RESEARCH ARTICLE

Fueling the Future: Exploring the Nexus of Renewable Energy, Population Shifts, and Economic Development in Five Global Economies

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Received: 15 April, 2025, Accepted: 18 June, 2025, Published: 17 August, 2025

Abstract
This study investigates the relationship between economic growth and key energy-related and demographic variables across five major economies—China, the United States (U.S.), Germany, Brazil, and India—from 2000 to 2023. Using panel data analysis, the study examines how renewable energy consumption, fossil fuel use, population growth, gross fixed capital formation (GFCF), and urbanization influence Gross Domestic Product (GDP) per capita. The findings suggest a robust positive association between renewable energy consumption and economic growth, while population growth and reliance on fossil fuels exert a negative influence. The effects of GFCF and urbanization vary across countries, with several results lacking statistical significance. Country-specific analyses reveal significant heterogeneity: fossil fuel consumption negatively affects GDP in Germany, India, and the U.S., but shows a positive impact in Brazil. Urbanization supports economic growth in some countries, while having limited or negative effects in others. These findings underscore the importance of formulating development and energy strategies that are attuned to each country's unique economic structures and policy environments.

Keywords: Renewable Energy; Economic Growth; GDP per Capita; Population Growth; Urbanization

Introduction

The relationship between economic growth and energy consumption has long been a central theme in economic and environmental research. Such a relationship is complex and varies across countries and different contexts. Understanding this nexus is pivotal in an era where countries face the dual challenge of fostering economic development while mitigating environmental degradation (Adanma and Ogunbiyi, 2024). Energy consumption is deeply intertwined with industrial output and technological innovation, making it an integral component of economic progress. However, overreliance on traditional fossil fuels, which accounts for over 80% of the global primary energy consumption as of 2023 (Igini, 2024), poses significant environmental risks, particularly in terms of climate change. Thus, the way economies manage their energy portfolios is increasingly seen as a decisive factor in shaping sustainable growth trajectories (Androniceanu et al., 2024). Recent global developments have intensified the focus on the energy-growth relationship. The rise in urbanization levels—whereby over 55% of the global population now lives in urban areas (United Nations, 2022)—has considerably altered energy demand patterns, often increasing the need for transportation and electricity fuels. At the same time, international agreements like the Paris Agreement and regional initiatives, such as the European Green Deal, have pushed countries to reshape their energy policies towards decarbonization (Wendler, 2022). Investments in renewable energy reached a record $495 billion in 2022 (Bulkot et al., 2023), reflecting a structural shift in the global energy landscape. Against this backdrop, renewable energy is no longer viewed solely as an environmental imperative but increasingly as a strategic driver of economic resilience and innovation (Sadorsky, 2009). Nevertheless, the transition toward a cleaner energy mix presents heterogenous effects across countries, influenced by differences in economic structure, investment patterns, demographic dynamics, and policy environments. Developed countries often have the financial and institutional capacity to support large-scale renewable energy adoption through subsidies and regulatory frameworks (Romano et al., 2017). In contrast, emerging economies may face challenges related to infrastructure gaps, financing constraints, and competing development priorities (Wu and Broadstock, 2015). Moreover, population growth rates and urbanization trends may further modulate how energy demand evolves over time, necessitating tailored strategies that align economic growth objectives with environmental sustainability goals (Avtar et al., 2019). Understanding these diverse national contexts is crucial for designing effective energy and development policies in an increasingly interconnected and climate-constrained world.

This study aims to empirically examine the relationship between economic growth and key energy-related and demographic variables, focusing on five major economies: China, the United States, Germany, Brazil and India. These countries are selected based on their crucial roles in the global energy landscape—ranging from leadership in renewable energy production and investment to pioneering energy transition policies and rapid capacity expansion. This study captures a wide array of energy transition experiences and developmental stage through examination of this diverse group. Using data for the period 2000-2023, this study investigates how renewable energy consumption, fossil fuel dependency, population growth, gross fixed capital formation, and urbanization influence GDP per capita. The study employs Panel date analysis along with a cross-country comparison model. Panel data analysis provides a robust framework by accounting for unobserved heterogeneity and time-invariant country-specific characteristics. This approach ensures more reliable inferences in comparison to traditional cross-sectional or time-series analyses (Baltagi, 2021). Ultimately, the findings of the study aim to contribute to a deeper understanding of the economic implications of energy transitions, providing insights that are valuable for policymakers, energy strategists, and scholars interested in sustainable economic development. This study acknowledges that the relationship between energy consumption, demographic change, and economic development has been explored in existing literature (e.g., Apergis and Payne, 2010; Stern, 2011; Ozturk, 2010). While our core methodological approach—the use of interaction terms to capture country-specific heterogeneity—is a standard econometric technique, the contribution of this study primarily lies in providing updated empirical insights using recent panel data (2000–2023) across a diverse set of developed and developing economies (China, the United States, Germany, Brazil, and India).

Analyzing such a recent and broad period is crucial as global developments, including significant investments in renewable energy and increased urbanization, may alter previously observed relationships, necessitating contemporary analyses (Wang, Li and Ge, 2023). This broad and current empirical analysis allows us to highlight the contemporary heterogeneous effects of energy and demographic factors on economic growth. The detailed country-specific analyses of this study go beyond simply identifying average relationships, revealing nuanced impacts that are critical for targeted policymaking). The existence of such cross-country heterogeneity is a well-recognized aspect in energy-growth nexus studies and underscores the need for context-specific understanding rather than one-size-fits-all conclusions (Gyimah et al., 2023).

From a policy perspective, the focus on implications derived from these heterogeneous effects provides practical guidance for countries navigating energy transitions and sustainable development pathways (Vlăduţ et al., 2024). This contributes to the ongoing discussions around the economic implications of decarbonization and urbanization, making the study relevant to environmental economics, energy policy, and development studies, and emphasizing the need for tailored energy and development policies. This study addresses these gaps by analyzing recent panel data from 2000 to 2023 across aforementioned five major economies, representing a mix of developed and developing countries with diverse energy and demographic profiles. By employing panel data analysis, this research captures both within-country and between-country variations over time and reveals the heterogeneous effects of key variables on GDP per capita. In doing so, the study contributes to the literature by offering updated empirical insights and highlighting the importance of context-specific approaches to energy and development policy.

