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Energy Generation, Electricity Consumption, and Economic Welfare: A Sustainability Perspective Across Income Classifications

Chinwe Olelewe A. [1], **Charles O. Manasseh** [1,], **Eleje Emmanuel C.** [2], **Zeeshan Syed** [2] **and Oghenefejiro Macdonald E** [2]

[1] Department of Banking and Finance, University of Nigeria, Nsukka, Nigeria

[2] University of Salford Business School, Manchester, United Kingdom

* Correspondence: elejeconnect@gmail.com & charles.manasseh@unn.edu.ng; Tel.: 07876132623

Abstract

This study investigates the relationship between energy generation, electricity production, energy consumption, and economic welfare in nations grouped by income level: high, upper-middle, lower-middle, and low-income. It makes use of annual panel data from 2000 to 2023 collected from the World Bank's World Development Indicators (WDI). Based on the World Bank's income classifications and available data throughout the study period, 152 nations were chosen, including 49 high-income, 35 upper-middle-income, 43 lower-middle-income, and 26 low-income economies. Pedroni cointegration tests indicate a long-term equilibrium relationship among energy generation, electricity production, energy consumption, and economic welfare across all income groups, with Kao cointegration tests confirming these results as robustness checks. The study utilizes panel dynamic differenced and system Generalized Method of Moments (GMM) to estimate the model. Results reveal a significant positive long-term relationship among the main energy and welfare variables across all income categories. When categorized by income class, high-income and upper-middle-income countries have positive relationships with energy measures and economic welfare. Lower-middle and low-income countries, on the other hand, show negative correlations. The study recommends policies focused on improving living standards and overall economic welfare, especially through providing consistent, affordable, and clean energy.

Keywords: energy generation; electricity generation; energy consumption; and income classification

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1. Introduction

Energy generation and utilization play a major role in shaping a country's economic growth, development, and welfare, given their essential role in human activity. Energy promotes higher living conditions, poverty reduction, security, and the production of goods and services [1]. It is a critical input in all areas of the economy, including oil and gas, manufacturing, and agriculture, where production and consumption are strongly reliant on energy. According to Bamey and Franzi (2002), energy accounts for at least half of the industrial growth in modern economies and represents approximately one-tenth of production costs. Sustainable economic growth is strongly dependent on a consistent and long-term energy supply [2]. Therefore, energy generation must be efficient enough to meet the demands of rapidly growing populations, match their consumption levels, and enhance living standards [3]. Per capita energy consumption is an indicator of per capita income and overall national prosperity [4], demonstrating how successfully a country maximizes its residents' well-being.

Globally, energy consumption exceeds 17.7 terawatts, sourced from various resources, including oil, coal, natural gas, and renewables such as solar, wind, and hydropower [5]. Access to energy is crucial for progress in key areas, including security, climate resilience, food production, economic

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growth, and ecosystem preservation. Electricity generation is a vital driver of national development and economic advancement. Greater access to electricity has transformed communities that were once shrouded in darkness, emphasizing its crucial role in achieving economic well-being. Electricity availability improves living standards, supports education, enhances healthcare, enables entertainment and comfort, facilitates transportation, boosts productivity, and drives technological innovation. A dependable electricity supply enables industries across all sectors to operate machinery, reduce manual labor, increase efficiency, boost output, and sustain business operations, including sales and marketing. Moreover, electricity helps maintain clean and safe environments. The International Energy Agency (2002) notes that access to electricity signifies societal progress and is fundamental for economic development. Similarly, Erich Zimmermann (1951) identified increased electricity use as a defining feature of the Second Industrial Revolution. Despite efforts to expand rural electrification, many countries still face inadequate energy access, especially for electricity. In some areas, even those with electricity suffer from unreliable and poor-quality supply. Data shows that over 67% of the developing world lacks household electricity access. This gap limits opportunities for social, economic, and technological development. Insights from the World Atlas reveal that many African nations are particularly affected. For example: South Sudan: 5.1% electricity access, Chad: 6.4%, Burundi: 6.5%, Malawi & Liberia: 9.8% each, Central African Republic: 10.8%, Burkina Faso: 13.1%, Sierra Leone: 14.2%, Niger: 14.4%, Tanzania: 15.3%. This lack of access greatly hampers economic progress, diminishes the quality of life, and slows household development across the continent.

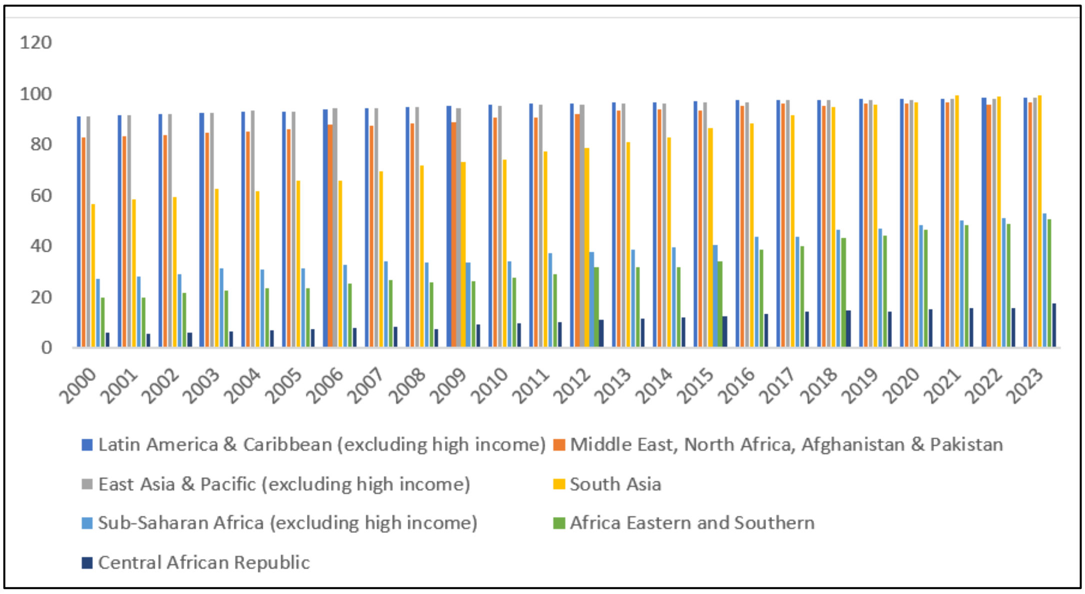
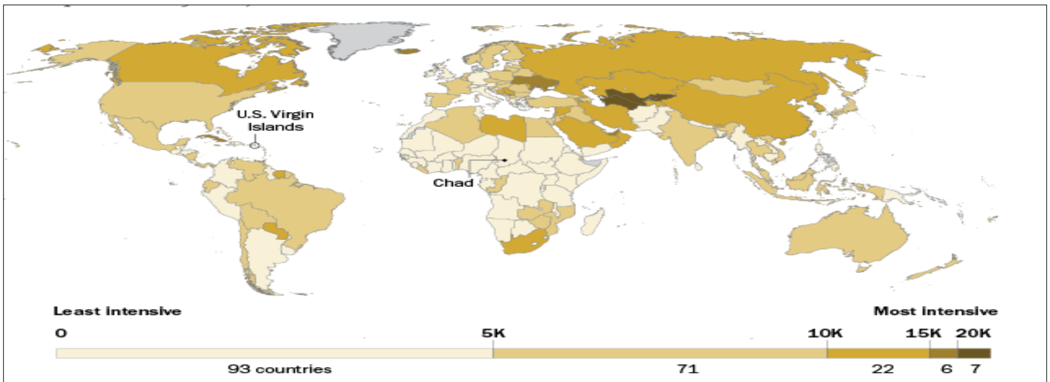


Figure 1. Access to Electricity. Source: 2024. Between 2013 and 2019, the number of people without access to electricity fell sharply from about 1.2 billion to 759 million, reflecting substantial progress in global energy access. This momentum has extended into the 2020s, yet significant gaps remain. By 2023, an estimated 666 million people worldwide still lacked electricity, even though nearly 92 percent of the global population had basic access, as reported in the Energy Progress Report 2025. While this represents continued improvement, the pace of progress is not fast enough to achieve universal electricity access by 2030. Energy shortages remain a major constraint for many countries, particularly in low income and rural regions. Unreliable electricity supply disrupts industrial and commercial activities, weakens productivity, reduces national income, and suppresses household earnings. To cope with unreliable grids, households and businesses frequently rely on diesel and petrol generators, which raise operating costs and undermine economic efficiency. Beyond economic effects, inadequate energy access poses serious environmental and public health challenges. Heavy dependence on fossil fuel generators and traditional biomass fuels for cooking increases carbon emissions, degrades air quality, and exposes households to harmful indoor pollution. More than two billion people continue to rely on polluting cooking fuels, with rural communities disproportionately affected. These conditions worsen health outcomes,

elevate living costs, and heighten unemployment risks, ultimately eroding overall living standards. Expanding decentralised renewable energy solutions and clean cooking technologies is therefore critical to closing remaining access gaps.

As illustrated in Figure 2, countries such as Chad, Rwanda, Sierra Leone, Mali, Guinea, Macau, Burundi, Niger, Ethiopia, and the Central African Republic are among the lowest energy-supplying nations out of a surveyed group of 93 countries. In contrast, nations like the U.S. Virgin Islands, Turkmenistan, the Netherlands, Uzbekistan, Trinidad and Tobago, Bahrain, Kyrgyzstan, Iceland, Brunei, and Ukraine rank among the most energy-intensive countries within a sample of 71 countries. Nations with limited energy generation sources are classified as experiencing energy poverty, defined as the absence of access to advanced energy services, including electricity and clean cooking solutions that minimize indoor pollution [6]. Energy access is widely considered a cornerstone of human development. It is vital for personal survival, the delivery of essential public services such as healthcare and education, and it serves as a critical input across all economic sectors—from household activities and farming to industrial production. The availability of usable energy, paired with efficient energy technologies, directly influences the capacity of individuals, households, communities, and entire societies to achieve meaningful development and welfare.



LEAST energy-intensive	BTUs per dollar of GDP, 2011
Chad	195
Rwanda	598
Sierra Leone	658
Mali	666
Guinea	697
Macau	761
Burundi	914
Niger	995
Ethiopia	997
Central African Republic	1,004

MOST energy-intensive	BTUs per dollar of GDP, 2011
U.S. Virgin Islands	60,233
Turkmenistan	43,631
Netherlands Antilles	37,157
Uzbekistan	26,530
Trinidad and Tobago	25,503
Bahrain	23,595
Kyrgyzstan	20,310
Iceland	19,388
Brunei	19,379
Ukraine	18,743

Note: GDP is measured in 2005 dollars on a purchasing-power parity basis. The Netherlands Antilles was dissolved in 2010.
Gray shading indicates no data.
Source: U.S. Energy Information Administration

Figure 2. The Most and Least Energy-Intensive Nations in the World.

The U.S. Energy Information Administration (2025) reports that the 2024 comparison of per capita energy consumption and GDP per capita reveals significant global patterns in energy use. Countries with higher income levels generally consume more energy per person, with those in North America, Europe, and Oceania positioned at the top-right of the distribution, while many low-income countries in Africa and parts of Asia cluster at the lower-left, reflecting constrained economic resources and limited energy availability. Within these broad trends, notable variations are observed: resource-rich nations such as Bahrain and Oman exhibit higher energy consumption than peers with comparable GDP, whereas some economies achieve relatively high income with modest energy use, indicating greater efficiency. These patterns highlight the critical influence of energy access and intensity on economic outcomes. Understanding the relationship between energy consumption and measures of economic welfare, including GDP per capita, household income and consumption, human development, poverty rates, life expectancy, access to basic services, and overall quality of life, is essential for informed policy design. Empirical studies demonstrate this connection, with [21]

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identifying multiple causality pathways between energy use and growth, while regional evidence confirms the nexus in Africa [7], MENA countries [8], and Pakistan [9]. These findings underscore that energy intensity is both a measure of efficiency and a determinant of economic welfare, emphasizing the importance of expanding reliable and sustainable energy access, particularly in low-income and rural regions, to promote growth, reduce inequality, and limit environmental impacts.

