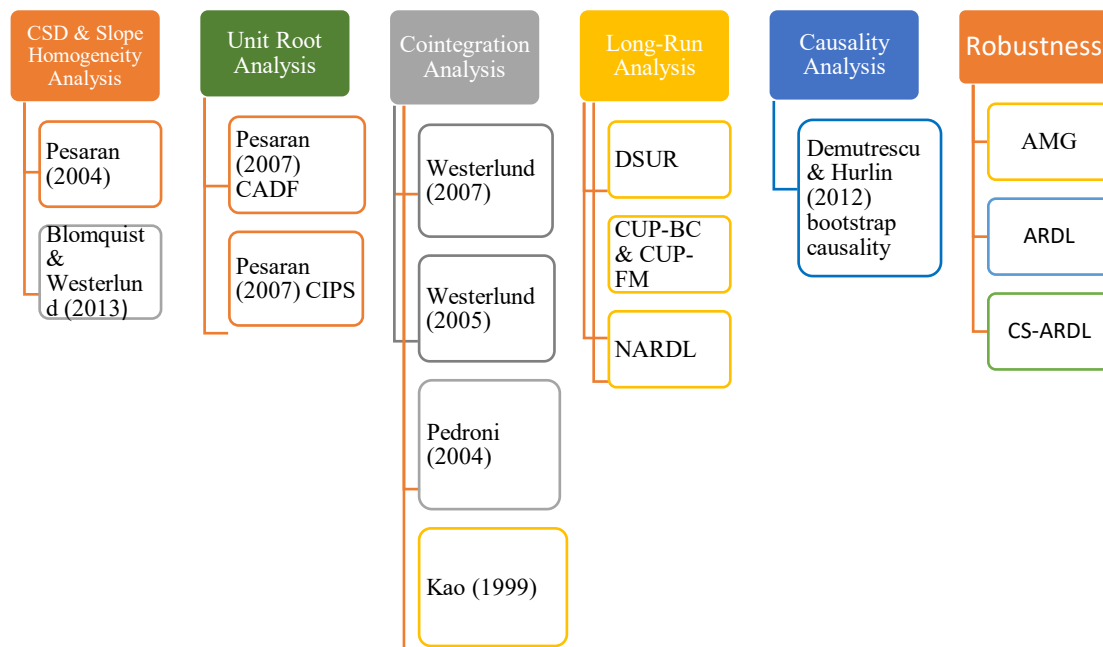


Fig 2. Flows of Estimations

managed sustainably, it can also increase resource extraction and environmental degradation. The impact of FDI on the environment is net of nature, depending on the nature of the investment and the regulatory framework.

The term capital formation refers to the net increment in the physical stock of capital in the economy, i.e., in machinery, buildings, and equipment. It is an investment in the building of a country's capital stock by investing in productive plants and equipment. Environmental improvements can be financed through the capital formation of eco-friendly infrastructure and green technologies. However, if the investments are funnelled into polluting industries, environmental destruction could worsen. Environmental considerations are integrated into investment decisions to promote long-term ecological balance (Solow, 1956) and, therefore, sustainable capital formation.

3.3 Estimation strategies

Stage 01: Cross-section dependence (CSD) analysis detects the presence of cross-sectional dependence in a given panel data set. This is important in order to avoid the wrong conclusion based on the correlation across units in the error terms of the regression models. (Pesaran, 2004) proposed a diagnostic test for CSD, which is the average of the pairwise correlation coefficients of the residuals from individual regressions, see Figure 2. This test assists in identifying the cross-sectional dependence that can be a source of the problem that can lead to panel data models being inaccurate.

The primary test statistic proposed by (Pesaran, 2004) is the CD test, which is defined as:

$$CD = \sqrt{\frac{2T}{N(N-1)} \sum_{i=1}^{N-1} \sum_{j=i+1}^N \rho_{ij}} \quad (3)$$

Here: T- time dimension, N- cross-sectional dimension, ρ_{ij} - sample estimate of the pairwise correlation of the residuals from a standard panel model for cross-sectional units for i and j .

Stage 02: In slope homogeneity analysis, we test the null hypothesis of equal slope regression coefficients across cross-sectional units in a panel data model. (Blomquist & Westerlund,

2013) Suggests a slope homogeneity test that takes into account the serial correlation and cross-sectional dependence. This helps one decide whether unit-level data pooling is justifiable or if it is preferred to have individual estimates of each unit.

$$\hat{H} = \frac{1}{N} \sum_{i=1}^N (\hat{\beta}_i - \bar{\beta})^2 \quad (4)$$

To allow for the presence of cross-sectional dependence, the cross-sectional augmented Dickey-Fuller (CADF) test (Pesaran, 2007) is used to test for the presence of unit roots in the panel data. The CADF test extends the standard ADF regression by including cross-sectional averages of lagged levels and the first differences of individual series (R. Wang et al., 2024; Yi & Qamruzzaman, 2024; Yingjun et al., 2024). The method aids in identifying unit roots of a correct form in the presence of cross-sectional dependence.