The remainder of this paper is organized as follows: the following section reviews the existing literature on the relationship between economic growth, renewable energy adoption, fossil fuel dependency, urbanization, and capital formulation. It is followed by the methodology section, describing the data, variables, and countries selected for analysis along with the empirical methodology encompassing the empirical models used for the analysis. Results and discussion section presents and discusses the empirical results, highlighting both general patterns and country-specific effects. The last part of the paper concludes the study by summarizing key findings, discussing policy implications, and suggesting directions for future research.

Literature Review

The relationship between energy consumption and economic growth has been extensively examined across various contexts, reflecting its crucial importance for both economic policy and sustainable development. Early studies predominantly focused on establishing the direction of causality between energy use and economic output, leading to several competing hypotheses such as the growth hypothesis, conservation hypothesis, feedback hypothesis, and neutrality hypothesis (Ozturk, 2010). Over time, research has expanded to explore how different types of energy sources—particularly the shift from fossil fuels to renewables—impact economic dynamics. Additionally, other factors such as urbanization, investment patterns, and demographic trends have been increasingly incorporated to capture the broader socio-economic environment influencing energy use and growth. This section reviews key findings from previous studies, with a particular focus on the role of renewable energy, fossil fuel dependence, urbanization, and capital formation. One prominent strand of the literature has examined the dynamic interplay between renewable energy consumption and economic growth. Several empirical studies have suggested that renewable energy not only supports environmental sustainability but can also drive economic expansion by fostering innovation, improving energy security, and creating new industries (Sadorsky, 2009; Apergis and Payne, 2010). For example, Sadorsky (2009) found a positive and significant relationship between renewable energy consumption and GDP per capita in emerging economies, emphasizing the growth-stimulating potential of investments in clean energy technologies. Similarly, Apergis and Payne (2010), using panel data from OECD countries, reported bidirectional causality between renewable energy consumption and economic growth, indicating that promoting renewables could reinforce growth, which in turn supports further renewable investments. However, other studies caution that the economic benefits of renewables are contingent on factors such as initial infrastructure, regulatory frameworks, and the maturity of the energy sector (Pablo-Romero and Sánchez-Braza, 2015), suggesting that the transition toward renewable energy might have uneven effects across countries and over time.

A contrasting body of literature has focused on the role of fossil fuel consumption in shaping economic outcomes. Fossil fuels have historically been the backbone of industrialization, providing affordable and reliable energy essential for economic growth. However, increasing reliance on fossil fuels has been linked to environmental degradation, rising carbon emissions, and energy insecurity (Stern, 2011). While fossil fuels remain a dominant source of energy, numerous studies have highlighted the need for transitioning towards more sustainable energy sources to decouple economic growth from environmental harm. For instance, a study by Odularu (2008) demonstrated that in many developing countries, energy consumption—especially from fossil fuels—has a significant positive impact on economic growth. Conversely, in developed economies, the relationship appears to be less pronounced due to the shift towards cleaner energy and greater energy efficiency (Stern, 2011). This suggests that while fossil fuels have contributed to growth historically, their future role may need to be reconsidered in light of sustainability goals and the rise of cleaner alternatives.

In recent years, research has increasingly emphasized the role of urbanization in shaping both energy consumption patterns and economic growth trajectories. Urbanization is typically associated with greater industrialization, higher energy demands, and shifts in energy consumption towards more diverse and efficient sources. Studies such as those by Ghosh (2002) have shown that urbanization significantly influences energy consumption, particularly by fostering greater energy efficiency due to the concentration of infrastructure and economies of scale. Additionally, the urbanization process has been linked to increased demand for renewable energy as cities seek to meet sustainability targets. A growing body of literature also suggests that urbanization may facilitate the adoption of green technologies and support policies aimed at promoting energy efficiency (Stern, 2011). However, the specific outcomes of urbanization on energy consumption and economic growth remain complex and vary across regions due to differences in infrastructure, policy environments, and socio-economic structures. Another key factor influencing the energy-economic growth nexus is the role of gross fixed capital formation (GFCF), which reflects investment in infrastructure, machinery, and technology. Investment in energy infrastructure has long been recognized as an essential driver of economic development. According to Qamruzzaman (2024), capital accumulation, including investments in energy infrastructure, is crucial for fostering economic growth, particularly in developing countries where energy access remains a significant challenge. GFCF is instrumental in facilitating the transition to cleaner energy systems, as it enables countries to invest in renewable energy technologies, improve energy efficiency, and expand grid capacity. Additionally, higher GFCF is associated with increased industrial activity, which in turn drives energy demand (Romer, 1990). In many emerging economies, GFCF in energy infrastructure not only supports economic growth but also enhances energy access and security, paving the way for a sustainable energy future. However, the impact of GFCF on energy consumption and growth is not linear, as it varies depending on the energy mix, the maturity of the economy, and the structure of the energy sector.

Urbanization and energy consumption are further intertwined through the development of smart cities and the adoption of sustainable urban planning practices. Recent literature has shown that as cities expand and become more densely populated, energy consumption patterns evolve. Smart cities, which leverage digital technologies and advanced data analytics to optimize energy use, have emerged as models of sustainable urbanization (GeSI, 2015). These cities are characterized by the integration of renewable energy sources, efficient transportation systems, and energy-efficient buildings, which collectively reduce per capita energy consumption while maintaining economic growth (Wu, Lin and Sun, 2023). While smart cities have the potential to decouple energy consumption from economic growth, the implementation of such initiatives is costly and requires significant investment in infrastructure. The degree to which urbanization drives energy efficiency thus depends on the extent to which governments and private sectors invest in smart city technologies. As urbanization continues, it is likely that energy consumption will become more localized and targeted, with renewable energy solutions becoming a central component of sustainable urban growth (Liu et al., 2021). This shift could lead to a more sustainable energy future, where urban centers play a leading role in promoting low-carbon economic growth.