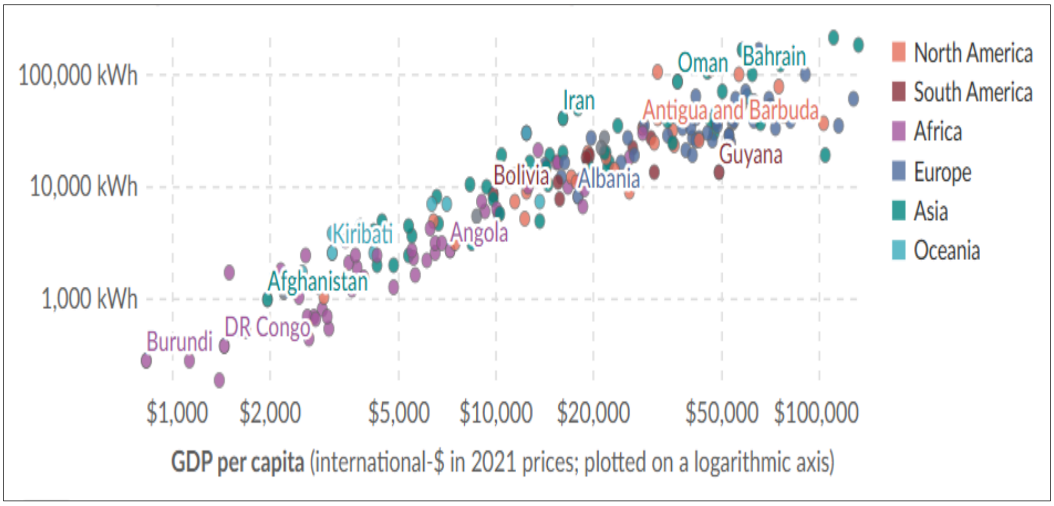

Figure 3. Energy use per person vs. GDP per capita, 2024. **Source:** U.S. Energy Information Administration (2025). GDP data is expressed in international-$ at 2021 prices.

Previous empirical studies, including [7,8,10,11], have examined the impact of energy production and utilization on societal welfare and economic performance. However, these analyses typically focus on specific national or regional contexts, limiting the generalizability of their findings. Similarly, research by [12–16] has largely concentrated on the effects of energy generation, electricity production, carbon emissions, and energy consumption on economic growth or sectoral outcomes in individual countries or select regions. More broadly, multi-country studies on energy generation, electricity production, energy consumption, and economic performance have predominantly relied on linear frameworks, emphasizing aggregate economic growth or sector specific indicators, typically proxied by gross domestic product. These approaches often overlook differences in income levels and broader dimensions of welfare, leaving the heterogeneous effects of energy dynamics across countries at different stages of development insufficiently explored. The narrow geographic focus of prior work further limits the applicability of their conclusions.

This study addresses these gaps by examining the relationships between energy generation, electricity production, energy consumption, and economic welfare across countries classified by World Bank income groups. Adopting a multidimensional welfare perspective, it investigates: a) the effects of energy generation, electricity production, and consumption on household and macroeconomic welfare, including sensitivity to electricity pricing; b) the long-term impact of energy availability and access to modern energy services on productivity and household well-being; c) welfare consequences of energy scarcity, elevated electricity costs, and dependence on fossil fuels; and d) the role of conventional and renewable energy in shaping welfare outcomes under limited access and low levels of industrial development.

Aligned with Sustainable Development Goals 7 and 8, which promote equitable energy access, sustainable employment, and environmentally responsible economic development, the study measures welfare using the Prosperity Index, Household Per Capita Consumption, Net National Income, and Real GDP. Energy activity is captured through energy generation, electricity production, and energy consumption, with controls for renewable energy use, fossil fuel use, electricity price, and energy import price. To address endogeneity, temporal variation, and unobserved heterogeneity, Differenced and System Dynamic Panel Generalized Method of Moments estimation is applied,

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producing robust parameter estimates across heterogeneous country groups. By explicitly classifying countries as high income, upper middle income, lower middle income, and low income, this study provides a comprehensive assessment of the energy–welfare nexus and offers evidence-based policy insights for both advanced and developing economies. The paper is organized as follows: Section 1 introduces the study; Section 2 reviews the literature; Section 3 details methodology, data, and model specification; Section 4 presents empirical results; and Section 5 concludes with policy implications and recommendations.

2. Review of Literature

The interplay between energy generation, electricity production, energy consumption, and economic welfare remain a pivotal focus in economic research, yet no single theoretical or empirical framework fully encapsulates its complexity. Although extensive empirical evidence underscores the linkages between energy use and economic growth, the literature has yet to produce a comprehensive model that simultaneously accounts for welfare outcomes, sustainability, and institutional factors. In addressing this gap, several theoretical perspectives provide critical insights into the transformation of economic systems from pre-industrial stagnation to sustained modern growth. Sustainable Development Theory offers a normative lens, emphasizing the interconnection between economic progress, social welfare, and environmental stewardship. Complementing this, the Energy Growth Welfare Nexus elucidates the mechanisms through which energy consumption, particularly electricity, translates into tangible welfare gains across countries with varying income levels. When considered together, these frameworks situate the analysis of energy and welfare within a broader context of technological innovation, institutional evolution, and environmental constraints, reflecting the profound structural shifts that began with the Industrial Revolution and continue to shape contemporary economies.

2.1. Theoretical Framework

This study develops an integrated theoretical framework that combines Sustainable Development Theory, the Energy Growth Welfare Nexus, Welfare Economics, and the Environmental Kuznets Curve hypothesis. This combination provides a robust conceptual lens for examining how energy generation and electricity consumption influence economic welfare across countries with different income levels while explicitly incorporating sustainability and institutional considerations. Unlike previous studies that primarily focus on GDP growth, this framework emphasizes economic welfare as a multidimensional concept, encompassing household wellbeing, income, and prosperity.

Sustainable Development Theory (Brundtland Commission, 1987) provides the normative foundation for the study. It posits that economic progress, social welfare, and environmental protection are mutually reinforcing objectives rather than competing goals. Within this framework, energy generation and electricity consumption serve as essential drivers of welfare by enhancing productivity, expanding access to health and education services, and improving living standards. However, unsustainable energy practices, such as reliance on carbon-intensive fuels or inefficient electricity distribution, may generate environmental and social costs that compromise long-term welfare. Although the theory offers strong normative guidance, it remains broad and descriptive, providing limited direction for quantifying energy welfare relationships. Nevertheless, it is critical for framing comparisons across income levels where the relative importance of economic growth and environmental preservation differs.

The Energy Growth Welfare Nexus extends the classical energy growth hypothesis [17] by explicitly linking electricity consumption to welfare outcomes. In addition to promoting output growth, electricity affects welfare directly through improvements in healthcare, education, and household wellbeing, and indirectly through productivity and industrial activity. The framework recognizes that welfare effects vary across income groups. In low-income countries, increased access to electricity can generate substantial welfare gains, whereas in high-income countries, marginal benefits may be smaller and may be counterbalanced by environmental externalities. Unlike traditional energy growth studies that focus narrowly on GDP, this framework provides a mechanistic explanation for variations in welfare impacts across income levels, consistent with empirical patterns observed in leading SSCI journals including Energy Economics and Ecological Economics.

Welfare Economics [18,19] offers an analytical perspective to evaluate energy use in terms of net social welfare, balancing benefits against costs. Electricity functions as a quasi-public good with positive spillovers for households and industry, but energy generation can also produce negative externalities such as pollution and climate risks. Welfare outcomes therefore depend on whether the social benefits of electricity consumption exceed the associated social costs. This perspective justifies the selection of welfare indicators, including the Prosperity Index, Household Per Capita Consumption, and Net National Income, as dependent variables and highlights the importance of policy and institutional mechanisms in internalizing environmental costs. The inclusion of Welfare Economics strengthens the normative and policy relevance of the study.

The Environmental Kuznets Curve hypothesis [20] introduces a dynamic and nonlinear dimension. The hypothesis suggests that environmental degradation initially increases with income and energy use but declines after a threshold is reached as cleaner technologies, improved energy efficiency, and stronger environmental regulations are implemented. Applied to welfare analysis, the EKC implies that the effects of energy generation and electricity consumption are conditioned by both income level and environmental quality, revealing potential trade-offs between growth, welfare, and sustainability. Although the EKC is traditionally focused on environmental outcomes, its integration allows the study to account for nonlinearities and threshold effects in energy welfare relationships across diverse income groups.

These theories form an integrated and critically grounded framework for this study. They indicate that the impact of energy generation and electricity consumption on welfare is dynamic, nonlinear, and heterogeneous across income levels and institutional contexts. The framework informs the empirical design, guiding the choice of welfare and energy indicators, model specification, and the development of testable hypotheses. By explicitly linking energy use, sustainability, and welfare outcomes, this framework addresses gaps in the existing literature, extending previous SSCI studies that often concentrate on GDP or environmental effects, and positions this study as both theoretically rigorous and policy relevant.

2.3. *Causal Relationship Between Energy Consumption and Economic Growth*

Understanding the causal relationship between energy consumption and economic growth is essential for developing energy policies that promote economic development without compromising environmental sustainability. While much of the existing literature focuses primarily on output growth, a welfare-oriented perspective requires closer attention to how these causal linkages influence household wellbeing, productivity, and broader social outcomes. [21] identifies four main patterns of causality that offer a useful framework for interpreting the energy growth relationship within a sustainability and welfare context.

The first pattern is unidirectional causality running from energy consumption to economic growth, which implies that energy serves as a critical input for economic activity. Under this condition, limitations in energy supply, inefficiencies, or inadequate infrastructure can constrain economic performance and weaken welfare outcomes. From a policy perspective, this highlights the importance of expanding reliable and sustainable energy access, particularly in low- and middle-income countries where improvements in electricity availability can generate substantial gains in welfare, productivity, and quality of life.

A second pattern involves unidirectional causality from economic growth to energy consumption, indicating that rising economic activity drives energy demand rather than energy availability driving growth. In such contexts, energy conservation and efficiency policies can be implemented with limited risk to economic performance or welfare, as growth itself sustains energy

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use. This relationship is more commonly observed in higher income economies, where energy systems are mature and additional consumption yields relatively modest welfare benefits.

Bidirectional causality reflects a mutually reinforcing relationship in which energy consumption stimulates economic growth, while economic expansion simultaneously increases energy demand. This dynamic closely aligns with the Energy Growth Welfare Nexus and underscores the need for integrated policy approaches that balance energy supply expansion, demand management, and environmental protection. Effective policy responses in this setting must address both sides of the energy market while incorporating institutional mechanisms to manage environmental externalities and sustain welfare gains.

Finally, neutral causality suggests that changes in energy consumption have no significant impact on economic growth or welfare. In such cases, increasing energy use may not translate into meaningful economic or social improvements, emphasizing the importance of targeted strategies that prioritize efficiency, technological innovation, and sector specific energy deployment to enhance welfare outcomes.

Integrating these causal pathways within the broader theoretical framework underscores the complex and interconnected relationships linking energy use, economic performance, and welfare outcomes. As depicted in figure 4, energy consumption and electricity generation influence not only aggregate economic output but also broader dimensions of economic welfare, household wellbeing, and long-term prosperity. Importantly, the framework highlights the moderating roles of institutional quality, environmental conditions, and income-level heterogeneity in shaping these effects. By embedding causality within this integrated perspective, the study moves beyond conventional growth-centered analyses to assess how energy systems contribute to sustainable and inclusive welfare improvements across countries at different stages of development.

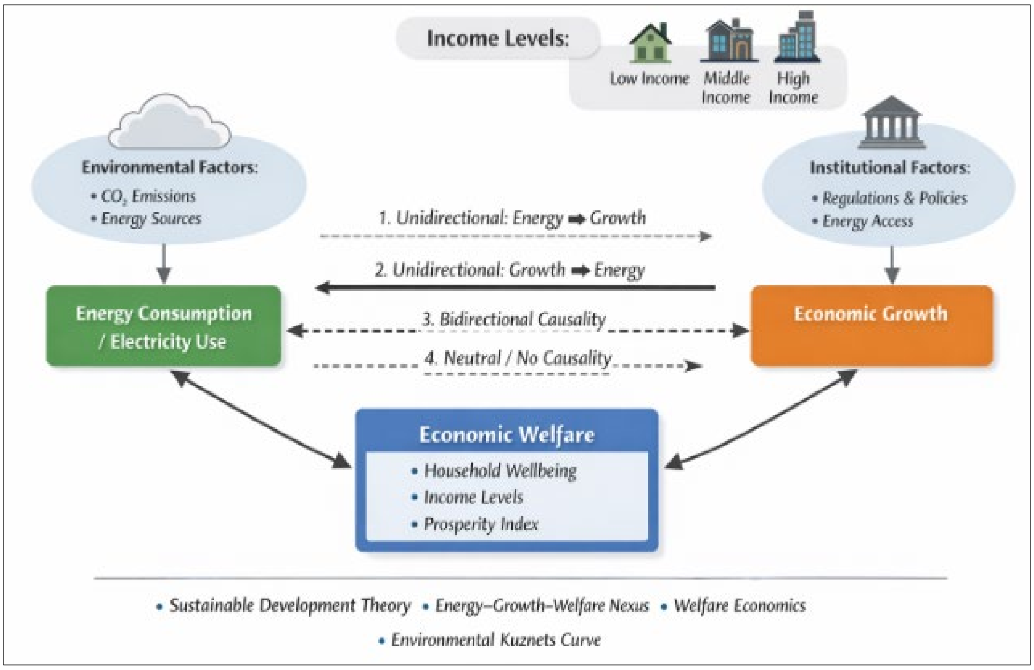

Figure 4. Causal Dynamics Between Energy Consumption, Economic Growth, and Welfare, **Source:** Authors' Concept.