$$\Delta y_{it} = \alpha_i + \rho_i y_{i,t-1} + \beta_i \bar{y}_{t-1} + \gamma_i \Delta \bar{y}_t + \epsilon_{it} \quad (5)$$

The other method proposed by (Pesaran, 2007) is the Cross-sectionally Augmented IPS (CIPS), which is an extension of the Im, Pesaran, and Shin (IPS) test for unit root in panel data. The CIPS test overcomes this by using cross-sectional means in the augmented Dickey-Fuller regressions. The whole test statistic is obtained by combining the individual test statistics of the panel.

$$CIPS = \frac{1}{N} \sum_{i=1}^N CADF_i \quad (6)$$

Stage 3: Cointegration Analysis

Cointegration analysis shows that variables integrated of the same order have a long-run relationship. Westerlund (2007) introduced cointegration tests for several structural shifts and cross-sectional endogeneity. The tests presented here are based on structural dynamics and error correction models, which are very reliable when cross-sectional dependence and structural breaks exist.

$$\Delta y_{it} = \alpha_i + \rho_i(y_{i,t-1} - \beta_i x_{i,t-1}) + \sum_{j=1}^p \phi_{ij} \Delta y_{i,t-j} + \sum_{j=1}^p \gamma_{ij} \Delta x_{i,t-j} + \epsilon_{it} \quad (7)$$

Pedroni (2004) suggests a set of cointegration tests that allow heterogeneity across panel data. The tests include several statistics to check cointegration in panels with heterogeneous characteristics in terms of the degree of heterogeneity.

$$y_{it} = \alpha_i + \delta_i t + \beta_i x_{it} + \epsilon_{it} \quad (8)$$

These tests are helpful because they deal with problems associated with heterogeneity in panel data members, which are common in empirical studies. It is a reliable method of cointegration detection, and hence, it is very good for panel data analysis. This technique improves the validity of long-term relationship analysis by covering all aspects of the relationship.

$$\epsilon_{it} = y_{it} - \alpha_i - \beta_i x_{it} \quad (9)$$

The test is easy to implement and simple, making it a good tool for researchers. This does not complicate the method, and a resultant loss in the ability to detect cointegration does not affect studying the long-term connection in panel data.

As described by Mark, Ogaki *et al.* (2005), the Dynamic Seemingly Unrelated Regression (DSUR) is a technique for estimating the long-run parameters using panel data models. To address the problem of cross-sectional dependence and dynamics in the model, DSUR allows error terms to be correlated at the same point in time and allows dynamic adjustment in the model.

$$y_{it} = \alpha_i + \beta_i x_{it} + u_{it} \quad (10)$$

Continuously Updated and Bias Corrected (CUP-BC) and Fully Modified (CUP-FM) also improve Cointegration estimation in panel data. The estimates of the parameters and control for endogeneity and cross-sectional dependence are efficient and consistent.

$$\hat{\beta}_{CUP-BC} = \arg \min \sum_{i=1}^N (y_{it} - \alpha_i - \beta_i x_{it})^2 \quad (11)$$

The asymmetric long—and short-run dynamics of the model variables are incorporated into the NARDL model. The conventional ARDL model is extended by permitting nonlinear adjustments and asymmetric responses to changes in exogenous variables.

$$\Delta EP_{it} = \beta_{0i} + \beta_{1t} EP_{t-1} + \beta_{2i} REC_{t-1} + \beta_{3i} TI_{t-1} + \beta_{4i} CO2_{t-1} + \sum_{j=1}^{M-1} \gamma_{ij} \Delta EP_{it-j} + \sum_{j=0}^{N-1} \gamma_{ij}^+ (\Delta REC_{t-j}^+ +$$

$$\sum_{j=0}^{N-1} \gamma_{ij}^- \Delta REC_{t-j}^-) + [\sum_{m=0}^{q-1} \gamma_{im} \Delta TI_{t-m}^+ + \sum_{m=0}^{q-1} \gamma_{im} \Delta TI_{t-m}^-] + (\sum_{m=0}^{q-1} \gamma_{im} \Delta CO2_{t-m}^+ + \sum_{m=0}^{q-1} \gamma_{im} \Delta CO2_{t-m}^-) + \mu_i + \epsilon_{it} \quad (12)$$

The decomposition of REC, TI, and CO2 can be extracted in the following way.