One of the most significant variables affecting the relationship between energy consumption and economic growth is population growth. As the global population continues to increase, the demand for energy rises accordingly, placing pressure on both renewable and non-renewable energy resources. Population growth is a driving factor behind higher energy consumption, as an expanding population requires more energy for residential, commercial, and industrial purposes. The positive relationship between population growth and energy consumption is well documented in the literature, as an increasing population directly translates to higher energy demand (Ehrlich and Holdren, 1971). However, the impact of population growth on energy consumption and economic growth is not uniform across countries. In developing nations, rapid population growth often leads to increased demand for traditional energy sources such as fossil fuels, whereas in developed countries, energy efficiency measures and a shift to renewable energy sources may help mitigate the effects of population growth on fossil fuel consumption (Sadorsky, 2009). In many cases, population growth also leads to urbanization, which further intensifies energy consumption, as larger populations tend to concentrate in urban centers with higher energy demands (Stern, 2004). The demographic changes occurring globally thus have far-reaching implications for both energy consumption patterns and the future trajectory of economic growth.

Fossil fuel consumption remains a major driver of energy use worldwide, and its relationship with economic growth is often characterized by a trade-off between short-term economic gains and long-term environmental sustainability. Fossil fuels have historically been the backbone of industrialization and economic development, particularly in emerging economies where access to affordable energy is crucial for supporting manufacturing and infrastructure development. According to the International Energy Agency (IEA, 2021), fossil fuels still account for a significant share of global energy consumption, despite the increasing penetration of renewable energy sources. The strong correlation between fossil fuel consumption and economic growth is especially evident in countries with heavy industrial sectors such as China and India, where fossil fuels, particularly coal and oil, are used to power factories, transportation systems, and power plants (Stern, 2004). However, the environmental and health costs associated with fossil fuel consumption, including air pollution, climate change, and resource depletion, have led many countries to reconsider their reliance on fossil fuels for energy production (Ozturk, 2010). As a result, the decoupling of economic growth from fossil fuel consumption has become a key policy objective for many countries aiming to achieve sustainable development (Sadorsky, 2009). This transition is particularly relevant for high-emission countries where the economic cost of continued fossil fuel dependence may eventually outweigh the short-term benefits of cheap energy.

Renewable energy consumption is increasingly recognized as a critical element in achieving sustainable economic growth. Unlike fossil fuels, renewable energy sources such as wind, solar, and hydroelectric power have minimal environmental impact and are considered key drivers of long-term sustainability. The relationship between renewable energy consumption and economic growth is complex, as countries that prioritize renewable energy often experience both environmental and economic benefits. Several studies have shown that increased investment in renewable energy technologies can lead to enhanced energy security, job creation, and technological innovation, all of which contribute to economic growth (Sadorsky, 2009; Ozturk, 2010). Furthermore, renewable energy is often seen as a key enabler of the transition to a green economy, where low-carbon technologies support sustainable development. For instance, countries such as Germany and Denmark, which have made significant strides in renewable energy adoption, have experienced positive economic growth while reducing their carbon emissions (IEA, 2021). However, the transition to renewable energy is not without its challenges. While renewables offer long-term economic and environmental benefits, they often require substantial initial investments in infrastructure and technology. This can be particularly challenging for developing countries that face budget constraints or lack access to the necessary technologies (Apergis & Payne, 2010). Therefore, understanding the economic implications of renewable energy consumption is crucial for designing policies that balance economic growth with environmental sustainability.

In addition to demographic factors, fossil fuel consumption, and renewable energy, several other variables also play crucial roles in shaping the dynamics of energy consumption and its impact on economic growth. Technological advancements in energy production, transmission, and utilization have long been recognized as key drivers of both economic development and energy consumption patterns. Over the past several decades, the rapid pace of innovation in energy technologies—such as the development of energy-efficient appliances, renewable energy technologies, and advanced energy storage systems—has facilitated more efficient use of energy across various sectors of the economy. Technological improvements have allowed for higher energy productivity, meaning that economies can grow while simultaneously reducing the amount of energy required to produce each unit of output (Apergis & Payne, 2010). The adoption of clean technologies, including energy-efficient machinery in industrial production, has become a core strategy for reducing energy consumption while supporting economic growth (Ozturk, 2010). Moreover, technological advancements in renewable energy systems, such as solar panels and wind turbines, have significantly lowered the cost of clean energy production, helping to increase their share in global energy consumption (Sadorsky, 2009). Therefore, the capacity of countries to innovate and implement new technologies plays a vital role in the sustainability of economic growth and energy use, especially in the context of reducing carbon emissions.

Energy efficiency is another critical variable influencing the energy-economic growth nexus. As the global economy becomes increasingly energy-intensive, the ability to improve energy efficiency becomes a fundamental aspect of achieving sustainable economic growth. Energy efficiency refers to the amount of energy required to produce a unit of economic output, and improvements in efficiency can significantly reduce energy consumption without impairing economic performance. The implementation of energy-efficient technologies, such as LED lighting, efficient building insulation, and advanced heating and cooling systems, can lower the overall energy demand of a country, reducing reliance on both fossil fuels and renewable energy sources. Studies have demonstrated that energy efficiency improvements can drive economic growth by lowering energy costs for businesses and consumers, improving productivity, and fostering greater innovation in energy technologies (Stern, 2004). In particular, energy-efficient investments can have a positive effect on economic competitiveness, especially in energy-intensive industries. However, energy efficiency gains are not automatically achieved; they often require strong policy frameworks, financial incentives, and significant investment in both infrastructure and human capital. As a result, government policies that incentivize energy efficiency improvements are essential for realizing the full economic potential of these advancements (Sadorsky, 2009).