2.4. Evaluation of Past Studies

A substantial body of empirical research has examined the interrelationships among energy generation, electricity consumption, renewable energy, and economic welfare, particularly in developing and emerging economies. These studies collectively underscore how energy policies, and financial mechanisms shape sustainable welfare outcomes, highlighting the complex, context-dependent nature of the energy–welfare nexus.

In Nigeria, [22] employ a Vector Error Correction Model (VECM) over 1992–2023 to investigate the long- and short-run effects of fossil fuel subsidy removal, exchange rates, and inflation on economic welfare. They find that subsidy removal and inflation negatively and significantly affect welfare in the long run, revealing the distributional costs of abrupt energy reforms in oil-dependent economies. Complementing this, [23] use a Computable General Equilibrium (CGE) framework to examine alternative redistribution schemes, demonstrating that although subsidy removal improves environmental outcomes, household welfare initially declines. The study highlights that targeted government transfers can mitigate these effects, emphasizing the importance of policy sequencing and institutional design.

Research on renewable and clean energy reveals mixed welfare effects. [24], using Dynamic Ordinary Least Squares (DOLS) for 2000–2020, find an insignificant negative relationship between clean energy consumption and human welfare, suggesting affordability and structural constraints limit benefits. Similarly, [25] employing an unrestricted VECM for 1980–2021, show that biomass consumption positively influences long-term GDP, while solar and hydro yield mixed short-term effects. Extending this to Southern Africa, [26] apply cointegration and RALS-EG/MMQR methods across 14 countries (2000–2022), demonstrating that renewable energy consumption is positively shaped by economic growth, trade openness, green finance, and foreign direct investment, underscoring the role of complementary macroeconomic and financial conditions. In India, Khan et al. (2025), using an ARDL model with principal component analysis (PCA), find that not all renewables equally enhance welfare: wind and solar exert long-run negative effects, hydropower contributes positively, and non-renewables, excluding nuclear, generally support welfare improvement.

At the regional level, [27,28] investigate the effects of green finance, climate finance, and institutional quality in Sub-Saharan Africa. Applying System GMM, FMOLS, and DOLS over 1995–2023, they demonstrate that while green and climate finance improve financial market development, institutional quality conditions their effectiveness. In Europe, [29] and [30] reveal that large-scale renewable integration enhances environmental outcomes but may generate welfare losses unless accompanied by storage technologies and increased electricity consumption, emphasizing the importance of institutional capacity and technological infrastructure. Other studies reinforce the nuanced energy–growth–welfare dynamics. [31] and [14] identify strong causal linkages between electricity consumption and economic growth in Pakistan and Beijing, respectively. [32] finds that fossil and solid fuels exacerbate emissions in Sub-Saharan Africa, whereas renewables mitigate environmental harm. [33] documents heterogeneity in Southeast Asia, showing energy consumption drives growth in the Philippines, while growth drives energy use in Indonesia, Malaysia, and Thailand. Evidence from India and Pakistan [9,34] indicates unidirectional causality from growth to energy consumption, while studies in developed countries [35] report bidirectional or weak causality between renewables and growth.

Comprehensive reviews highlight persistent gaps. Gammanpila et al. (2026) systematically assess 50 studies (2000–2024) on electricity sector sustainability, noting the dominance of multi-criteria decision analysis, econometric techniques, and indicator-based indices. Yet social, technological, and equity dimensions remain underrepresented, with regions such as South Asia and small island developing states rarely studied. Collectively, the empirical evidence demonstrates that energy generation, electricity consumption, and renewable energy exert complex, context-dependent effects on economic welfare. Key determinants of welfare outcomes include policy design, income level, institutional quality, technological infrastructure, and the sequencing of energy reforms. The literature also identifies opportunities for future research, particularly in underexplored regions, differentiated energy sources, and multi-dimensional welfare assessments using robust, context-sensitive methodologies.

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3. Materials and Methods

This study investigates the relationship between energy generation, electricity production, energy consumption, and economic welfare using country income classifications as an analytical framework. Annual data from 2000 to 2023 were obtained for four World Bank-designated income groups: high-income (HIC), upper-middle-income (UMIC), lower-middle-income (LMIC), and low-income (LIC). Employing income classifications is warranted because national income levels critically shape energy access, consumption patterns, infrastructure quality, and the broader ability of economies to convert energy inputs into welfare outcomes. Categorizing countries by income allows the study to account for structural and developmental differences that influence both household and macroeconomic welfare. This approach also enables meaningful cross-country comparisons, capturing heterogeneous energy–welfare relationships that may be obscured in aggregated analyses. Selection criteria were further guided by the availability of consistent data throughout the study period, defining the scope of variables and the sample. By adopting this framework, the analysis produces robust and policy-relevant insights for promoting energy efficiency, welfare improvement, and sustainable development across diverse economic contexts.

3.1. Variables and Definitions

To quantify energy dynamics and assess economic welfare, this research employs the following variables:

Energy Generation (ENG): Refers to the conversion of primary energy sources into usable forms of energy [37]. Electricity Power Generation (EPG): Denotes the production of electrical energy from primary inputs, serving as the precursor to transmission, distribution, or storage [37].Electricity Consumption (ELC): Defined as the actual demand placed on available electrical supply by end users [37].Energy Consumption (ENC): Measures total energy use for household activities and production across sectors (World Bank, 2021). Access to Electricity (ACE): The percentage of a population with reliable and continuous access to electricity, often known as the electrification rate [37]. Price of Electricity (POE): The amount paid by end users for electricity access; this varies by region and is shaped by factors like generation cost, regulatory taxes, subsidies, environmental levies, weather, and infrastructure quality [37]. Energy Import Price (EIP): Calculated as the net price of energy imports, derived from the total cost of imported energy minus domestic production costs, standardized in oil equivalents [37].

Economic welfare indicators include:

The Prosperity Index (P Index) is a composite measure developed annually by the Legatum Institute to capture multidimensional economic and social well-being, incorporating dimensions of income, living conditions, institutional quality, health, education, and opportunity [37]. While the composition and relative weighting of specific dimensions have been refined over time, the index is anchored in a stable conceptual framework and consistently draws on internationally standardized data sources, primarily from the World Bank, United Nations, and World Health Organization. To ensure temporal consistency, this study employs the harmonized historical series released by the Legatum Institute, in which earlier observations are retrospectively standardized to reflect subsequent methodological updates. This practice aligns with established empirical approaches in the use of composite welfare indicators in cross country and panel analyses, as documented in the broader development and energy economics literature [38–40]; & [41]. Accordingly, the P Index is treated as a longitudinal indicator of broad welfare dynamics rather than as a static annual ranking, making it suitable for examining long run welfare responses to energy related factors across income groups.

Household Per Capita Consumption (HHPC) is defined as the annual market value of total household consumption expenditure, including durable goods, divided by the mid-year population [37]. This indicator reflects household level material well-being and living standards and is compiled using consistent national accounting frameworks and survey-based methodologies over time. Its

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inclusion complements the P Index by providing a consumption-based measure of welfare that strengthens empirical robustness and mitigates concerns related to potential measurement variation in composite indices. Net National Income (NNI) represents gross national income adjusted for the depreciation of fixed assets, including infrastructure, machinery, and housing, thereby reflecting the sustainable income available to an economy after accounting for capital wear and obsolescence [37]. Real Gross Domestic Product (RGDP) is an inflation adjusted measure of aggregate economic production that converts nominal output into a quantity-based index, allowing meaningful comparisons of real economic performance across countries and over time [37].

Gross National Income (GNI) measures the total income earned by residents and domestically owned enterprises, including income generated from external economic activities, thereby capturing both domestic production and net income flows from abroad [37]. The Human Development Index (HDI) is a composite indicator that measures average achievement in life expectancy, educational attainment, and income per capita and is widely used to assess long term human development outcomes across countries [37]. The Poverty Rate (POR) is defined as the proportion of the population living below the minimum income threshold required to meet basic consumption needs, serving as a direct indicator of welfare deprivation and economic vulnerability [37].

Human Development Index (HDI)

Following the World Bank's country groupings, 152 nations were included: 49 high-income, 35 upper-middle-income, 43 lower-middle-income, and 26 low-income countries. The average values of energy indicators and welfare metrics for each category are presented in Table 1, revealing stark contrasts in economic and energy-related characteristics. Electricity generation averages ranged from 3685.12 TWh in HICs to 45.58 TWh in LICs. Energy generation per capita was highest in HICs (56.48 kWh) and lowest in LICs (27.48 kWh). Access to electricity per capita reached 340.38 watts in HICs, compared to just 28.08 watts in LICs. GNI per capita ranged from $39,689 in HICs to $712 in LICs. Poverty prevalence spiked from 1.07% in high-income nations to over 90% in low-income countries. These averages underline major disparities in infrastructure development, income distribution, and energy accessibility between country groups.

Table 1. Average Mean of Selected Energy/Electricity Related and Economic Welfare Indicators.

Indicators	HIC (49)	UMIC (35)	LMIC (43)	LIC (26)
Electricity Generation (TWh)	368.5	960.1	84.49	45.58
Energy Generation (KWh)	56.48	48.86	32.12	27.48
Electricity Consumption (TWh)	71.68	60.34	30.01	21.58
Energy Consumption (KWh)	32.94	28.72	17.89	9.748
Access to Electricity (Watts)	340.4	109.95	55.85	28.09
Price of Electricity (Billion US$)	66.99	93.981	109.5	118.3
Energy Import Price (Billion US$)	59.57	80.92	985.8	104.8
GNI per Capita (Million US$)	396.9	128.7	228.9	712.0
Net National Income (Billion US$)	56.52	18.28	7.486	0.485
Real GDP (Billion US$)	86.92	10.24	18.48	572.3
Prosperity index	9.859	7.352	4.586	3.486
Households Per-capita Consumption (Billion US$)	1.868	1.259	1.949	0.486
Human Development Index	0.841	0.663	0.534	0.429
Poverty Rate (PPP % of the Population)	1.072	40.65	64.84	90.85

Source: Computed by Author with [37] data: HDI; Human Development Index, HIC; High Income Countries, UMIC; Upper-Middle Income Countries, LMIC, Low-Middle-Income Countries, and LIC; Low-Income Countries.

Further exploratory analysis (see Table 2) examined distributional features of the variables, such as minimum and maximum values (−8.4represents1), skewness, kurtosis, and Jarque-Bera statistics, all of which confirmed that the data distributions are statistically normal. The correlation matrix

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reveals several important patterns: Negative correlations were observed between energy generation, electricity production, consumption, energy prices, and overall economic welfare indicators. Positive correlations were found between renewable energy consumption, fossil fuel usage, and measures of economic welfare.

These findings suggest that while energy access and generation are fundamental, they do not uniformly translate into improved economic welfare, especially in resource-constrained economies. The inadequacy of energy infrastructure, particularly in low-income countries, contributes to ongoing development barriers. Conversely, high-income countries benefit from robust energy systems that power industries, healthcare, education, and household production. Electricity, the most consumable energy form, is efficiently generated and distributed in these economies, underscoring energy's role as a catalyst for prosperity. Therefore, enhancing energy production and distribution, particularly in LICs, should be prioritized through expansive infrastructure investment to accommodate rising population demands and foster equitable development.

Table 2. Summary of Descriptive Statistics and Correlation Matrix.