$$REC_i^+ = \sum_{k=1}^t \Delta REC_{ik}^+ = \sum_{K=1}^T \text{MAX}(\Delta REC_{ik}, 0)$$

$$REC_i^- = \sum_{k=1}^t \Delta REC_{ik}^- = \sum_{K=1}^T \text{MIN}(\Delta REC_{ik}, 0)$$

$$TI_i^+ = \sum_{k=1}^t \Delta TI_{im}^+ = \sum_{K=1}^T \text{MAX}(\Delta TI_{im}, 0)$$

$$TI_i^- = \sum_{k=1}^t \Delta TI_{im}^- = \sum_{K=1}^T \text{MIN}(\Delta TI_{im}, 0)$$

$$CO2_i^+ = \sum_{k=1}^t \Delta CO2_{im}^+ = \sum_{K=1}^T \text{MAX}(\Delta CO2_{im}, 0)$$

$$CO2_i^- = \sum_{k=1}^t \Delta CO2_{im}^- = \sum_{K=1}^T \text{MIN}(\Delta CO2_{im}, 0)$$

To examine the causality connection in panel data, we use the Bootstrap Panel Granger Causality test (Dumitrescu & Hurlin, 2012). It is a cross-sectional dependence and small sample bias method; hence, bootstrap methods are used for causality inferences.

$$Y_{it} = \alpha_i + \sum_{k=1}^p \gamma_{ik} Y_{i,t-k} + \sum_{k=1}^p \beta_{ik} X_{i,t-k} + \mu_{it} \quad (13)$$

$$W_{NT}^{Hnc} = N^{-1} \sum_{i=1}^N W_{i,t} \quad (14)$$

$$Z = \sqrt{\frac{N}{2P}} \times \frac{T-2P-5}{T-P-3} \times \left[\frac{T-2P-3}{T-2P-} \bar{W} - P \right] \quad (15)$$

4. Estimation and Interpretation

Following Bersvendsen and Ditzen (2021) SH test detects structural breaks in time series data, indicating relationship changes between variables over time. The structural breaks are significant at the 1% level (***), as shown by the Delta Statistic and Adjusted Delta Statistic, see Table 2. Table 3 displays the results of the CSD test by following (Breusch & Pagan, 1980), (Pesaran, 2004), (Pesaran *et al.*, 2008), (Pesaran, 2006), and (Juodis & Reese, 2022). The findings revealed that variables are cross-sectionally dependent.

Table 2
Slope of heterogeneity test

Panel SH test of (Bersvendsen & Ditzen, 2021)			
	Delta Statistic	Adjusted Delta Statistic	SH exits
Model	3.6701***	4.8119***	Yes

Table 3
Cross-sectional dependency test

	(Breusch & Pagan, 1980)	(Pesaran, 2004)	(Pesaran et al., 2008)	(Pesaran, 2006)	(Juodis & Reese, 2022)
EP1	312.029***	39.122***	234.104***	51.335***	9.598***
REC	288.488***	22.339***	185.331***	19.489***	11.6694***
TI	280.037***	23.32***	173.346***	33.319***	8.2857***
CO2	224.252***	36.815***	198.486***	8.386***	10.8054***
UR	312.993***	20.499***	238.393***	7.863***	12.2635***
FD	170.739***	29.135***	223.377***	51.469***	10.5973***

Table 4

Panel unit root test

Variables	CADF test statistic		CIPS test statistic		Herwartz and Siedenburg -2008	
	Level	first difference	Level	first difference	Level	first difference
ER	-2.162	-4.889***	-1.619	-5.291***	1.0119	7.8123***
REC	-1.075	-5.258***	-2.908	-3.08***	0.2346	4.6534***
TI	-1.644	-2.142***	-2.004	-4.945***	-0.3219	5.7384***
CO2	-2.025	-2.688***	-1.917	-7.297***	-0.2306	8.2391***
UR	-2.924	-5.475***	-1.281	-4.457***	1.0575	6.5395***
FD	-2.748	-4.274***	-2.039	-4.673***	1.4784	8.8892***

Table 5

Panel Cointegration test

	no shift		mean shift		regiem shift	
	LMr	LMΦ	LMr	LMΦ	LMr	LMΦ
Model 1	-3.7896***	-3.0821***	-2.4162***	-3.2426***	-3.898***	-3.6975***
Model	Gt	Ga	Pt	Pa		
Model 1	-14.88***	-14.043***	-14.409***	-10.737***		

The panel unit root test results, see Table 4, indicate that most variables are nonstationary at their level, implying that their statistical properties (e.g., mean and variance) vary over time, rendering regression results unreliable if left untreated. After first differencing, all variables are stationary (significant test statistics implying that they are integrated of order one or (1). These variables are, therefore, random walk variables, and their trends must be taken into account by using first differences in further analysis to avoid spurious relationships.

Table 5 shows the panel cointegration tests based on the (Westerlund & Edgerton, 2007) and (Westerlund & Edgerton, 2008) methodologies, showing the long-run relationship among the variables. The LMr and LMΦ test statistics are statistically significant ($P < 0.05$) across all changes, indicating a strong long-term relationship among the variables tested. The GT and Ga test statistics are statistically substantial ($P < 0.05$ or $P < 0.01$) across each model, supporting the cointegration of the variables in each of the respective models and suggesting strong evidence of a long-run relationship among the variables.