Government policies play a pivotal role in shaping both the energy consumption patterns and the trajectory of economic growth. Policymakers have the ability to direct energy consumption towards more sustainable pathways through regulatory frameworks, taxation policies, subsidies, and investment in infrastructure. In recent years, many governments have adopted policies aimed at reducing carbon emissions and promoting the use of renewable energy, with the intention of decoupling economic growth from environmental harm. For instance, the introduction of carbon pricing mechanisms, such as carbon taxes or cap-and-trade systems, incentivizes firms to reduce their emissions by internalizing the environmental costs of fossil fuel consumption (Apergis and Payne, 2010). Furthermore, government policies promoting renewable energy through subsidies, tax breaks, and mandates have accelerated the transition to clean energy sources. The role of government policy is particularly evident in countries like Denmark and Germany, which have successfully integrated renewable energy into their national grids while maintaining strong economic growth. However, the effectiveness of these policies varies depending on political, economic, and social contexts. In some cases, countries with weaker institutions or less favorable market conditions may face challenges in implementing policies that balance economic growth with environmental sustainability (Ozturk, 2010). The interaction between government regulations, market forces, and technological innovations is thus crucial in determining the overall success of energy policies in fostering sustainable economic growth.

As global interconnectedness continues to deepen, international trade and globalization have emerged as significant external factors influencing both energy consumption and economic growth. Trade openness, which facilitates the exchange of goods and services across borders, has profound implications for energy demand. Globalization often leads to increased production and consumption, thereby driving energy consumption to support expanded industrial activities, transportation, and service sectors. In many emerging economies, economic growth has been fueled by access to global markets, which has simultaneously contributed to higher energy consumption (Ozturk, 2010). However, the relationship is complex, as globalization also promotes the transfer of energy-efficient technologies and renewable energy solutions, which can mitigate the environmental impacts of increased trade and production. For example, multinational companies may implement energy-efficient technologies in their supply chains, driving productivity gains while lowering energy intensity. Nonetheless, the growth of international trade also means that countries are increasingly dependent on external sources of energy, which exposes them to fluctuations in global energy prices and potential supply disruptions. Thus, trade liberalization and economic integration shape energy consumption patterns, while also affecting the broader economic context in which energy use and growth are situated.

Geopolitical factors, including energy security and political stability, are also crucial in understanding the energy-growth nexus. Political instability and conflicts in energy-producing regions can disrupt global energy supplies, influencing energy prices and availability. For instance, geopolitical tensions in the Middle East often result in fluctuations in global oil prices, which can have far-reaching effects on both developed and developing economies (Apergis and Payne, 2010). Additionally, energy security concerns have prompted many countries to diversify their energy sources, investing in alternative fuels and renewable energy to reduce dependency on fossil fuels imported from politically volatile regions. Geopolitical factors may also affect energy policy decisions, as countries may prioritize energy independence in the face of external pressures. These considerations shape the trajectory of energy consumption and economic growth by influencing the availability of affordable energy resources and driving national strategies for energy diversification.

While earlier literature on the energy–growth nexus primarily focused on identifying correlations, the field has increasingly evolved to incorporate more sophisticated econometric methodologies aimed at establishing causal relationships and addressing pervasive endogeneity concerns. Researchers now frequently employ causal identification techniques such as instrumental variable (IV) methods, Granger causality tests, and dynamic panel data models like the Generalized Method of Moments (GMM). These advanced approaches are crucial for mitigating biases arising from reverse causality (e.g., economic growth influencing energy consumption) and unobserved time-varying confounders, thereby enabling a more robust understanding of the direction and magnitude of impact between energy, demographic factors, and economic growth (e.g., see examples by Arellano & Bond (1991), Zakari, Toplak and Tomažič (2022)). Acknowledging the complexities of disentangling these relationships, a comprehensive literature review necessitates a discussion of these methodological advancements and their implications for drawing robust conclusions.

Furthermore, the growing body of empirical work within the energy–growth nexus has led to a proliferation of findings, some of which present contradictory evidence across different contexts and methodologies. To synthesize these diverse results and identify overarching trends, critical gaps, or unresolved debates, recent meta-analyses and systematic review studies have become invaluable resources (Odongo et al., 2023). Integrating insights from such comprehensive reviews allows for a more nuanced understanding of the existing evidence,

highlights areas where consensus has emerged, and critically, identifies specific avenues for future research to address persistent empirical inconsistencies or unexplored dimensions within the energy–growth relationship.
The literature review reveals that the relationship between energy consumption and economic growth is influenced by a multitude of factors. While technological advancements, energy efficiency, and government policies are central to understanding these dynamic, external variables such as international trade and geopolitical factors add complexity to the equation. These variables interact in diverse ways, and their effects are often context-dependent, highlighting the importance of a nuanced approach in analyzing energy policies and economic strategies. In particular, the ongoing shift towards renewable energy, coupled with the global drive for carbon neutrality, suggests that the future of energy consumption and economic growth will be shaped by the integration of environmental sustainability goals into economic frameworks.

Methodology

Data and Countries

This study utilizes a panel dataset covering five key countries—China, the United States, Germany, Brazil, and India—over the period 2000 to 2023. These countries were selected based on their significant roles in the global energy landscape:

- China is the world's largest producer of renewable energy (World Economic Forum, 2024).
- The United States is a major investor in renewable energy technologies (IEA, 2023).
- Germany is a pioneer in energy transition policies (Agora Energiewende, 2023).
- Brazil leads in hydropower production (International Hydropower Association (IHA), 2023).
- India has rapidly expanded its solar and wind energy capacity (IEA, 2024).

The dataset includes macroeconomic and energy-related indicators, allowing for an analysis of how economic growth, energy consumption, and urbanization interact across different economic and policy contexts.

Variables

The dataset comprises six key variables, namely GDP per capita represented as GDPPC, Renewable Energy per Capita represented as Re_Energy, Population Growth Rate represented as Pop_Growth, Fossil Fuel Energy Consumption represented as Fossil_Fuel, Gross Fixed Capital Formation represented as GFCF and Urban Population Share represented as Urban_Pop. Apergis and Payne (2010) and Sadorsky (2009) also employed GDP per capita as a proxy for economic growth. Ozturk (2010) used renewable energy as dependent variable while determining the impact of renewable energy usage on economic growth. Shahbaz et al. (2017) used population growth as a control variable to control for demographic effects on energy demand. Dogan and Seker (2016) employed fossil fuel consumption as a dependent variable, while examining energy transitions. Apergis and Payne (2014) used as an indicator of investment levels affecting economic performance and energy demand. Table.1 provides descriptions of these variables.