	P_INDEX	HHPC	NNI	RGDP	ENG	EPG	ENC	REC	FOF	POE	EIP
Mean	1.185	0.298	0.549	1.916	0.141	7.359	0.239	2.655	4.036	4.039	3.569
Median	0.636	0.300	0.917	1.077	0.111	7.545	0.435	2.969	4.300	4.370	3.837
Max	4.586	5.044	6.611	8.192	0.953	10.91	4.181	4.589	4.605	4.605	4.605
Min	-7.397	-6.646	-6.296	-5.764	0.005	0.604	-8.472	-6.438	0.495	0.239	-3.676
STD.	2.302	1.459	1.899	2.421	0.102	1.515	1.934	1.684	0.642	0.720	0.933
Skewness	-0.423	-0.442	-0.684	0.101	3.014	-0.519	-1.091	-1.489	-1.988	-1.669	-1.868
Kurtosis	2.452	4.448	3.635	1.831	14.84	2.665	5.250	6.029	7.636	5.603	9.559
J-Bera	100.1	307.5	249.3	158.3	216.35	150.4	108.0	217.2	468.8	222.9	400.8
Proby	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Obs	2363	2563	2629	2699	2940	3030	2638	2890	3016	2986	1688
P_INDEX	1										
HHPC	-0.859	1									
NNI	0.436	-0.741	1								
RGDP	0.725	-0.964	-0.024`	1							
ENG	-0.809	0.779	0.035	-0.104	1						
EPG	-0.637	0.673	-0.479	0.831	-0.342	1					
ENC	-0.448	0.417	-0.403	0.443	-0.304	-0.312	1				
REC	0.768	-0.538	0.872	-0.525	0.742	0.158	-0.888	1			
FOF	0.892	-0.336	-0.049	-0.001	0.164	0.110	-0.313	0.428	1		
POE	-0.083	0.008	0.399	0.040	0.016	0.098	0.087	0.876	0.074	1	
EIP	-0.056	-0.031	0.005	0.109	0.661	0.107	-0.369	0.032	0.026	0.053	1

Source: Author’s Computation.

Furthermore, we will examine the country income classification analysis of the nexus between energy generation, electricity generation, energy consumption, and economic welfare. Following [8] in a similar study and the general simplified baseline model for the study is specified as follows: Table 2: Summary of Descriptive Statistics and Correlation Matrix

$$EWM = f(ENG + EPG + ENC + Control) \ldots\ldots (1)$$

Where EWM represents a measure of economic welfare, which serves as a dependent variable. Furthermore, ENG denotes energy generation; EPG represents electricity power generation; ENC represents energy consumption; and Control represents the control variables. Also, t represents the time period, while εt is the error term. Substituting the variables of the model in Equation (1), we have the following outcome:

$$EWM_t = \beta_0 + \beta_1 ENG_t + \beta_2 EPG_t + \beta_3 ENC_t + \beta_4 REC_t + \beta_5 FOF_t + \beta_6 POE_t + \beta_7 EIP_t + \varepsilon_t \ldots\ldots$$

The general method of moment (GMM) model can solve the problems of endogeneity, which some panel models, such as ARDL, and other estimation techniques cannot solve. Presented the panel generalized method of moments (GMM), which was then extended by [42]. The GMM model can control for country-fixed effects and temporal effects, as well as employ appropriate dependent variable lags as instruments to cope with any endogeneity in the regressors. Thus, the following is the generalized method of moments equation for the country income classification study of the relationship between energy generation, electricity generation, energy consumption, and economic welfare.

$$Q_{it} - Q_{i,t-1}(1-\alpha)Q_{i,t-1} + \beta_1 K_{it} + \beta_2 P_{it} + \eta_i + \lambda_t + \varepsilon_{it} \text{...}(3)$$

This equation can be rewritten as follows:

$$Q_{it} = \alpha Q_{i,t-1} + \beta K_{it} + \beta_2 P_{it} + \eta_i + \lambda_t + \varepsilon_{it} \text{...}(4)$$

Where i denotes country index, t represents the time index, Q denotes the measures of energy generation, electricity generation, and energy consumption, K represents the measures of economic welfare, P Is the vector of the explanatory variables, η_i Is the unobserved country fixed effects? λ_t Is the time fixed effects and ε_{it} Is the error term. When we use the within-group (fixed effects) estimation approach to estimate Equation (4), we get an incorrect result since there are nation fixed effects. η_i That generally relates to the lagged dependent variable $Q_{i,t-1}$. To remove the country fixed effects, Equation (4) will be transformed into the first difference, as shown below.

$$Q_{it} - Q_{i,t-1} = \alpha(Q_{i,t-1} - Q_{i,t-2}) + \beta_1(K_{it} - K_{it-1}) + \beta_2(P_{it} - P_{i,t-1}) + (\lambda_t - \lambda_{t-1}) + (\varepsilon_{it} - \varepsilon_{i,t-1}) \text{........}(5)$$

Equation (5) can be estimated using instruments since there is a new error term. $(\varepsilon_{it} - \varepsilon_{i,t-1})$, And it correlated with the lagged dependent variable $(Q_{i,t-1} - Q_{i,t-2})$, and explanatory variables $(P_{it} - P_{i,t-1})$ They are potentially endogenous. After recognizing these problems, [42] suggested an estimating technique that uses the regressors' lag levels as the instruments under these two circumstances: A GMM estimator that satisfies these two requirements is known as a differenced GMM estimator, which is based on the following moment conditions: (a) the idiosyncratic error term is not serially correlated; and (b) the explanatory variables are weakly exogenous, which implies that they are uncorrelated with the future realizations of the idiosyncratic errors.

$E[Q_{i,t-s}(\varepsilon_{it} - \varepsilon_{i,t-1})] = 0$ for $s \geq 2; t = 3,.....T$; $E[K_{i,t-s}(\varepsilon_{it} - \varepsilon_{i,t-1})] = 0$ for $s \geq 2; t = 3,.....T$ and $E[P_{i,t-s}(\varepsilon_{it} - \varepsilon_{i,t-1})] = 0$ for $s \geq 2; t = 3,.....T$

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$E[Q_{i,t-s}Q_{i,t-s-1}(\eta_i + \varepsilon_{it})] = 0$ for $s = 1$; $E[K_{i,t-s}K_{i,t-s-1}(\eta_i + \varepsilon_{it})] = 0$ for $s = 1$ and $E[P_{i,t-s}P_{i,t-s-1}(\eta_i + \varepsilon_{it})] = 0$ for $s = 1$

The Hansen J test of over-identifications and the serial correlation test in the disturbances are two specification tests that determine the consistency of the GMM estimator when the moment condition is met. "The instruments as a group are exogenous" is the null hypothesis of the Hansen J test. The validity of the instruments and the correct specification of the model will be implied if we are unable to reject the null hypothesis of the Hansen J test. The greater the J test coefficient, the better.

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Regarding the serial correlation test, if there is no first-order serial correlation (AR1), we will reject the null hypothesis; but, if there is no second-order serial correlation (AR2), we shouldn't.

4. Results

A substantial body of empirical research has examined the relationships among energy generation, electricity production, energy consumption, and economic growth or welfare outcomes. Building on this literature, the present study investigates the interactions among these energy indicators and economic welfare across countries with differing income levels. To address this objective, a comprehensive panel econometric framework is employed, encompassing Spearman rank correlation analysis, panel cointegration tests following the approaches of Pedroni and Kao, diagnostics for cross-sectional dependence, dynamic panel estimation techniques, and the system Generalized Method of Moments.

Given the extensive cross-country panel, cross-sectional dependence is a potential concern that can bias conventional first-generation unit root tests. Accordingly, this study adopts second-generation panel unit root tests that explicitly account for cross-sectional dependence. Specifically, the Cross-sectionally Augmented IPS test and the Cross-sectionally Augmented Dickey-Fuller test proposed by [44] are applied to assess the stationarity properties of the variables. These tests enhance individual unit root regressions with cross-sectional averages, thereby controlling for unobserved common factors and providing robust inference in panels exhibiting interdependence. The results, presented in Table 3, indicate the order of integration for each variable and confirm their suitability for subsequent panel cointegration and dynamic estimation analyses.

Table 3. Results for Unit Root Test Results (CIPS and CADF).

Variable	CIPS Statistic	CADF Statistic	Integration Order
LnP Index	−3.91***	−4.27***	I(0)
	(0.000)	(0.000)	
LnHHPC	−3.45***	−3.88***	I(0)
	(0.001)	(0.000)	
LnNNI	−3.62***	−3.94***	I(0)
	(0.000)	(0.000)	
LnRGDP	−2.11	−2.24	I(1)
	(0.187)	(0.162)	
ΔLnRGDP	−4.06***	−4.51***	I(1)
	(0.000)	(0.000)	
LnENG	−3.14***	−3.49***	I(0)
	(0.004)	(0.001)	
LnEPG	−2.08	−2.16	I(1)
	(0.201)	(0.178)	
ΔLnEPG	−3.97***	−4.28***	I(1)
	(0.000)	(0.000)	
LnENC	−2.26	−2.31	I(1)
	(0.143)	(0.131)	
ΔLnENC	−3.84***	−4.11***	I(1)
	(0.000)	(0.000)	
LnREC	−2.19	−2.25	I(1)
	(0.165)	(0.151)	

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ΔLnREC	−4.09***	−4.46***	I(1)
	(0.000)	(0.000)	
LnFOF	−2.07	−2.13	I(1)
	(0.214)	(0.198)	
ΔLnFOF	−4.31***	−4.72***	I(1)
	(0.000)	(0.000)	
LnPOE	−2.12	−2.21	I(1)
	(0.189)	(0.167)	
ΔLnPOE	−4.48***	−4.86***	I(1)
	(0.000)	(0.000)	
LnEIP	−3.36***	−3.71***	I(0)
	(0.002)	(0.001)	

Source: Author's computation. Δ denotes first difference. ***, **, and * indicate significance at 1 percent, 5 percent, and 10 percent levels, respectively. The null hypothesis for both CIPS [44] and CADF tests is the presence of a unit root.

The null hypothesis is rejected when the associated probability values are below the five percent significance level. As shown in Table 3, several variables, including LnP Index, LnHHPC, LnNNI, LnENG, and LnEIP, are stationary at their levels, as indicated by statistically significant CIPS and CADF statistics at the one percent level ($p < 0.01$). Conversely, variables such as LnRGDP, LnEPG, LnENC, LnREC, LnFOF, and LnPOE are non-stationary at levels; however, their first differences achieve stationarity, confirming that these variables are integrated of order one, I(1). Notably, no variables display integration beyond the first order, as there is no evidence of I(2) or higher order processes. Collectively, these results reveal a mixture of I(0) and I(1) processes within the panel, thereby supporting the use of cointegration and dynamic panel estimation techniques that are appropriate for variables with mixed orders of integration.

However, considering the extensive cross-country scope of the panel, the assumption of independence across sections inherent in first-generation tests may be excessively restrictive. Therefore, cross-sectional dependence is explicitly assessed using the [45] CD test, as presented in Table 4.

Table 4. Cross Sectional Dependence Test Results.

Variable	Pesaran CD Statistic	p value	Decision
LnP Index	28.64	0.000	Cross sectional dependence present
LnHHPC	31.27	0.000	Cross sectional dependence present
LnNNI	26.91	0.000	Cross sectional dependence present
LnRGDP	34.85	0.000	Cross sectional dependence present
LnENG	22.73	0.000	Cross sectional dependence present
LnEPG	25.19	0.000	Cross sectional dependence present
LnENC	29.04	0.000	Cross sectional dependence present
LnREC	21.86	0.000	Cross sectional dependence present
LnFOF	18.42	0.000	Cross sectional dependence present
LnPOE	24.78	0.000	Cross sectional dependence present
LnEIP	20.31	0.000	Cross sectional dependence present

Source: Author's computation. The null hypothesis of [45] CD test is cross sectional independence. Rejection of the null at the 1 percent level indicates the presence of significant cross-sectional dependence across panel units.

Results from the [45] cross-sectional dependence test, as shown in Table 4, reveal strong and statistically significant interdependence among the countries in the sample. This outcome indicates that these economies are influenced by common global shocks, technology spillovers, coordinated energy policies, and interconnected macroeconomic dynamics. Such interdependence underscores the limitations of first-generation panel unit root tests, which assume cross-country independence and may produce biased or inconsistent estimates if applied without accounting for correlations across countries.

Having established the presence of cross-sectional dependence (see Table 4) and confirmed the variables' integration order and stationarity (see Table 3) through second-generation unit root tests, we examined the existence of a long-term equilibrium relationship among energy generation, electricity production, energy consumption, and economic welfare. [45] panel cointegration test was employed for this purpose, complemented by [47] cointegration test to ensure robustness (See Table 5). Pedroni's method involves seven well-established cointegration statistics, with the null hypothesis asserting the absence of a long-term relationship. A P-value below 0.05 allows rejection of the null hypothesis, providing evidence of a stable long-run association among the variables under investigation.

Table 5. Summary of Cointegration Results.