Referring to the coefficient of REC, see Table 6, that is $DSUR_{0.0814}$; $CUPFM_{0.11059}$; $CUPBC_{0.0842}$, revealed positive statistical significance at 1% towards access to clean energy, suggesting that the state of energy poverty can be managed by accelerating energy sources with renewable sources. Precisely, a 10% change in REC will augment the process of reducing the EP by the range between 0.814% to 1.105%. Renewable energy

sources diversify and stabilise the energy supply, increasing accessibility and driving down electricity costs, directly alleviating energy poverty.

Next, the coefficient of TI, which is $DSUR_{0.1215}$; $CUPFM_{0.15636}$; $CUPBC_{0.14576}$, also revealed a positive statistical significance at 1% towards access to technological innovations, suggesting that the state of energy poverty can be improved by the increase in energy sources with the help of technological innovations. Precisely, a 10% change in TI will augment the process of reducing the EP by the range between 1.215% to 1.5636%. Technologies enhance efficiency in energy generation, transmission, and storage, leading to lower costs and helping increase access to energy, especially in neglected areas.

The coefficient of CO2 that is $DSUR_{0.1287}$; $CUPFM_{0.13985}$; $CUPBC_{0.0914}$, revealed a positive statistical significance at 1%, suggesting that the state of energy poverty can be improved by increasing energy sources by reducing CO2 emissions. Precisely, a 10% change in CO2 will augment the process of lowering the EP by the range between 0.914% to 1.3985%. Replacing high-emission energy technologies with low-emission energy technologies reduces CO2 emissions and enhances environmental sustainability through increased access to modern energy sources.

Now, referring to the coefficient of UR, that is $DSUR_{0.1690}$; $CUPFM_{0.08751}$; $CUPBC_{0.1830}$, reveals a positive

Table 6

Coefficients estimation with DSUR, CUP-FM, CUPBC: Access to electricity, urban (% of urban population)

	Coefficient	Std. Error	t-Statistic	Coefficient	Std. Error	t-Statistic	Coefficient	Std. Error	t-Statistic
	DSUR			CUM-FM			CUP-BC		
REC	0.0814	0.0434	1.8769	0.11059	0.0336	3.2913	0.08424	0.0419	2.0105
TI	0.1215	0.0286	4.251	0.15636	0.0403	3.8799	0.14576	0.0279	5.2243
CO2	0.1287	0.0206	6.249	0.13985	0.0169	8.2751	0.0914	0.0281	3.2537
UR	0.1690	0.0327	5.1691	0.08751	0.0468	1.8698	0.1830	0.0276	6.6315
FD	-0.13094	0.0139	-9.4201	-0.13977	0.0227	-6.15726	-0.0799	0.0276	-2.896
C	10.818	0.24013	45.0505	7.555	0.24013	31.462125	18.14	0.24013	75.542415
R2	0.9075			0.9			0.8939		
Adj R ²	0.9426			0.948			0.9508		

Table 7
Nonlinear estimation

Variables	Coefficient	st. error	t-stat	Coefficient	st. error	t-stat
Long-run asymmetric coefficients				Short-run asymmetric coefficients		
REC+	0.1019	0.0404	2.5222	0.0096	0.00735	1.3061
REC-	0.1112	0.0243	4.5761	-0.0068	0.00847	-0.8028
TI+	0.1349	0.0375	3.5973	-0.0114	0.00449	-2.5389
TI-	0.1376	0.0363	3.7906	-0.0389	0.00316	-12.3101
CO2+	0.1162	0.0404	2.8762	0.0096	0.00591	1.6243
CO2-	0.1465	0.0208	7.0432	-0.0104	0.00787	-1.3214
UR	0.1406	0.0279	5.0394	0.0466	0.00741	6.2887
FD	0.0927	0.0272	3.408	0.0427	0.00435	9.816
cointEq (-1)				-0.3239	0.047	-6.8914

statistical significance at 1%, suggesting energy poverty can be improved by increasing urbanisation. Precisely, a 10% change in UR will augment the process of reducing the EP by the range between 0.8751% to 1.830%.

Finally, referring to the coefficient of FD, that is $DSUR_{0.13094}$; $CUPFM_{0.13977}$; $CUPBC_{0.0799}$, also reveals a positive statistical significance at 1%, suggesting we can reduce energy poverty by increasing financial development. A 10% change in FD will augment the process of reducing EP by the range between 0.799% to 1.3977%.