Table.1 Source and Description of Variables

Variables	Description	Unit of Measurement	Source
GDPPC	It represents the economic output per person and serves as a primary indicator of economic development.	Current US$	World Bank
Re_Energy	It captures the extent of renewable energy consumption on a per-person basis, reflecting a country's progress in energy transition.	kWh - equivalent	Energy Institute - Statistical Review of World Energy (2024)
Pop_Growth	It indicates annual population changes, which can impact energy demand and economic growth.	Annual % growth	World Bank
Fossil_Fuel	It measures fossil fuel consumption as percentage of total energy consumption and reflects the dependence on non-renewable energy sources.	% of total energy consumption	World Bank
GFCF	It indicates the level of investment in infrastructure, machinery, and equipment, serving as a proxy for economic development and industrial expansion.	% of GDP	World Bank
Urban_Pop	It reflects the level of urbanization, which is associated with energy demand patterns and economic activity.	% of total population	World Bank

Empirical Methods

Panel Data Analysis Model

Panel data (also known as longitudinal data) tracks multiple entities (in this case, likely 5 countries, as indicated by n = 5) over multiple time periods (here, 24 years, as indicated by T = 24). This allows you to control for factors that vary across entities but are constant over time (like culture or geography in the case of countries) and factors that vary over time but are constant across entities (like global economic shocks).

To rigorously analyze the complex relationships between economic growth and the aforementioned energy and demographic factors, this study employs a panel data regression framework. Given the longitudinal nature of the dataset, which tracks five distinct countries over a 24-year period, panel data methods offer significant advantages over traditional cross-sectional or time-series approaches. Specifically, these methods allow us to account for unobserved heterogeneity—factors unique to each country that remain constant over time (e.g.,

historical endowments, persistent institutional differences)—and common time-varying shocks that affect all countries similarly (e.g., global economic cycles, technological diffusion).
To analyze the relationship between economic growth and energy consumption variables, a Fixed Effects (FE) model is employed. The fixed effects approach controls for all time-invariant differences between countries, focusing solely on within-country variations over time.

The model is specified as follows:

$$GDPPC_{it} = \alpha_i + \beta_1 Re\_Energy_{it} + \beta_2 Pop\_Growth_{it} + \beta_3 Fossil\_Fuel_{it} + \beta_4 GFCF_{it} + \beta_5 Urban\_Pop_{it} + \varepsilon_{it}$$

Where $GDPPC_{it}$ is dependent variable for country i at time t, Re_Energy_{it}, Pop_Growth_{it}, $Fossil\_Fuel_{it}$, $GFCF_{it}$, and $Urban\_Pop_{it}$ are independent variables. ε_{it} is the error term. α_i are the country-specific intercept, capturing all time-invariant heterogeneity and β_1..... β_5 are coefficient estimates, and ε_{it} is the error term.
The One-way (individual) fixed effects model is estimated using the Within transformation, which removes the individual country effects by de-meaning the variables (i.e., subtracting the country-specific averages). The choice of a fixed or random effects model is determined through Hausman test. The model is estimated using R software, applying the *plm ()* function.

Country-Specific Effects

Ppanel regressions (Fixed Effects / Random Effects) provide the average relationships between variables like renewable energy use (Re_Energy), fossil fuel consumption (Fossil_Fuel), gross fixed capital formation (GFCF), urban population (Urban_Pop), and GDP per capita (GDPPC). However, assuming a homogeneous relationship across countries is unrealistic due to structural and policy differences. Therefore, country-specific interaction analyses are conducted to uncover heterogeneous effects and policy-relevant insights. Ghafoor et al. (2024) and Kim and Jeon (2024) also considered country-specific characteristics while using panel data analysis.
Country-specific analysis is necessary to take heterogeneity among countries into account. It may encompass variations in economic structures, energy profiles and development stages. Moreover, a single energy policy may not fit the five countries included in this study. It is also relevant for model precision as pooling could hide or distort the true nature of variable effects.

Results and Discussion

This section encompasses results from the estimated methods discussed in the methodology part of this study.

Descriptive Statistics

This dataset provides economic and energy-related data for five key countries—China, the USA, Germany, Brazil, and India—from 2000 to 2023. Table.2 presents the descriptive statistics, helping us to understand what they tell us about these countries and their energy-economic landscape.
Table.2. shows that the GDP per capita varies widely across these five countries. The high standard deviation suggests that some countries (like the USA and Germany) have much higher GDP per capita than others (like India and China). The median ($9,993) is much lower than the mean ($22,186.9), which suggests that a few

high-income countries (USA, Germany) are pulling up the average, while the majority of the dataset has lower GDPPC values (as seen in China, India, and Brazil). The large variation in Re_Energy suggests that some countries have much higher per capita renewable energy production than others. Brazil, as a hydropower leader, likely contributes significantly to the higher values, while China and India, despite being large producers, have lower per capita values due to their large populations. The USA and Germany, with advanced energy transitions, likely push the upper range.

The low standard deviation of Pop_Growth suggests that population growth rates are relatively stable across countries, with most values staying around 0.7% annually. However, the negative minimum (-1.85%) indicates that some years had population declines, likely in Germany, where population stagnation or decline has been a concern. Countries like India and Brazil contribute to the higher end with strong population growth, while Germany and possibly China have had periods of slower or even negative growth. The extreme variation in Fossil_Fuel consumption suggests that some countries rely heavily on fossil fuels (likely China and India), while others (like Germany and Brazil) have significantly reduced their dependence. The USA and China likely push up the mean, while the median (6,207%) is much lower than the mean (11,899%), suggesting a skewed distribution with a few high fossil-fuel-consuming countries dominating the dataset.

Table 2. Descriptive Statistics

Variable	Mean	Median	Std. Deviation	Min	Max
GDPPC	22186.9	9993.0	22,531.43	442.8	82769.4
Re_Energy	4046	3875.3	2854.548	194.9	9282.5
Pop_Growth	0.7070	0.7275	0.542	-1.8537	1.8794
Fossil_Fuel	11899	6207	10991.67	1339	38677
GFCF	26.14	21.52	8819	14.56	44.52
Urban_Pop	64.99	77.17	21.004	27.67	87.79

GFCF measures investment in infrastructure and long-term economic development. China likely has the highest values, as it has historically invested heavily in infrastructure. The wide variation suggests different economic strategies: China with a high GFCF prioritizes investment-driven growth while Germany and the USA with a lower GFCF focus more on consumption-driven economies.