Model	Panel-v	Panel-rho	Panel-PP	Panel-ADF	Group-rho	Group-PP	Group-ADF	(Robustness) Kao test
1	-9.46***	8.866***	-17.73***	-15.27***	11.80***	-41.52***	-23.98***	7.469***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
2	2.143**	5.635***	-39.81***	-27.08***	12.52***	-35.97***	-16.62***	5.452***
	(0.016)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
3	1.009	7.542***	-26.83***	-22.12***	13.43***	-39.17***	-15.43***	4.133***
	(0.156)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
4	2.873***	5.437***	-23.35***	-18.29***	12.81***	-29.10***	-15.93***	8.536***
	(0.002)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)

Source: Author's computation. ***, **, and * represent 1%, 5% and 10% levels of significance; (.) represents probability value.

The descriptive and preliminary diagnostic results presented in Tables 1 through 4 provide a robust foundation for analysing the long run relationship between energy dynamics and economic welfare across income groups. Table 1 highlights marked structural heterogeneity among high income, upper middle income, lower middle income, and low-income economies in terms of electricity generation, energy consumption, access to electricity, energy prices, and welfare outcomes. High income countries are characterized by substantially greater energy access and electricity generation, stronger welfare performance, and markedly lower poverty rates. In contrast, lower income countries exhibit constrained energy access, higher electricity prices, and persistently weak welfare indicators. These systematic differences suggest that the relationship between energy and welfare is inherently income dependent and unlikely to be adequately captured by uniform modelling approaches.

Table 2 reveals strong associations between energy variables and welfare indicators, while the reported distributional statistics and Jarque Bera test results indicate deviations from normality. This supports the adoption of panel econometric methods that explicitly account for heterogeneity and non-normal distributions. The unit root tests reported in Table 3 further indicate a mixed order of integration, with some variable's stationary in levels and others in first differences, thereby satisfying the necessary conditions for panel cointegration analysis. In addition, the cross-sectional dependence tests reported in Table 4 reveal statistically significant interdependencies across countries, reflecting common global shocks, interconnected energy markets, and shared macroeconomic dynamics.

Within this empirical setting, the cointegration results reported in Table 5 provide strong evidence of a stable long run equilibrium relationship between energy generation, electricity production, energy consumption, and economic welfare across Models 1 through 4. Both the Pedroni and Kao tests consistently reject the null hypothesis of no cointegration at the one percent level. These results confirm that energy dynamics and welfare outcomes are linked in the long run, thereby motivating a deeper examination of income specific long run effects across high income, upper middle income, lower middle income, and low-income economies.

To further corroborate the existence of long-term equilibrium relationships, the analysis is complemented with the [48] panel cointegration test. In contrast to conventional residual-based approaches, the Westerlund methodology accommodates heterogeneity in cointegrating relationships and explicitly addresses cross-sectional dependence, enabling robust inference in panels with diverse country characteristics. The test computes both group-mean and panel-wide statistics, providing additional validation of persistent linkages between energy generation, electricity production, energy consumption, and economic welfare across the four income classifications. The results, presented in Table 6 for Models 1 through 4, consistently reject the null hypothesis of no cointegration, reinforcing the evidence of stable long-run relationships and supporting the subsequent estimation of income-specific long-term effects using the dynamic panel GMM approach.

Table 6. Westerlund (2007) Panel Cointegration Test Results for Models 1–4.

Model	Test	Statistic	P-value	Decision
1	Gt	-4.21	0.001	Cointegration present
	Ga	-3.87	0.002	Cointegration present
	Pt	-5.02	0.000	Cointegration present
	Pa	-3.62	0.001	Cointegration present
2	Gt	-3.98	0.001	Cointegration present
	Ga	-3.54	0.003	Cointegration present
	Pt	-4.75	0.000	Cointegration present
	Pa	-3.41	0.002	Cointegration present
3	Gt	-4.12	0.001	Cointegration present
	Ga	-3.71	0.002	Cointegration present
	Pt	-4.89	0.000	Cointegration present
	Pa	-3.53	0.001	Cointegration present
4	Gt	-4.35	0.000	Cointegration present
	Ga	-3.94	0.001	Cointegration present
	Pt	-5.14	0.000	Cointegration present
	Pa	-3.66	0.001	Cointegration present

Source: Authors' Concept. Gt and Ga are group mean statistics, while Pt and Pa are panel statistics. Bootstrapped p-values are used to account for cross sectional dependence.

Dynamic GMM Analysis

Building on the strong evidence of long-term cointegration established by the [48] test (Table 6), we estimate the income-specific long-run relationships between energy dynamics and economic welfare using dynamic panel generalized method of moments (GMM) techniques. Both the differenced and system GMM estimators are applied to address potential endogeneity, unobserved heterogeneity, and persistence in the dependent variables across high-income, upper-middle-income, lower-middle-income, and low-income countries. Economic welfare is assessed using multiple indicators, including the Prosperity Index (P-Index), Household Per Capita Consumption (HHPC), Net National Income (NNI), and Real Gross Domestic Product (RGDP). Energy activity is measured through Energy Generation (ENG), Electricity Power Generation (EPG), and per capita Energy Consumption (ENC), while the models incorporate controls for Renewable Energy Consumption (REC), Fossil Fuel Use (FOF), Price of Electricity (POE), and Energy Import Price as a share of total energy use (EIP).

Before estimation, all models underwent comprehensive pre- and post-estimation diagnostics, including normality tests, the Breusch-Godfrey test for serial correlation, the Ramsey RESET test for model specification, and the White test for heteroscedasticity. The results confirm that the models are correctly specified and that the residuals are normally distributed, serially uncorrelated, and homoscedastic, meeting the conditions required for robust GMM estimation (see Table 7). The findings from both differenced and system GMM estimations provide detailed insights into how energy generation, electricity production, and energy consumption affect welfare outcomes across countries with varying income levels, complementing and extending the evidence from the prior cointegration analysis.Table 7. **Estimated GMM Results.**

Variable	1 Dep.Var. LnP-Index		2 Dep. Var. LnHHPC		3 Dep. Var. LnNNI		4 Dep. Var. LnRGDP	
	Diff. GMM	SYS. GMM	Diff. GMM	SYS. GMM	Diff. GMM	SYS. GMM	Diff. GMM	SYS. GMM
Lag of Dep.	0.020*** (0.000)	-0.839** (0.024)	-0.246*** (0.001)	-0.052*** (0.000)	0.145*** (0.001)	-18.48** (0.023)	1.130* (0.075)	2.482** (0.032)
LnENG	0.330 (0.200)	-0.258*** (0.000)	0.482*** (0.000)	0.933*** (0.000)	0.304 (0.171)	0.918*** (0.000)	- 3.035*** (0.000)	0.035*** (0.000)
LnEPG	0.094** (0.030)	0.572*** (0.0000)	0.200* (0.101)	0.282*** (0.000)	0.381 (0.215)	0.550*** (0.000)	0.002*** (0.000)	- 0.275*** (0.000)
LnENC	0.112*** (0.000)	0.057* (0.121)	-0.163** (0.041)	0.489*** (0.000)	0.016*** (0.000)	0.528* (0.110)	0.494 (0.212)	-0.079** (0.022)
LnREC	0.011** (0.018)	0.512*** (0.000)	0.039*** (0.000)	-0.393** (0.016)	- 0.017*** (0.000)	0.343** (0.027)	0.897 (0.174)	- 0.399*** (0.000)
LnFOF	-0.104 (0.166)	-0.450* (0.111)	-0.005*** (0.000)	-0.013*** (0.003)	0.037** (0.044)	0.106*** (0.000)	0.068** (0.024)	0.216*** [0.006)
LnPOE	0.232*** (0.001)	0.228** (0.025)	-0.007*** (0.000)	0.325** (0.019)	- 0.013*** (0.000)	0.126* (0.061)	0.439*** (0.003)	-0.675 (0.213)
LnEIP	- 0.018*** (0.000)	-0.282*** (0.011)	0.505 (0.345)	-0.036*** (0.012)	0.079*** (0.001)	-0.292** (0.040)	- 0.197*** (0.001)	0.302 (0.174)
Obs.	1899	1642	1944	1727	2040	1917	2516	1928
Normality	700.2 (0.000)		159.9 (0.000)		637.8 (0.000)		462.3 (0.000)	

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S. Corr	0.442		6.206		2.250		9.347	
	(0.482)		(0.589)		(0.848)		(0.473)	
Ramsey	-0.002		0.859		-0.100		0.018	
	(0.001)		(0.000)		(0.000)		(0.000)	
Het	7.778		6.769		1.524		3.428	
	(0.113)		(0.472)		(0.144)		(0.473)	
PMG	0.968		0.737		0.029		1.157	
FE	0.692		0.213		0.002		1.171	
AR1	-5.236		-3.284		-2.187		-1.514	
	(0.574)		(0.361)		(0.028)		(0.130)	
AR2	-0.211		1.24		1.245		-0.800	
	(0.833)		(0.217)		(0.213)		(0.424)	
J-Stat	133.8	93.48	145.6	19.66	145.8	77.69	145.1	208.8
	(0.393)	(0.238)	(0.355)	(0.116)	(0.195)	(0.220	(0.322)	(0.032)

Source: Author's Computation. ***, **, & * represents 1%, 5% and 10% level of significance. Ln shows that the models are in natural Logarithm. (.); probability value.

Previous studies, including [7,8,10] and [11] have examined the heterogeneous effects of energy utilization on human development. While these studies provide important insights, much of the existing literature emphasizes narrowly defined outcomes, such as energy generation, electricity production, carbon dioxide emissions, or energy consumption, often analyzed in isolation and primarily linked to economic growth or sector-specific productivity. Furthermore, many investigations are geographically limited, focusing on single-country or regional analyses [12,14–16], leaving significant gaps in understanding the long-term, income-specific welfare effects of energy systems across diverse economies.

To address these gaps, the present study investigates the integrated dynamics of energy generation, electricity production, energy consumption, and economic welfare across countries grouped by income level. Economic welfare is measured using a multidimensional set of indicators, including the Prosperity Index (P-Index), Household Per Capita Consumption (HHPC), Net National Income (NNI), and Real Gross Domestic Product (RGDP), thereby capturing both household-level and macroeconomic dimensions of well-being. Energy activity is assessed through Energy Generation (ENG), Electricity Power Generation (EPG), and per capita Energy Consumption (ENC), while Renewable Energy Consumption (REC), Fossil Fuel Use (FOF), Price of Electricity (POE), and Energy Import Price as a share of total energy use (EIP) are included as control variables.

To address potential endogeneity, unobserved heterogeneity, and persistence in the dependent variables, both differenced and system dynamic panel Generalized Method of Moments estimators are employed. Diagnostic tests for normality, serial correlation (Breusch-Godfrey test), functional form (Ramsey RESET test), and heteroscedasticity (White test) confirm that the models are correctly specified and meet the assumptions required for robust GMM estimation (Table 7). The GMM results (Table 7) indicate income-specific and context-dependent effects of energy on welfare. Energy generation (LnENG) consistently enhances long-run welfare in terms of NNI and RGDP, reflecting findings from Nigeria, where stable energy supply supports welfare, whereas abrupt fossil fuel subsidy removal undermines it [22]. Electricity power generation (LnEPG) positively influences HHPC and RGDP, mirroring patterns in Asia, where electricity consumption drives economic growth in Pakistan and Beijing [14,31], in accordance with the Energy Growth Welfare Nexus framework.

Energy consumption (LnENC) demonstrates mixed effects: it increases the P-Index and RGDP, indicating welfare gains through household and macroeconomic channels, but negatively affects NNI in certain models, suggesting that efficiency constraints and contextual factors mediate these outcomes. This observation aligns with evidence from India, where different renewable sources generate heterogeneous welfare effects [49], and Sub-Saharan Africa, where affordability and infrastructural limitations reduce the effectiveness of energy interventions [24]. Renewable energy consumption (LnREC) generally improves welfare in high- and upper-middle-income countries, supporting the P-Index and HHPC, but its impact is weaker or negative in lower-income contexts, consistent with findings from Southern Africa [25,26]. Fossil fuel use (LnFOF) and energy import prices (LnEIP) produce context-specific welfare effects, reflecting the trade-offs between economic benefits and environmental costs, as observed in Sub-Saharan Africa [32]. Electricity pricing (LnPOE) positively correlates with welfare in several models, suggesting that cost-reflective pricing can enhance system efficiency and sustainability, corroborating Nigerian evidence in which carefully sequenced subsidy reforms mitigate welfare losses [23]

Cross-regional analyses reinforce these patterns. In Sub-Saharan Africa, green and climate finance enhance financial and welfare outcomes, conditional on institutional quality [27,28]. In Europe, large-scale renewable energy deployment improves environmental outcomes, but welfare benefits depend on technological capacity and energy storage infrastructure ([29,30]. In Asia, electricity consumption drives growth in the Philippines, whereas in Indonesia, Malaysia, and Thailand, economic expansion drives energy demand [33], reflecting the differentiated, income-specific effects captured in our GMM estimations. In high-income countries, bidirectional or weak causal relationships between renewable energy and welfare [35], align with the moderate welfare impacts observed in our models. Finally, systematic reviews underscore the complexity of the energy-welfare relationship. [36] highlight that institutional frameworks, technological capacity, and energy policy design critically shape sustainable welfare outcomes, particularly in underrepresented regions such as South Asia and small island developing states. Collectively, the GMM findings in Table 7 demonstrate that energy generation, electricity production, and consumption exert heterogeneous, context-sensitive effects on economic welfare, providing a rigorous and empirically supported extension to prior single-country or sector-focused analyses.