Regarding the asymmetric effects, see Table 7 of REC on energy poverty, and in accordance with the study findings, it is apparent that REC plays a critical role in mitigating EP, which is found in all three model estimations. For positive (negative) shock, REC demonstrates a positive connection with EP in the long run. A 1% increase(decrease) in REC will improve the possibility of clean energy consumption by 0.1019% (0.1112%). In the short run, for a positive shock, REC will positively impact EP by 0.0096%, and for every 1% negative shock, REC will impact EP by -0.0068%. REC positively impacts EP by making clean energy accessible and affordable for everyone. In the long run, the positive shock in REC reduces dependence on costly fossil fuels and supports sustainable energy systems. In the short run, REC diversifies energy sources and stabilises the energy supply for immediate improvement in energy access, supported by (Xia, Yang, *et al.*, 2022) (Adusah-Poku & Takeuchi, 2019), Ogwumike and Ozughalu (2015), Okushima (2017), and Taušová (2024a).

TI has a positive impact on EP in the long run. A 1% positive(negative) shock will increase EP by 0.1349% (0.1376%). However, in the short run, any positive(negative) change will negatively impact EP, supported by the coefficients -0.0114 (-0.0389). TI positively impacts EP by making advancements in energy efficiency and the development of affordable clean energy sources. Study findings suggested that TI accelerates the deployment of innovative technologies, ensuring immediate improvements in energy distribution and reducing barriers to clean energy consumption, effectively mitigating energy poverty.

CO2 impacts positively in the long run. For every 1% positive (negative) shock, the change in EP is 0.1162% (0.1465%). In the short run, we can see that a 1% positive change has a positive impact of 0.0096% on EP. However, negative shock causes EP to deteriorate by 0.0104%. CO2 emissions impact EP by influencing the energy mix and access to affordable energy sources (Haoyan, 2023). Moreover, (Duong & Flaherty, 2022) noted that in the long run, higher CO2 emissions linked to energy production can improve EP, indicating increased energy availability from traditional sources.

For control, UR has a positive impact on EP. In the long run, for every 1% positive shock in UR, the EP will change by

0.1406%. In the short run, for a 1% change, EP will have a positive change of 0.0466%. UR positively impacts EP by ensuring improved infrastructure and access to energy. Finally, a change in FD also shows a positive impact on EP in the long run and the short run. In the long run, a 1% positive shift in FD will change EP by 0.0927%. In the short run, a 1% positive shock in FD will change it by 0.0427%. FD enables an increase in investments in energy infrastructure, which, in turn, makes energy affordable. This is how FD positively impacts EP both in the short and long run.

Increases or decreases in REC, TI, and CO2 emissions in the long run, which increase energy access and efficiency and reduce energy poverty. In the short run, though REC and CO2 improvements increase energy access, negative shocks (such as disruptions) decrease it somewhat. TI shows the opposite trend: While both positive and negative changes are beneficial in the long term, they exacerbate energy poverty in the short term, probably because of high initial costs, disruptions, or transition issues.

5. Discussion of the findings

The study results make a conclusive case for the idea that renewable energy consumption (REC) is necessary for energy poverty reduction in LDCs, as renewable energy has the potential to stimulate a significant transformation towards ensuring universal access to affordable, reliable electricity. Empirically, our results show that a 10% increase in REC decreases energy poverty by 0.814% to 1.105%, highlighting the role of renewable energy in underserved communities. This outcome aligns with earlier work by Karekezi and Kithyoma (2002), who find that decentralised renewable energy systems, including solar mini-grids and wind and bioenergy solutions, bridge the energy access gap in rural and off-grid regions. This is further emphasised by the International Renewable Energy Agency (IRENA 2020), which argues that decentralised renewable energy infrastructure is a low-cost option for accelerating energy access in developing economies, especially where traditional grid expansion is not economically viable. The primary benefit of renewable energy use is that it can diversify the energy mix and help reduce dependence on costly and environmentally damaging fossil fuels. Many LDCs depend on unclean and polluting energy, including kerosene and traditional biomass, which not only compromise home energy security but also worsen health risks from indoor pollution. The findings of the study indicate that increasing renewable energy infrastructure can significantly decrease energy prices, making electricity more accessible to those with lower incomes and minimising environmental and health risks. According to the World Bank (2019), demand for solar home systems and small-scale hydropower has significantly lowered energy expenditures for rural communities. Moreover, investing in

renewable energy spurs local economic growth, creating jobs in installation, maintenance, and manufacturing, thus bolstering socioeconomic resilience. All these are consistent with the study findings of IRAM *et al.* (2021), (Jiang & Khan, 2023), (Mirziyoyeva & Salahodjaev, 2023). However, despite these clear benefits, the adoption of LDCs is still limited due to challenges like high upfront investment costs, unavailability of financing mechanisms, and policy uncertainty. Governments can overcome these barriers by providing financial incentives, including subsidies, feed-in tariffs, and concessional loans, as well as public-private partnerships to increase investment in renewable energy projects.