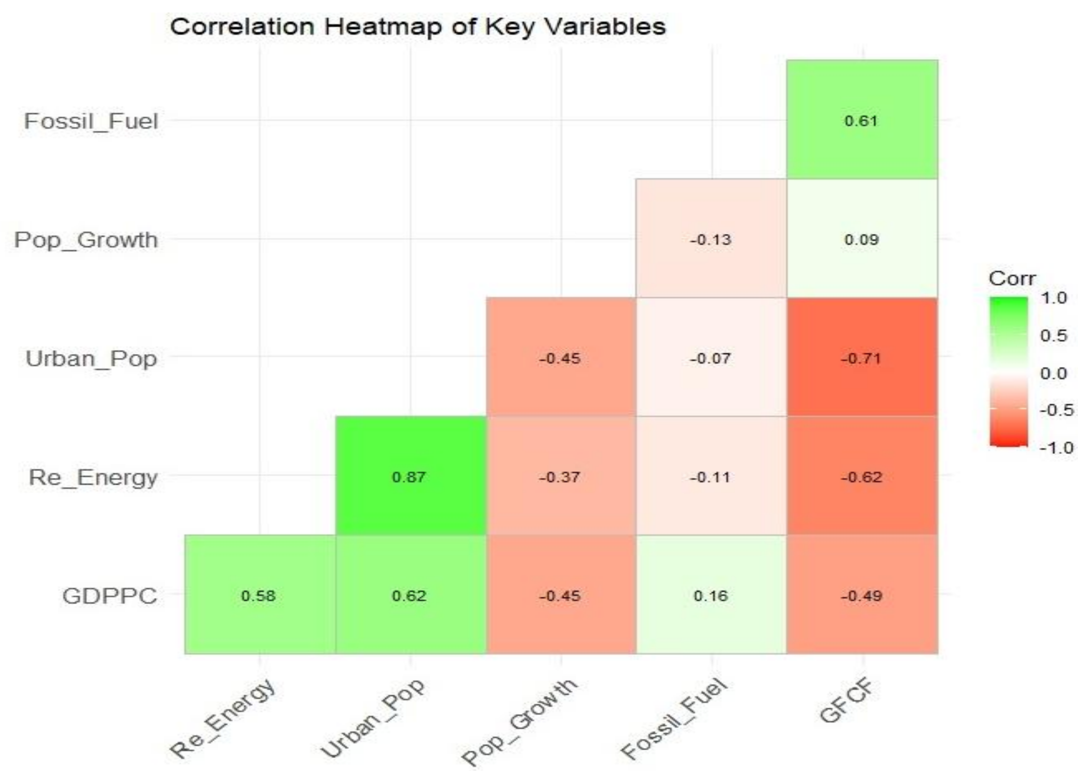
The high median (77.17%) of Urban_Pop compared to the mean (64.99%) suggests that most countries have high urbanization, but one or two (likely India and China in earlier years) still had significant rural populations, pulling the mean downward. Germany and the USA are likely in the upper range (above 80%), while India and Brazil contribute to the lower urbanization levels.

Correlation

Figure.1 shows a correlation heatmap, representing the relationships between key variables. Green indicates a perfect positive correlation (1), red indicates a perfect negative correlation (-1), while white/neutral shows no correlation (0). Renewable Energy (Re_Energy) and Urban Population (Urban_Pop) have a strong positive correlation (0.87). Similarly, Fossil Fuel (Fossil_Fuel) and Gross Capital Fixed Formation (GFCF) have a moderate positive correlation (0.61). Moreover, GDP per Capita (GDPPC) also have a moderate positive correlation with Urban_Pop (0.62) and Re_Energy (0.58). It shows that urbanization is associated not only with greater renewable energy use but also with higher GDP per capita.

Furthermore, Figure. 1 shows that Urban_Pop and GFCF have strong negative correlation (-0.71), while Re_Energy and GFCF have a moderate negative correlation (-0.62). Similarly, GDPPC and Population Growth (Pop_Growth) also have a moderate negative correlation (-0.45). It reveals that higher investment in GFCF negatively correlates with urban population and renewable energy use, suggesting that industrial investment relies on traditional energy sources. Furthermore, GDPPC and GFCF have moderate negative correlation (-0.49). Besides, these stronger correlation, weaker relationships can also be observed in the heatmap. Pop_Growth and Fossil_Fuel has a very weak negative correlation (- 0.07), while Pop_Growth and GFCF have a very weak positive correlation (0.09). It shows that population growth has a weak or negligible relationship with most economic and energy indicators.

Figure 1. Correlation Heatmap of Variables



The study can obtain more robust estimates through panel data methods as these account for country-level heterogeneity and time trends, leading to more precise policy implications.

Panel Data Analysis

To enhance accuracy, Fixed Effects and Random Effects models are employed. A Hausman test can help determine whether the FE model (more appropriate for policy-focused research) or RE model (better for generalizable results) is preferable. Panel data analysis will enhance the robustness of our conclusions by accounting for country-level heterogeneity and addressing omitted variable bias.

Panel Data Regression

Fixed Effects Model

The fixed effects model focuses on the variations *within* each entity over time. It assumes that there are unobserved, time-invariant individual effects that may be correlated with the independent variables. By including individual-specific intercepts, the fixed effects model essentially "differences out" these time-invariant effects. Oneway (individual) effect Within Model code is employed in R, which indicates that the fixed effects are specific to each individual entity (the 5 countries in the dataset). The "within" model signifies that the analysis focuses on the changes within each entity over time.

An R-squared of 0.76161 shows that approximately 76.16% of the variation in GDPPC *within* the countries over time is explained by the included independent variables and the individual fixed effects. The adjusted R-squared is a modified version of R-squared that accounts for the number of predictors in the model. It penalizes the inclusion of unnecessary variables. A value of 0.7421 suggests that the model explains about 74.21% of the variation in GDPPC after adjusting for the number of predictors. The very small p-value (< 2.22e-16) indicates that we reject the null hypothesis, meaning that at least one of the independent variables has a statistically significant effect on GDPPC *within* the countries.