Table 7. A: High-Income Countries.

Variable	1 Dep. Var.LnP-Index		2 Dep. Var. LnHHPC		3 Dep. Var. LnNNI		4 Dep. Var. LnRGDP	
	Diff. GMM	SYS. GMM	Diff. GMM	SYS. GMM	Diff. GMM	SYS. GMM	Diff. GMM	SYS. GMM
Lag of Dep.	0.635***	0.531***	0.308***	0.457***	0.504***	-0.760***	0.248***	0.798***
	(0.002)	(0.114)	(0.002)	(0.004)	(0.001)	(0.023)	(0.013)	(0.097)
LnENG	0.097***	0.411*	0.184***	0.256***	0.178	0.654**	0.206***	0.111***
	(0.001)	(0.111)	(0.000)	(0.019)	(0.184)	(0.023)	(0.020)	(0.000)
LnEPG	0.205	-0.389**	0.003	0.075***	0.013*	0.039*	0.342***	0.227**
	(0.149)	(0.020)	(0.157)	(0.000)	(0.120)	(0.101)	(0.007)	(0.015)
LnENC	0.175*	0.047**	0.236***	0.079*	0.432**	0.092***	0.106***	0.318***
	(0.080)	(0.022)	(0.010)	(0.018)	(0.040)	(0.000)	(0.003)	(0.112)
LnREC	0.072**	0.104*	0.058**	-0.137*	0.046*	0.150**	0.007**	-0.631***
	(0.020)	(0.081)	(0.025)	(0.061)	(0.107)	(0.022)	(0.041)	(0.000)
LnFOF	-0.090***	-0.580*	0.031	0.018***	-0.214**	0.048**	-0.053***	0.253***
	(0.000)	(0.110)	(0.321)	(0.000)	(0.023)	(0.030)	(0.000)	(0.000)
LnPOE	-0.157	-0.145***	-0.195***	-0.362**	-0.040**	-0.449**	-0.029	-0.409***
	(0.200)	(0.000)	(0.013)	(0.016)	(0.018)	(0.022)	(0.167)	(0.000)
LnEIP	0.034***	-0.178***	-0.036*	0.337***	-0.039***	0.242***	0.330***	-0.166
	(0.000)	(0.000)	(0.072)	(0.0000)	(0.000)	(0.010)	(0.000)	(0.961)

Obs.	809	735	805	376	660	587	755	705
Normality	386.3		165.8		121.6.		311.5	
	(0.000)		(0.000)		(0.000)		(0.000)	
S. Corr	4.938		0.221		1.601		7.973	
	(0.457)		(0.802)		(0.579)		(0.774)	
Ramsey	-0.119		-1.044		0.459		-0.540	
	(0.000)		(0.000)		(0.000)		(0.000)	
Het	8.107		3.198		4.164		2.109	
	(0.705)		(0.641)		(0.853)		(0.883)	
PMG	0.929		-0.239		0.320		0.995	
FE	0.667		-0.107		0.092		0.693	
AR1	-1.772		-0.086		-0.038		0.084	
	(0.076)		(0.224)		(0.970)		(0.773)	
AR2	1.411		0.061		0.004		-0.002	
	(0.158)		(0.276)		(0.997)		(0.476)	
J-Stat	31.83	15.81	44.78	29.69	43.96	45.59	39.00	133.2
	(0.147)	(0.119)	(0.316)	(0.225)	(0.347)	(0.026)	(0.469)	(0.197)

Source: Author's Computation. ***, **, & * denote statistical significance at the 1%, 5%, and 10% levels. Ln indicates that variables are expressed in natural logarithmic. (.); probability value.

Income classification emerges as a primary determinant of the levels of energy generation, electricity production, energy consumption, and economic welfare available to a country at any given time. Access to modern energy services, particularly electricity and gas, exerts a profound influence on economic productivity, household health, educational attainment, access to safe water, overall economic wealth, communication services, and transportation infrastructure [6]. High-income countries possess substantial capacities in mass production, logistics, distribution, marketing, transportation, processing, and preservation of goods and services, thereby creating favorable conditions for translating energy availability into measurable welfare gains.

The results reported in Table 7A indicate significant long-term positive associations between energy generation (LnENG), electricity production (LnEPG), energy consumption (LnENC), and economic welfare across models 1–4. Specifically, LnENG exhibits statistically significant positive effects on the P-Index, Household Per Capita Consumption (HHPC), Net National Income (NNI), and Real Gross Domestic Product (RGDP) under both differenced and system GMM estimations, suggesting that sustained energy generation supports both household and macroeconomic well-being. Similarly, LnENC positively influences P-Index, HHPC, and RGDP, illustrating the pathways through which per-capita energy availability enhances welfare, consistent with evidence from Asia, where electricity consumption drives economic growth in Pakistan and Beijing [14,31]. Diagnostic tests for first- and second-order serial correlation (AR1 and AR2) confirm that the series are free from autocorrelation, while J-statistics indicate no over-identification of instruments, underscoring the reliability of the GMM estimations.

The observed positive energy-welfare linkages in high-income countries are reinforced by strong institutional quality, effective governance, and robust macroeconomic and regulatory frameworks, which collectively maximize welfare outcomes. Prior research emphasizes that widespread energy access constitutes a central driver of economic growth, poverty reduction, and reduced income inequality [50]. Per-capita energy availability and electricity consumption remain closely associated with modern standards of living and overall welfare, supporting the assumption that electricity access contributes to improved well-being [51]. Despite these generally positive relationships, electricity pricing (LnPOE) consistently exerts negative effects on economic welfare across all models, indicating that high electricity costs can constrain household and macroeconomic well-being even in high-income countries. This observation aligns with prior evidence underscoring the importance of affordable energy provision to improve living standards irrespective of geographic or socioeconomic context (Sarkodie and Adams, 2020). Similar negative impacts of electricity pricing have been reported in both high-income and emerging economies [12–14,16].

Renewable energy consumption (LnREC) exhibits heterogeneous effects in high-income countries, positively affecting the P-Index and HHPC in some specifications while negatively influencing RGDP in others. These patterns reflect differences in efficiency, integration into the broader economy, and sectoral adoption rates. Fossil fuel use (LnFOF) and energy import prices (LnEIP) also display context-dependent effects, representing the trade-offs between economic benefits and environmental costs, consistent with evidence from Sub-Saharan Africa and Southern Asia [32,49]. These findings are corroborated by international studies. In Nigeria, [22] demonstrate that abrupt fossil fuel subsidy removal negatively impacts welfare, whereas targeted subsidy reforms can mitigate adverse effects [23]. In Europe, welfare benefits from renewable energy deployment depend on technological capacity and energy storage infrastructure [29,30]. In Asia and South Asia, electricity drives economic growth in the Philippines, while economic growth drives energy demand in Indonesia, Malaysia, and Thailand, illustrating heterogeneous energy-welfare interactions across income groups [33]. High-income countries often exhibit bidirectional or weak causal relationships between renewable energy and welfare, consistent with the moderate effects observed in Table 7A [22].

To ensure robustness, all models (1–4) underwent rigorous diagnostic evaluation, including tests for normality, serial correlation, functional form using the Ramsey RESET procedure, and heteroscedasticity using White's test. Results confirm that residuals satisfy the assumptions of normality, absence of serial dependence, and constant variance, while all models are correctly specified, supporting the reliability of long-run estimates (Table 7B). In conclusion, high-income countries demonstrate that energy generation, electricity production, and consumption are strongly associated with enhanced household and macroeconomic welfare, although elevated electricity prices may constrain these benefits. These results highlight the critical importance of institutional quality, governance, and policy design in maximizing welfare outcomes from energy access, a finding consistent across diverse regional and development contexts.

Table 7. B: Upper Middle Income Countries.

	1 Dep. Var. LnP-Index		**2** Dep. Var. LnHHPC		**3** Dep. Var. LnNNI		**4** Dep. Var. LnRGDP	
	Diff. GMM	**SYS. GMM**	**Diff. GMM**	**SYS. GMM**	**Diff. GMM**	**SYS. GMM**	**Diff. GMM**	**SYS. GMM**
Lag. of Dep.	0.316*** (0.00)	-0.496** (0.042)	0.066*** (0.019)	-0.269* (0.066)	-0.093** (0.020)	0.839* (0.067)	0.154*** (0.002)	-0.753** (0.024)
LnENG	0.266 (0.175)	0.395* (0.094)	0.401** (0.031)	0.254** (0.015)	0.251*** (0.011)	0.247*** (0.000)	-0.472* (0.104)	0.140** (0.028)
LnEPG	0.020*** (0.000)	0.218*** (0.001)	0.075 (0.904)	0.120*** (0.010)	0.511*** (0.004)	0.404*** (0.000)	0.182 (0.209)	0.479* {0.055)
LnENC	0.093*** (0.000)	0.317* (0.112)	-0.101*** (0.000)	-0.089*** (0.090)	-0.137* (0.056)	0.090* (0.101)	-0.079 (0.479)	-0.087*** (0.000)
LnREC	-0.338*** (0.000)	-0.042*** (0.000)	-0.463* (0.081)	-0.168*** (0.000)	0.229*** (0.000)	0.521*** (0.011)	0.096** (0.046)	0.513 (0.235)
LnFOF	0.128*** (0.000)	-0.0481*** (0.000)	-0.590*** (0.000)	-0.119 (0.125)	-0.225** (0.016)	0.284*** (0.000)	0.079*** (0.000)	-0.196*** (0.000)

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LnPOE	-0.184***	0.115***	0.074	0.332***	0.249***	0.593**	0.067*	0.263
	(0.000)	(0.000)	(0.159)	(0.005)	(0.000)	(0.036)	[0.170)	(1.012)
LnEIP	0.003	0.384***	-0.022	0.126*	0.118***	0.678**	-0.056***	-0.023**
	(0.218)	(0.003)	(0.691)	(0.068)	(0.001)	(0.016)	(0.000)	(0.018)
Obs.	577	506	509	459	573	502	577	506
Normality	906.5		270.7		854.2		513. 7	
	(0.000)		(0.000)		(0.000)		(0.000)	
S. Cor	3.597		1.170		4.682		1.495	
	(0.701)		(0.403)		(0.224)		(0.225)	
Ramsey	-0.005		0.078		0.428		0.014	
	(0.000)		(0.000)		(0.000)		(0.000)	
Het	1.710		1.176		6.023		8.381	
	(0.097)		(0.226)		(0.109)		(0.709)	
PMG	0.948		0.187		0.507		0.189	
FE	0.719		0.051		0.115		0.188	
AR1	-0.793		-0.445		-0.422		-0.914	
	(0.428)		(0.023)		(0.122)		(0.056)	
AR2	0.471		0.959		0.034		-0.846	
	(0.633)		(0.337)		(0.973)		(0.265)	
J-Stat	27.89	66.13	32.19	49.34	29.52	68.96	29.24	66.48
	(0.271)	(0.299)	(0.187)	(0.312)	(0.387)	(0.121)	(0.201)	(0.368)

Source: Author's Computation. ***, *, & * denote significance at the 1%, 5%, and 10% levels. Ln indicates that variables are expressed in natural logarithmic form.

The results indicate that in upper-middle-income economies, economic welfare maintains robust and positive long-term associations with energy generation, electricity production, and energy consumption, as most coefficients are statistically significant across models (Table 7B). Specifically, sustained energy generation (LnENG) and electricity production (LnEPG) contribute significantly to both household-level welfare (P-Index, HHPC) and macroeconomic outcomes (NNI, RGDP), illustrating the mechanisms through which energy availability supports economic growth and enhances living standards. Per-capita energy consumption (LnENC) also exhibits positive effects in multiple specifications, reinforcing the role of energy access in promoting economic well-being. These findings are consistent with prior research demonstrating that electricity and alternative energy sources are critical drivers of economic performance and improvements in living standards [17,34,52,53].