A comparative perspective underscores the relative effectiveness of renewable energy expansion in LDCs versus middle-income countries. While this study finds that a 10% increase in renewable energy consumption reduces energy poverty by up to 1.105%, similar magnitudes have been observed in emerging economies, albeit with more robust institutional support. For instance, Taušová (2024b) showed that in Slovakia, comparable increases in renewable energy usage led to a 0.9% drop in energy deprivation, largely attributed to integrated policy frameworks and financing mechanisms. In contrast, LDCs often face systemic barriers—policy fragmentation, limited credit access, and grid unreliability—that limit the impact of renewables despite comparable potential. Studies by Nussbaumer *et al.* (2012) and Adusah-Poku and Takeuchi (2019) also highlighted that although solar and mini-grid adoption significantly improve access in off-grid areas, their success rates are higher where governments coordinate support with international partners. These comparisons reinforce that renewable energy in LDCs requires not only infrastructure but also institutional scaffolding. The variation in outcomes across contexts suggests that similar technical interventions yield different results depending on governance, investment capacity, and user adaptability. These cross-national contrasts provide a benchmark for LDCs to align domestic energy reforms with globally tested strategies.

This study explicates that technological innovation (TI) has a significant impact in ameliorating energy poverty, with empirical results of the study depicting that a 10% rise in TI causes a decline in energy poverty between 1.215% to 1.5636%, underling the importance of energy-efficient technologies, smart grids and digital innovations to enhance energy accessibility, which is consistent with studies like (Batoool *et al.*, 2022), (Zhang *et al.*, 2022), and D'ARLON (2014), highlighting that the development of technology helps to make energy systems more efficient. Power can be better distributed, and transmission losses can be reduced. Smart Meters, Mobile-based Pay-as-you-go energy systems, and Blockchain-based energy trading are contributing to making access to energy affordable to low-income households in areas where metering and grid expansion are either too costly or impractical. Decentralised and off-grid energy solutions have emerged as one of the biggest breakthroughs in this regard, allowing LDCs to "leapfrog" the challenges of extending traditional electric grids. Solar photovoltaic (PV) systems, mini-grids, and energy storage solutions (such as lithium-ion and saltwater batteries) sustain households and businesses through sustainable and uninterrupted power. The paper (Bhattacharyya & Palit, 2014) explored that in Bangladesh, as well as rural India, the rise in solar home systems has given millions of households clean and affordable electricity, enhancing education, healthcare, and economic productivity. Importantly, energy-efficient appliances like LED lighting, solar-powered cookstoves, and high-efficiency refrigeration systems have lowered household energy

demand, reducing the burden of energy costs for poor households. This is consistent with the findings of Palma *et al.* (2022), for whom energy efficiency is the key to reducing energy expenditure and improving affordability in developing countries. However, technological innovation has many obstacles in LDCs despite its large contributions. The deployment of advanced energy solutions is impeded by limited research and development (R&D) funding, a shortage of technical expertise, and lack of infrastructure. Moreover, the up-front capital costs of adopting renewable technologies continue to be a blockage for many households and small businesses, despite the fact that such technologies ultimately save money. Governments can accelerate the role of tech innovation in reducing energy poverty by creating incentives (R&D grants, tax credits, public-private collaborations and the like) to spur innovation. International organizations and financial institutions too need to scale up investments in energy technology innovations that can be made accessible and affordable for the low-income population.

Technological innovation in energy systems has shown varying impacts across national development tiers, and this study adds to that growing body of evidence. In LDCs, a 10% rise in technological innovation correlates with up to a 1.5636% reduction in energy poverty, highlighting its significance. However, this impact appears more modest than the effects reported in advanced economies. For instance, (Wang & *et al.*, 2023) found that in China, a similar increase in innovation resulted in an approximate 2.3% reduction, a gap likely due to differences in absorptive capacity, R&D spending, and infrastructure readiness. Moreover, innovations in LDCs often remain externally driven, with limited local integration. This contrasts with findings from Anais and *et al.* (2022), who emphasise that innovation embedded within local governance systems achieves higher success rates. Technological adaptation in LDCs must consider local constraints—affordability, technical literacy, and maintenance capabilities—factors often overlooked in top-down interventions. Cross-study comparisons reveal that merely transferring technologies without building adaptive ecosystems leads to suboptimal outcomes. Therefore, innovation policy in LDCs should prioritise contextual customisation and capacity-building rather than replication, which reinforces the need for LDC-specific frameworks that leverage innovation not as imported tools but as co-created solutions aligned with user realities.

When examining CO₂ emissions, this study's findings challenge some prevailing assumptions about the energy-development-environment nexus in lower-income settings. A 10% reduction in CO₂ emissions corresponds with a decrease in energy poverty of up to 1.3985%. This outcome differs from trends in more industrialised nations, where emissions reductions often coincide with energy cost increases that exacerbate affordability issues. For instance, Barbier (2014) and Ampatzidis (2023) argue that without redistributive policies, carbon pricing can disproportionately burden low-income households. In contrast, the LDCs in this study show a positive link between emission cuts and improved energy access, likely due to the replacement of costly fossil fuels with cheaper renewables. However, this divergence also reflects underlying structural differences. LDCs generally lack legacy fossil-fuel infrastructure and subsidies that skew energy markets in developed countries. Moreover, carbon mitigation in LDCs is often externally financed through mechanisms like the Green Climate Fund, which changes the dynamics of cost and benefit distribution. The study's comparative insight highlights that decarbonization in LDCs, when coupled with energy access

strategies, can yield dual dividends. This finding suggests the need to recalibrate global policy models, ensuring that carbon mitigation aligns with equity-focused energy transitions in resource-constrained environments.