Table. 4. shows results of the fixed effects model. Re_Energy is highly statistically significant positive effect on GDPPC. The coefficient .49453 indicates that a 1 unit increase in Renewable Energy consumption per capita is associated with an estimated increase of $3.49 in GDP per capita *within* a country over time. Inglesi-Lotz, R. (2016) conducted panel data analysis using data from OECD countries for the period 1990--2010 and found that renewable energy consumption positively impacts economic growth, especially in lower and low-middle quantiles.

Pop_Growth has a statistically significant negative effect on GDPPC and its coefficient reveals that a 1 percentage point increase in Population Growth is associated with an estimated decrease of $4085.26 in GDP per capita *within* a country over time. Oluoch, Lal and Susaeta (2021) analyzed data from Sub-Saharan African countries and found that higher population growth rates are associated with lower GDP per capita, suggesting that rapid population increases can strain economic resources.

Table.4. shows that Fossil_Fuel has weakly significant negative impact on GDPPC and a 1 unit increase in Fossil Fuel consumption per capita is associated with an estimated decrease of $0.67 in GDP per capita *within* a country over time. Muhammad and Majeed (2024) also found that increased reliance on fossil fuels negatively affects renewable energy production, which, in turn, impact economic growth. Moreover, the impact of GFCF is not statistically significant and a 1 unit increase in GFCF per capita is associated with an estimated increase of $303.41 in GDP per capita *within* a country over time. Vlăduţ et al. (2024) also showed that while capital formation is crucial, its impact on GDP per capita can be limited if not complemented by other factors like technological advancement and efficient resource allocation

Similarly, the impact of Urban_Pop is also not significant and a 1 percentage point increase in Urban Population is associated with an estimated increase of $311.90 in GDP per capita *within* a country over time.

Table 4. Fixed Effects Model Results

Coefficients	Estimate	Std. Error	t-value	Pr (|t|)
Re_Energy	3.49453	0.36136	9.6705	2.229e-16 ***
Pop_Growth	-4085.25996	1225.29497	-3.3341	0.001167 **
Fossil_Fuel	-0.66922	0.40045	-1.6711	0.097535
GFCF	303.40822	195.08569	1.5553	0.122758
Urban_Pop	311.89814	395.21609	0.7892	0.431702

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
Total Sum of Squares: 6013800000
Residual Sum of Squares: 1433700000
R-Squared: 0.76161
Adj. R-Squared: 0.7421
F-statistic: 70.2839 on 5 and 110 DF, p-value: < 2.22e-16

Random Effects Model

The random effects model also accounts for unobserved individual heterogeneity, but it assumes that these individual effects are uncorrelated with the independent variables and are drawn from a random distribution. Instead of estimating a separate intercept for each entity, it estimates the variance of these random individual effects. The random effects model includes random effects specific to each individual entity, employing Amemiya's transformation, which is a method used to estimate the random effects model.

The variance of the error term is 12466609, the standard deviation is 3531 and the share is 0.03. The share indicates the proportion of the total error variance that is idiosyncratic. The variance of the random individual effects is 403764884, standard deviation is 20094 and share is 0.97. The large standard deviation and high "share" (97%) suggest that a substantial portion of the unexplained variation in GDPPC is due to differences between the countries that are relatively constant over time. The value of Theta is 0.9642. Theta is a factor used in the estimation of the random effects model. It essentially determines how much weight is given to the within-entity variation versus the between-entity variation. A theta close to 1 suggests that the random effects estimator gives more weight to the within-entity variation, making it behave more like the fixed effects estimator.

The R-Squared value is 0.75455, suggesting that the proportion of the total variation in GDPPC explained by the random effects model is approximately 75.46%. Adjusted R-squared value is 0.74378, indicating that the adjusted R-Squared for the random effects model is approximately 74.38%. The very small p-value (< 2.22e-16) indicates that the model as a whole is statistically significant.

Table. 5. shows results of the random effects model. These coefficients represent the estimated impact of each independent variable on GDPPC, considering both the within-entity and between-entity variation, and assuming the individual effects are random and uncorrelated with the regressors. The coefficient estimates for Re_Energy (3.58099) and Pop_Growth (-4252.38301) are quite similar to those in the fixed effects model, and they remain statistically significant. The coefficients for Fossil_Fuel (-0.52863), GFCF (266.18497), and Urban_Pop (182.59497) are also in the same direction as in the fixed effects model but remain statistically insignificant (except for Fossil_Fuel which is weakly significant).

Table 5. Random Effects Model Results

Coefficients	Estimate	Std. Error	t-value	Pr (|t|)
(Intercept)	-1827.94371	19767.59731	-0.0925	0.9263233
Re_Energy	3.58099	0.31446	11.3877	< 2.2e-16 ***
Pop_Growth	-4252.38301	1166.35569	-3.6459	0.0002665 ***
Fossil_Fuel	-0.52863	0.30894	-1.7111	0.0870598
GFCF	266.18497	192.38589	1.3836	0.1664812
Urban_Pop	182.59497	296.44923	0.6159	0.5379340

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Total Sum of Squares: 6083700000