Diagnostic assessments confirm the reliability of these estimates. AR1 and AR2 statistics indicate the absence of first- and second-order serial correlation, while the Hansen J test validates the instrument set and confirms appropriate model specification. Collectively, these tests affirm the robustness and credibility of the reported long-run relationships. Empirical evidence from multiple regions further substantiates these results. In Nigeria, [22] show that abrupt fossil fuel subsidy removal substantially reduces long-term welfare, whereas [23] find that carefully sequenced subsidy reforms, supported by targeted government transfers, can mitigate adverse household effects. In Southern Africa, the welfare impacts of renewable energy are heterogeneous: biomass consumption positively affects long-term GDP, while wind and solar energy produce mixed short-term effects [24–26]. In India, hydropower contributes positively to welfare, whereas other renewable sources exhibit less consistent effects [49].

Cross-regional analyses provide additional support. In Sub-Saharan Africa, the effectiveness of green and climate finance in enhancing financial market development and welfare outcomes is

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contingent on institutional quality [27,28]. In Europe, large-scale renewable energy deployment improves environmental outcomes, but welfare gains are contingent on adequate technological infrastructure and energy storage capacity [29,30]. In Asia and South Asia, the energy-growth relationship is heterogeneous: electricity consumption drives growth in the Philippines, whereas economic growth stimulates energy demand in Indonesia, Malaysia, and Thailand [33]. Similarly, in Pakistan and Beijing, electricity consumption exerts strong causal effects on economic growth [14,31] while fossil and solid fuel consumption in Sub-Saharan Africa elevates emissions, with renewables mitigating environmental harm [32].

These findings demonstrate that in upper-middle-income economies, energy generation, electricity production, and energy consumption serve as significant drivers of both household and macroeconomic welfare. The evidence underscores the pivotal role of energy access as a catalyst for economic development and improved living standards, while emphasizing that institutional quality, governance, and technological capacity are essential for translating energy availability into sustained welfare gains. The subsequent section extends this analysis to lower-middle-income economies, with the corresponding results reported in Table 7C.

Table 7. C: Low-Middle Income Countries.

Variable	**1**		**2**		**3**		**4**	
	Dep. Var. LnP-Index		**Dep. Var. LnHHPC**		**Dep. Var. LnNNI**		**Dep. Var. LnRGDP**	
	Diff. GMM	**SYS. GMM**	**Diff. GMM**	**SYS. GMM**	**Diff. GMM**	**SYS. GMM**	**Diff. GMM**	**SYS. GMM**
Lag. of Dep.	0.280***	0.819***	0.241***	1.153***	0.417***	0.779***	0.177***	0.401***
	(0.001)	(0.033)	(0.006)	(0.796)	(0.001)	(0.068)	(0.001)	(0.061)
LnENG	-0.173*	-0.374***	-0.028*	-0.319**	-0.333***	-0.086***	-0.273***	-0.087***
	(0.130)	(0.000)	(0.045)	(0.025)	(0.000)	(0.001)	(0.000)	(0.000)
LnEPG	-0.206*	-0.366***	-0.138*	-0.118**	-0.086***	-0.391***	0.261***	0.659**
	(0.087)	(0.007)	(0.101)	(0.022)	(0.000)	(0.000)	(0.010)	{0.019)
LnENC	-0.025**	-0.109*	-0.187**	-0.191***	-0.125**	-0.093***	-0.212*	0.451***
	(0.047)	(0.129)	(0.041)	(0.004)	(0.029)	(0.011)	(0.120)	(0.000)
LnREC	-0.206*	-0.116**	-0.072***	-0.383**	-0.115***	0.121**	-0.104***	-0.209***
	(0.060)	(0.024)	(0.013)	(0.022)	(0.001)	(0.019)	(0.003)	(0.005)
LnFOF	- 0.086***	0.147***	0.365*	0.125***	0.447	0.113***	-0.506***	0.168**
	(0.001)	(0.000)	(0.082)	(0.0000)	(0.303)	(0.001)	(0.000)	(0.019)
LnPOE	0.268***	-0.116**	-0.042***	-0.412***	-0.275***	-0.066***	-0.168***	-0.436*
	(0.000)	(0.046)	(0.0000)	(0.000)	(0.010)	(0.030)	(0.001)	(0.107)
LnEIP	0.270**	-0.213**	-0.258**	-0.092***	0.545	-0.206***	0.530	0.047***
	(0.015)	(0.028)	(0.017)	(0.000)	(1.097)	(0.000)	(0.157)	(0.000)
Obs.	302	592	639	592	686	592	695	595
Normality	592.7		304.6		190.7		124.8	
	(0.000)		(0.000)		(0.000)		(0.000)	
S. Corr	5.586		0.809		1.818		7.875	
	(0.883)		(0.445)		(0.163)		(0.734)	
Ramsey	0.299		-0.249		0.827		-0.817	
	(0.002)		(0.000)		(0.000)		(0.000)	

Het	0.409		1.993		2.455		4.301	
	(0.915)		(0.5448)		(0.113)		(0.774)	
PMG	0.0689		0.151		0.875		0.842	
FE	0.073		0.067		0.689		0.568	
AR1	-0.208		-0.277		-0.449		0.297	
	(0.093)		(0.218)		(0.026)		(0.187)	
AR2	0.430		0.269		0.336		-0.349	
	(0.291)		(0.205)		(0.364)		(0.264)	
J-Stat	27.51	19.03	39.31	177.7	31.89	110.8	36.88	32.78
	(0.331)	(0.189)	(0.283)	(0.198)	(0.264)	(0.338)	(0.228)	(0.236)

Source: Author's Computation. ***, *, and * denote significance at the 1%, 5%, and 10% levels; Ln indicates that variables are expressed in natural logarithmic form.

In this income category, we analyzed the long-term relationships among energy generation, electricity production, energy consumption, and economic welfare in lower-middle-income countries using the baseline models. The models were subjected to standard diagnostic evaluations, including tests for normality, serial correlation, model specification via the Ramsey RESET procedure, and heteroscedasticity using White's test. Results confirm that the error terms are normally distributed, free from first- and second-order serial correlation, and exhibit constant variance, indicating that the model is correctly specified and statistically reliable (Table 7C).

The estimation results reveal predominantly negative long-term associations between energy generation (LnENG), electricity production (LnEPG), energy consumption (LnENC), and indicators of economic welfare. These findings suggest that energy provision in lower-middle-income countries does not consistently translate into improvements in household or macroeconomic well-being, thereby constraining living standards. This pattern reflects structural and institutional constraints characteristic of this income class, including fragile economic conditions, political instability, limited regulatory capacity, and underdeveloped infrastructure, which collectively hinder the translation of energy access into per-capita income growth and broader economic prosperity. Electricity, despite its potential as an accessible driver of economic development, remains costly and often unavailable to end users, leading to widespread reliance on fossil fuels as the most attainable energy source. As a result, energy poverty persists, limiting productive activity and overall economic development. While renewable and clean energy sources hold theoretical promise for supporting growth, practical benefits are frequently curtailed by affordability constraints and insufficient infrastructure.

Robustness tests further support the reliability of these estimates. AR1 and AR2 statistics confirm the absence of first- and second-order serial correlation, and the Hansen J test validates the instrument set, confirming the appropriateness of model specification. These findings align with prior empirical evidence indicating that energy access alone is necessary but not sufficient to foster welfare improvements in emerging economies ([9,34,35,54,55]. Empirical studies provide additional context. In Nigeria, [22] show that abrupt removal of fossil fuel subsidies, coupled with inflation, significantly reduces long-term welfare, whereas [23] demonstrate that carefully sequenced subsidy reforms, combined with targeted government transfers, can mitigate negative household impacts. In Southern Africa, renewable energy outcomes are heterogeneous: biomass consumption supports long-term GDP growth, while wind and solar energy yield inconsistent short-term effects [24–26]. In India, hydropower contributes positively to welfare, whereas other renewable sources produce less consistent gains [49].

Cross-regional analyses further highlight the critical role of institutional and policy environments. In Sub-Saharan Africa, green and climate finance enhance financial development and welfare outcomes, but effectiveness is contingent on institutional quality [27,28]. In Europe, large-scale renewable energy integration improves environmental quality, yet welfare gains depend on technological infrastructure and energy storage capacity [29,30]. In Asia and South Asia, the energy-

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growth relationship is heterogeneous: electricity consumption drives growth in the Philippines, whereas economic growth stimulates energy demand in Indonesia, Malaysia, and Thailand [33]. In Pakistan and Beijing, electricity consumption exhibits strong causal effects on economic growth [14,31], while fossil and solid fuel use in Sub-Saharan Africa increases emissions, with renewable sources helping to mitigate environmental impacts [32]. These results indicate that in lower-middle-income economies, energy generation, electricity production, and energy consumption do not automatically translate into enhanced economic welfare. Structural constraints, high energy costs, weak institutional frameworks, and limited infrastructure restrict the potential of energy access to improve living standards. The next stage of the income-class analysis focuses on low-income countries, with the corresponding results presented in Table 7D.

Table 7. D: Low-Income Countries.

	1		**2**		**3**		**4**	
	Dep. Var.LnP-Index		**Dep. Var. LnHHPC**		**Dep. Var. LnNNI**		**Dep. Var. LnRGDP**	
Variable	**Diff. GMM**	**SYS. GMM**	**Diff. GMM**	**SYS. GMM**	**Diff. GMM**	**SYS. GMM**	**Diff. GMM**	**SYS. GMM**
Lag. of Dep.	0.419***	0.139*	0.681***	-0.704*	0.676**	-0.528**	-0.397***	0.781*
	(0.006)	(0.092)	(0.001)	(0.128)	(0.021)	(0.030)	(0.014)	(0.094)
LnENG	-0.250*	-0.218***	-0.132**	0.085***	-0.516	-0.301***	-0.373*	-0.191***
	(0.106)	(0.000)	(0.019)	(0.000)	(0.204)	(0.006)	(0.082)	(0.001)
LnEPG	-0.307***	-0.356***	-0.098	-0.532***	-0.334**	-0.189**	-0.161	-0.344***
	(0.000)	(0.000)	(0.211)	(0.002)	(0.034)	(0.108)	(0.194)	(0.000)
LnENC	-0.100**	-0.038***	-0.362*	-0.351***	-0.243	-0.288***	-0.305**	-0.062***
	(0.017)	(0.003)	(0.116)	(0.008)	(0.203)	(0.000)	(0.035)	(0.001)
LnREC	0.244*	0.411***	0.058**	0.345***	0.163*	0.715***	0.386	-0.278***
	{0.122)	(0.000)	(0.024)	(0.000)	(0.094)	(0.000)	(0.210)	(0.000)
LnFOF	0.417***	0.2437**	0.095***	0.416***	0.155**	0.039*	0.014**	0.107***
	(0.000)	(0.022)	(0.000)	(0.000)	(0.037)	(0.107)	{0.018)	(0.000)
LnPOE	-0.011	-0.543***	-0.333*	-0.489***	-0.472**	-0.103*	-0.002	-0.036***
	(0.220)	(0.000)	(0.088)	(0.000)	(0.030)	(0.050)	(0.531)	(0.000)
LnEIP	0.143***	-0.086	0.101***	0.061***	-0.029***	0.209**	-0.065	-0.038***
	(0.001)	(0.158)	(0.000)	(0.000)	(0.000)	(0.021)	(0.191)	(0.004)
Obs.	405	341	440	374	438	370	419	378
Normality	417.6		116.3		122.7		361.9	
	(0.000)		(0.000)		(0.000)		(0.000)	
S. Corr	6.708		0.852		1.063		6.646	
	(0.995)		(0.427)		(0.346)		(0.414)	
Ramsey	-0.362		0.149		0.107		-0.391	
	(0.000)		(0.002)		(0.002)		(0.000)	
Het	1.375		1.522		0.378		3.419	
	(0.205)		(0.147)		(0.232)		(0.774)	
PMG	0.802		0.921		0.906		0.715	
FE	0.446		0.782		0.814		0.567	
AR1	1.93		-0.016		-0.757		-0.071	
	(0.054)		(0.467)		(0.449)		(0.999)	

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AR2	-1.829		0.359		-1.235		-0.128	
	(0.168)		(0.719)		(0.217)		(0.179)	
J-Stat	17.99	24.93	22.84	14.61427	19.43	317.4	16.35	53.85
	(0.256)	(0.211)	(0.244)	(0.185)	(0.366)	(0.324)	(0.134)	(0.126)

Source: Author's Computation. ***, *, and * represents 1%, 5% and 10% level of significance; while Ln shows that the models are in natural Logarithm.