Furthermore, the paper presents a 10% decline in CO₂ emissions, resulting in a decrease in energy poverty between 0.914% and 1.3985%, showing the correlation between CO₂ emissions and energy poverty, which indicates that switching to low-carbon sources of energy is beneficial for sustainable development, supporting the findings of (Li *et al.*, 2024) and (X. Wang *et al.*, 2024), as it is in line with sustainable energy for all, and thus contributes to the global efforts to attaining the sustainable development goals (SDGs), especially SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action). The shift to low-carbon energy systems foregoes fossil fuels as both an expensive form of energy and a source of climate change and air pollution that disproportionately burdens the working class and marginalised communities. We find that a heavy reliance on CO₂-producing energy production causes economic vulnerability, volatile energy prices, and health risks, as consistent with Ogwumike and Ozughalu (2015) and Chen (2021), leading to an increase in energy-poor individuals. LDCs can achieve energy security while also reducing environmental costs by investing in renewable energy infrastructure and reducing reliance on carbon-intensive energy sources. Carbon market mechanisms like carbon taxes and cap-and-trade systems already implemented have shown how national environmental policies offer valuable returns on investment in the context of renewable energy projects and social welfare programs. In Scandinavian nations, for instance, revenue generated from carbon pricing systems has been reinvested in renewable energy benefits and energy efficiency programs, further democratizing clean energy wealth by making it affordable for poorer communities. In addition, international climate finance through mechanisms like the Green Climate Fund (GCF) and the Clean Development Mechanism (CDM) have been instrumental in assisting low-carbon energy transitions in developing economies. Despite these positive outcomes, challenges remain in securing a fair and inclusive energy transition in LDCs. Many developing countries have already lost their fight against fossil fuel subsidies, which distort energy markets and deter investment in renewable energy solutions. Moreover, there is a lack of coherence in policies and regulatory frameworks, which also leads to uncertainty for investors and delays the transition to cleaner energy sources. Policy-makers must gradually eliminate fossil fuel subsidies, implement progressive carbon pricing mechanisms, and ensure there is clear regulatory policy to facilitate the uptake of renewable energy to overcome these challenges. The technical knowledge transfer and capacity-building programs should also be scaled up through international collaboration to allow LDCs successfully implement low-carbon energy strategies.

In addition to reducing emissions, effective climate action in Least Developed Countries (LDCs) must integrate mitigation with adaptation strategies. The study by Martin-Ortega (2024) underscores how transparent, integrated frameworks like MITICA can support national low-carbon development plans, particularly by targeting sectors such as transport, an emerging contributor to GHG emissions in developing economies. These insights are critical for LDCs, where sectoral emission reductions must align with broader socio-economic goals. Transport-sector mitigation, supported by transparent monitoring and reporting, helps ensure accountability and strengthens international cooperation. However, mitigation alone is not sufficient. As climate impacts intensify, adaptation

policies become essential to build resilience, particularly in vulnerable urban and rural systems. Nydrioti *et al.* (2024) emphasise the role of adaptive water resource management in semiarid regions under shifting climate scenarios. For LDCs, similar adaptation planning—targeting infrastructure, water, and health systems—must accompany emission reduction measures. The dual approach enhances system-level resilience and ensures that climate stressors do not reverse development gains. Integrating adaptation into national climate strategies thus strengthens policy coherence, improves local relevance, and supports long-term sustainable development pathways in climate-vulnerable contexts.

6. Conclusion and Policy Suggestions

6.1. Conclusion

This study comprehensively investigates the dynamic interplay among renewable energy consumption (REC), technological innovation (TI), and carbon dioxide (CO₂) emissions in alleviating energy poverty across Least Developed Countries (LDCs) from 2000 to 2020. Empirical results confirm that a 10% rise in REC reduces energy poverty by up to 1.105%, affirming renewable energy's pivotal role in expanding clean, decentralised, and affordable energy access. Technological innovation similarly demonstrates a significant alleviating effect, with a 10% increase in TI reducing energy poverty by as much as 1.5636%. TI enhances the reach and efficiency of energy systems, particularly through off-grid and smart technologies tailored to rural or underserved regions. Moreover, reductions in CO₂ emissions also correlate with improved energy equity, with a 10% cut linked to a 1.3985% decrease in energy poverty. These findings underscore a synergy between environmental sustainability and social equity, aligning directly with global Sustainable Development Goals (SDGs), particularly SDG 7 (Affordable and Clean Energy), SDG 13 (Climate Action), and SDG 1 (No Poverty). Nonetheless, the analysis faces notable limitations. It relies heavily on aggregate panel data, which may mask country-specific disparities, localised energy conditions, and informal energy systems prevalent in many LDCs. Furthermore, short-term disruptions in TI and REC adoption were shown to adversely affect energy access, hinting at a transitional cost not fully addressed in this study. Future research should, therefore, employ disaggregated national-level or household-level data, incorporate multidimensional energy poverty indices, and explore social-cultural drivers of energy behaviour in-depth. Additionally, the role of governance, financing mechanisms, and institutional quality in enabling these transitions deserves further empirical attention.