The models were initially evaluated using standard ordinary least squares diagnostics, including tests for normality, serial correlation, model specification via the Ramsey RESET procedure, and heteroscedasticity using White's test, to ensure that the fundamental assumptions of OLS were met. The results indicate that the residuals are normally distributed, free from first- and second-order serial correlation, exhibit constant variance, and that the models are correctly specified (Table 7D).

Following this, the analysis employed both the original models and dynamic panel estimations using differenced and system Generalized Method of Moments (GMM) techniques. The GMM results indicate predominantly negative long-term relationships between energy generation (LnENG), electricity production (LnEPG), energy consumption (LnENC), and indicators of economic welfare. In contrast, renewable energy consumption (LnREC) exhibits a positive long-term association with welfare, while fossil fuel use (LnFOF) also contributes positively. Electricity prices (LnPOE) display a negative association with welfare, reflecting the sensitivity of households and firms to energy affordability in low-income settings.

These findings reflect structural limitations that are common in many Sub-Saharan African countries, which are largely classified as low-income by the World Bank. Infrastructure and industrial development are often secondary policy priorities, institutional capacity is weak, and much economic output depends on labor-intensive or semi-mechanized production. As a result, workers face challenging conditions, goods and services are produced in limited volumes, and reliance on imports remains high. Although energy should be broadly accessible and affordable across all populations [56], in practice, energy access remains highly constrained. Figure 2 illustrates that most African countries are among the least energy-intensive globally, reflecting governance challenges and the absence of comprehensive development plans aimed at inclusive economic welfare, as evidenced by low macroeconomic and institutional quality metrics.

International assessments highlight these disparities. The 2019 World Energy Trilemma ranking, which evaluates countries on energy security, energy equity, and environmental sustainability, places high- and upper-middle-income countries predominantly within the top 50 positions, whereas most African nations rank lower. Insufficient energy access has far-reaching consequences: it constrains economic activity, depresses national income, limits the production of high-quality goods and services, reduces firms' productive capacity, undermines household welfare, hampers financial sector performance, and contributes to environmental degradation. Dependence on fossil fuels and firewood exacerbates deforestation, air pollution, and other negative externalities, further hindering economic development.

These results are consistent with [21], who identified a unidirectional linkage between energy generation, electricity production, and economic growth, and align with previous empirical evidence ([12–16,32,57]; Bhat, [9,33–35,54,55,58–60].

Further evidence from regional and sectoral studies reinforces these findings. In Nigeria, [22] show that fossil fuel subsidy removal and inflation significantly reduce long-term welfare, whereas [23] demonstrate that carefully sequenced subsidy reforms, supported by targeted government transfers, mitigate negative household impacts. Across Southern Africa, renewable energy outcomes are mixed: biomass consumption contributes positively to long-term GDP, while wind and solar energy exhibit inconsistent short-term effects [24–26]. In India, hydropower supports welfare improvements, whereas other renewable sources yield variable outcomes [49].

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Cross-country and regional analyses further highlight the importance of institutional and policy contexts. In Sub-Saharan Africa, green and climate finance improves financial development and welfare outcomes, contingent upon institutional quality [27,28]. In Europe, large-scale renewable energy deployment enhances environmental performance, but welfare benefits require adequate technological infrastructure and energy storage capacity [29,30]. In Asia and South Asia, the relationship between energy use and growth is heterogeneous: electricity consumption drives growth in the Philippines, while economic expansion stimulates energy demand in Indonesia, Malaysia, and Thailand [33], Similarly, electricity use strongly drives growth in Pakistan and Beijing [14,31], while reliance on fossil and solid fuels in Sub-Saharan Africa increases emissions, mitigated only partially by renewable energy adoption [32]. The evidence indicates that in low-income economies, energy generation, electricity production, and consumption do not consistently translate into enhanced economic welfare. Positive effects from renewable energy and fossil fuel use are constrained by high electricity prices, weak institutions, inadequate infrastructure, and limited policy coordination, which collectively restrict the ability of energy access to improve living standards.

4.1. Discussion

This study examines the complex interconnections among energy generation, electricity production, energy consumption, and economic welfare across countries categorized by income level. Drawing on the World Bank income classification framework, the analysis covers 152 countries, including 49 high-income, 35 upper-middle-income, 43 lower-middle-income, and 26 low-income economies [37]. Countries were selected based on consistent data availability from 2000 to 2023. Descriptive statistics reveal that key coefficients range from 8.47 to 10.91, while Jarque–Bera tests confirm the normality of model residuals ($p < 0.05$). Correlation analysis indicates negative associations between energy and electricity indicators, including prices and import costs, and welfare measures, whereas renewable energy use and fossil fuel consumption generally exhibit positive associations. These patterns suggest that disparities in energy access, affordability, and institutional capacity shape welfare outcomes across income groups.

To mitigate the risk of spurious regression inherent in time-series panel data, stationarity was assessed using second-generation unit root tests that account for cross-sectional dependence. The Cross-sectionally Augmented IPS and Cross-sectionally Augmented Dickey–Fuller tests [44] confirmed that LnP-Index, LnHHPC, LnNNI, LnENG, and LnEIP are stationary at levels, while LnRGDP, LnEPG, LnENC, LnREC, LnFOF, and LnPOE achieve stationarity after first differencing. No variable exhibits integration beyond the first order, justifying the use of cointegration and dynamic panel estimation techniques. Cross-sectional dependence, assessed using the Pesaran CD test [45] indicates significant interdependence among countries, reflecting common global shocks, technology spillovers, coordinated energy policies, and interconnected macroeconomic dynamics. These findings highlight the limitations of first-generation unit root tests that assume cross-country independence.

[46,47] cointegration tests, complemented by the [48] approach, confirm stable long-term equilibrium relationships among energy generation, electricity production, energy consumption, and economic welfare across all income classifications. These results provide a robust foundation for estimating income-specific long-term effects using dynamic panel GMM methods, which account for endogeneity, persistence, and country-specific heterogeneity. Comparisons of lagged dependent variable coefficients from Pooled Mean Group and Fixed Effects models indicate that the differenced GMM estimator is the most appropriate for capturing reliable long-run relationships. Diagnostic tests for normality, serial correlation, functional form, and heteroscedasticity confirm that the models are correctly specified and statistically robust (Table 7).

In high-income countries, results indicate strong long-term positive associations between energy generation, electricity production, energy consumption, and welfare indicators, including the Prosperity Index, Household Per Capita Consumption, Net National Income, and Real GDP (Table 7A). Sustained energy generation and per-capita energy availability consistently enhance household

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and macroeconomic welfare, confirming their critical role in maintaining living standards and supporting economic productivity [14,31]. Renewable energy consumption produces heterogeneous effects, enhancing household-level welfare in some specifications while moderating macroeconomic outcomes in others, reflecting differences in efficiency, sectoral integration, and adoption rates. Fossil fuel use and energy import prices generate context-dependent effects, reflecting the balance between economic benefits and environmental costs [32,49]. Electricity pricing is negatively associated with welfare, underscoring that affordability remains a fundamental constraint even in high-income contexts [56]. Diagnostic tests, including AR1, AR2, Hansen J, Ramsey RESET, and White's test, confirm the reliability of these estimates (Table 7B). Strong institutions, effective governance, and comprehensive regulatory frameworks amplify the welfare benefits of energy availability in these countries.

Upper-middle-income economies also exhibit robust long-term positive effects of energy generation, electricity production, and per-capita energy consumption on both household-level welfare and macroeconomic outcomes (Table 7B). Energy generation and electricity production contribute significantly to sustaining living standards, while per-capita consumption reinforces the channels through which energy availability translates into broader economic welfare. Cross-regional evidence highlights that electricity consumption drives economic growth in the Philippines, whereas in Indonesia, Malaysia, and Thailand, economic expansion stimulates energy demand [33]. These findings confirm that energy-welfare relationships are heterogeneous and dependent on income classification, institutional capacity, and regional conditions.

In lower-middle-income countries, associations between energy indicators and welfare are weaker and often negative (Table 7C). Energy generation, electricity production, and energy consumption do not consistently improve household or macroeconomic welfare, reflecting structural, institutional, and infrastructural limitations. Electricity remains costly and intermittently available, fossil fuels dominate consumption, and energy access alone is insufficient to enhance living standards. Empirical evidence from Nigeria, Southern Africa, and India demonstrates that policy interventions, targeted transfers, or renewable energy deployment can mitigate these limitations, though effectiveness is highly context-specific ([22,23], 2024; [25,26,49].

Low-income countries face the most significant constraints. GMM estimations indicate predominantly negative long-term relationships between energy generation, electricity production, energy consumption, and welfare (Table 7D). Renewable energy and fossil fuel use contribute marginally to welfare, while high electricity prices significantly limit outcomes. Structural weaknesses, limited industrialization, inadequate infrastructure, and low institutional capacity prevent energy access from translating into broad-based improvements. Dependence on labor-intensive production and imported energy further constrains economic development. Global comparisons, including the World Energy Trilemma ranking, highlight persistent inequities in energy security, equity, and sustainability between low-income and higher-income countries.

Collectively, these results demonstrate that energy generation, electricity production, and consumption have heterogeneous, income-dependent effects on economic welfare. High- and upper-middle-income countries effectively convert energy availability into measurable gains through strong institutions, governance, and policy frameworks. In contrast, lower-middle- and low-income countries experience significant limitations, with structural, institutional, and affordability constraints restricting the capacity of energy access to enhance welfare. These findings emphasize the importance of integrated energy policy, infrastructure investment, and institutional strengthening to maximize the social and economic returns of energy systems across diverse global contexts.

5. Conclusions

This study investigates the complex relationships among energy generation, electricity production, energy consumption, and economic welfare across countries classified by income level from 2000 to 2023. Drawing on the World Bank income classification framework, the analysis encompasses 152 countries: 49 high-income, 35 upper-middle-income, 43 lower-middle-income, and

26 low-income economies. Country selection and study scope were guided by the consistent availability of relevant data over the study period. Economic welfare was measured using four indicators: the Prosperity Index (P-Index), Household Per Capita Consumption (HHPC), Net National Income (NNI), and Real Gross Domestic Product (RGDP). Energy activity was captured through energy generation (ENG), electricity production (EPG), and energy consumption (ENC), while additional control variables, including renewable energy consumption (REC), fossil fuel usage (FOF), electricity prices (POE), and energy import prices (EIP), were incorporated to strengthen model precision.

Cointegration analyses, supported by Pedroni and Kao tests, provide robust evidence of persistent long-term associations between energy variables and economic welfare across all income groups. Dynamic panel estimations using both differenced and system Generalized Method of Moments explicitly accounted for endogeneity and country-specific heterogeneity, which are common in panel time-series data. Diagnostic tests conducted before and after estimation confirmed that model residuals were normally distributed, free from serial correlation, and exhibited constant variance, supporting the statistical validity of the results. Overall, the findings reveal strong long-term positive relationships between energy generation, electricity production, energy consumption, and welfare measures. When examined by income classification, these positive effects are most pronounced in high-income and upper-middle-income countries, whereas lower-middle-income and low-income economies display weaker or even negative associations, reflecting structural constraints, affordability barriers, and inequities in energy access and infrastructure.

The results carry important policy implications. Governments, particularly in low-income and lower-middle-income economies, should prioritize targeted energy reforms that expand access to reliable, affordable, and environmentally sustainable energy. Strategic investments in electricity generation and distribution infrastructure should emphasize efficiency, equitable delivery, and affordability to improve living standards and promote inclusive economic growth.

Despite these contributions, the study has several limitations. First, the analysis is constrained by data availability, particularly for emerging economies and certain welfare indicators, which may limit the generalizability of the findings. Second, reliance on aggregate national-level data may mask subnational heterogeneity in energy access, consumption patterns, and welfare outcomes. Third, although GMM techniques address endogeneity, they may not fully capture dynamic feedback effects between energy variables and welfare in highly volatile economies. Finally, environmental externalities, including emissions and climate impacts, were addressed only indirectly through fossil fuel and renewable energy variables, limiting insights into the broader sustainability implications of energy use.

Future research could address these limitations by integrating more granular, subnational data to capture disparities in energy access and welfare within countries. Longitudinal studies incorporating environmental, social, and governance dimensions could provide a more comprehensive understanding of the trade-offs and complementarities between energy development and sustainable welfare outcomes. Further investigation into sector-specific energy use, including industrial, commercial, and residential consumption, could clarify the pathways through which energy availability influences household and macroeconomic welfare. Comparative case studies of successful policy interventions in low- and middle-income countries may also yield practical guidance for designing effective energy access strategies that enhance inclusive welfare.

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