6.2. Policy suggestions in the view of the target nations

First, investing in renewable energy consumption is one of the most effective ways to alleviate existing energy poverty. Governments, particularly in Least Developed Countries (LDCs), need to implement policies that encourage the growth of renewable energy infrastructure by providing targeted subsidies and tax incentives. These measures can also reduce the overall cost of renewable energy, making it more affordable for low-income households by lessening the financial burden on renewable energy producers. For example, countries such as Germany and China have widely adopted feed-in tariffs (FITs), which guarantee fixed payments to renewable energy producers, thereby creating a stable market for clean energy production. Consequently, investment in renewable technologies, including solar and wind energy, is encouraged. By purchasing electricity from renewable sources at set rates

and through power purchase agreements (PPAs), governments gain greater market certainty. The adoption of these mechanisms can help jump-start the development of renewable energy projects in LDCs, which is essential for expanding energy access in rural and underserved areas.

In addition to supporting producers, governments can implement programs specifically designed to subsidize the installation of renewable energy systems for low-income households. For example, households may receive renewable energy through grants or low-interest loans for solar panel installations or gain access to community solar projects. These initiatives function as community-based renewable energy projects by enabling shared ownership of energy resources, which reduces the burden of energy provision while simultaneously enhancing community energy security. Small-scale renewable energy projects have successfully addressed both the affordability and sustainability of energy access in Asia. Similar approaches can be employed in least developed countries (LDCs) to combat energy poverty and improve environmental sustainability.

Moreover, the financial incentives can also sustain the broader energy transition by generating revenue from REC (Renewable Energy Certificates). A portion of these revenues can be set aside for energy poverty alleviation programs, such as energy efficiency projects that upgrade personal houses by improving insulation or purchasing more energy-efficient appliances. In LDCs, technological innovation is often the critical factor that overcomes infrastructure challenges, as energy grids do not reach remote or rural areas. Decentralised energy systems and public and private partnerships in R&D can expand the rollout of governments in energy access.

There is a lot of policy work to be done in the area of off-grid and mini-grid solutions. However, these systems have proven themselves able to provide electricity to places that traditional grid infrastructure cannot. For instance, off-grid solar home systems have been deployed in many African countries, allowing rural households to produce their electricity at a small fraction of the cost of traditional grid extension. Second, smart grid technologies can also be vital to secure and affordable energy access in LDCs, like those where they enable more efficient energy distribution and management.

With targeted government support, the perception of risks in renewable energy projects can be mitigated, enhancing their attractiveness to investors. Governments can promote technological innovation by awarding incentives for energy-efficient appliances and through technology transfer agreements that stimulate local innovation. International organisations, universities, and local enterprises work together to develop cost-effective energy solutions that respond to local needs. This includes, for example, households installing cheaper energy-saving devices, such as LED lighting or solar-powered water heaters, to reduce energy use.

The combination of nascent technology and the urgent need to expand energy access in LDCs creates space for public-private partnerships (PPPs) in clean energy technology development to foster new markets and jobs to help reduce poverty. Giving R&D funding to energy innovation allows governments to encourage local communities to become self-sufficient in sustainable energy. In LDCs, access to the latest technologies that would really have made a difference in reducing energy poverty is usually constrained by financial restraints.

Governments may empower themselves to alleviate energy poverty through carbon pricing methods: carbon taxes or carbon emissions cap-and-trade. These systems provide

financial incentives to enterprises to reduce their carbon footprints while they become less able to pay to emit greenhouse gases. If carbon pricing revenues are spent on projects that expand access to sustainable energy and energy efficiency for low-income communities, then that is a good investment.

In addition, carbon tax revenue could be used to subsidise renewable energy technologies and retrofits for low-income households to reduce their energy spending and improve their lives. A well-designed carbon pricing system could also help spur investment in renewable energy infrastructure in places where fossil fuels are necessary. By channelling these funds into the development of decentralised renewable energy systems, governments can direct these already energy-poor communities to benefit directly from the transition of the economy to a low-carbon economy.

The LDCs can also draw on the international climate finance mechanisms, the Green Climate Fund (GCF) and the Clean Development Mechanism (CDM), to collaborate with them on emission reductions and clean energy access in addition to domestic policies. Policymakers can effectively use these funds to finance renewable energy projects in the most energy-poor areas.

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