Residual Sum of Squares: 1493200000

R-Squared: 0.75455

Adj. R-Squared: 0.74378

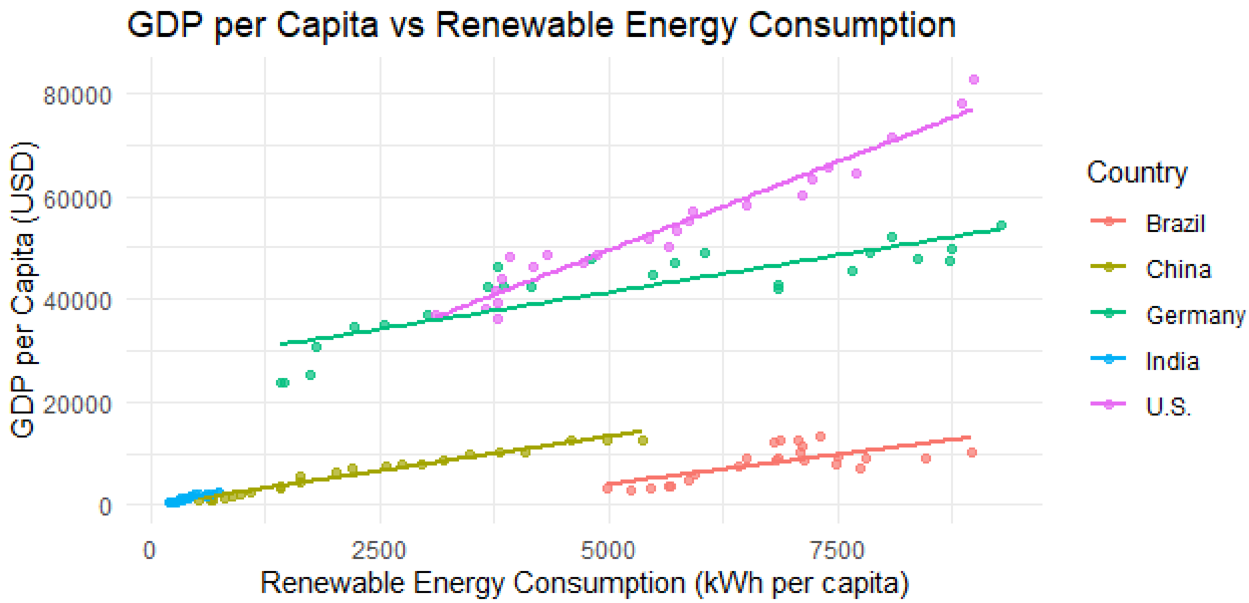
Chisq: 350.453 on 5 DF, p-value: < 2.22e-16

Hausman Test

The Hausman test is used to decide between the fixed effects and random effects models. It tests the null hypothesis that the individual effects are uncorrelated with the regressors (the assumption underlying the random effects model). The alternative hypothesis is that there is correlation (which is better handled by the fixed effects model). While examining renewable energy consumption and economic growth, Bilalli et al. (2024) employed Hausman test to choose between fixed and random effects models. The test results guided the selection of the appropriate model based on the correlation between individual effects and regressors.

Regarding the choice between FE and RE models, the Hausman test is employed to formally assess which specification is more appropriate for our data. The null hypothesis of the Hausman test posits that the Random Effects model is consistent and efficient, implying that the unobserved country-specific effects are uncorrelated with the explanatory variables. Our test results yielded a p-value of 0.5308. Since this p-value is greater than the conventional significance level of 0.05, we fail to reject the null hypothesis. This statistical outcome suggests that the assumption of no significant correlation between the unobserved individual effects and the regressors holds for our dataset. Consequently, the Random Effects model, which allows for more efficient estimation by incorporating both within-country and between-country variation, is statistically preferred over the Fixed Effects model. While Fixed Effects models are often favored when unobserved heterogeneity is likely correlated with explanatory variables, our Hausman test results indicate that the Random Effects model provides a consistent and more efficient estimation for our specific panel, allowing us to generalize our findings beyond the sample based on the assumption that individual effects are random draws from a larger population.

Figure 4. GDP per Capita vs Renewable Energy Consumption



Country-Specific Effects Comparison

After running the OLS and panel data regressions (like Fixed Effects and Random Effects), we get *average* effects of explanatory variables across all countries and time. However, that approach assumes that the relationship between predictors (like renewable energy use or fossil fuel consumption) and GDP per capita is homogeneous across countries—which may not hold true in reality. Countries like China, Germany, India, the U.S., and Brazil have very different economic structures, energy policies, stages of development, and urban dynamics. Therefore, a country-specific analysis is necessary to uncover heterogeneous effects, reveal policy-relevant insights and address misspecification risks. For this purpose, an interactions model is employed.

The main reference country is Brazil in the interaction model. It is chosen purely as an arbitrary base country for the purpose of illustrating heterogeneous effects through interaction terms. This choice does not imply any theoretical significance, empirical superiority, or representativeness of Brazil compared to the other countries in the sample. Its selection facilitates the direct interpretation of the interaction terms as the incremental (or decremental) effect of a variable for a specific country compared to Brazil's baseline effect.

Table. 6. reveals the results of the model, where coefficients without interaction terms (e.g., Re_Energy, Fossil_Fuel, Urban_Pop) reflect effects for Brazil (baseline country). The main coefficients (like Re_Energy, Fossil_Fuel, GFCF, Urban_Pop) reflect their effect on GDP per capita in the reference country, which is Brazil (since all other countries are included as dummies).

Table.6. shows the output of the interaction model, which provides insights into how different countries' GDP per capita (GDPPC) responds to various factors like renewable energy (Re_Energy), fossil fuel consumption (Fossil_Fuel), gross fixed capital formation (GFCF), and urban population (Urban_Pop). The model includes both main effects (i.e., the effects of each predictor on GDPPC) and interaction terms (i.e., how the relationship between predictors and GDPPC changes for different countries). Main Effects show the general relationship between a predictor and GDPPC, averaged across all countries. Interaction Effects show how the relationship between a predictor (e.g., Re_Energy, Fossil_Fuel) and GDPPC changes for different countries.

Table 6. Interaction Terms Model Results

Coefficient	Estimate	Std. Error	t-value	Pr (| t |)
(Intercept)	9.545e+04	6.321e+04	1.510	0.134361
Re_Energy	3.121e+00	1.181e+00	2.642	0.009650 **
China	-1.064e+05	6.441e+04	-1.652	0.101869
Germany	-1.014e+06	1.468e+05	-6.910	5.51e-10 ***
India	-9.725e+04	7.356e+04	1.322	0.189334
U.S.	-6.751e+05	1.304e+05	-5.179	1.25e-06 ***
Fossil_Fuel	1.235e+01	3.303e+00	3.738	0.000316 ***
GFCF	2.788e+02	2.785e+02	1.001	0.319246
Urban_Pop	-1.591e+03	8.412e+02	-1.891	0.061676
Re_Energy_China	-1.788e+00	1.900e+00	-0.941	0.348931
Re_Energy_Germany	-4.501e+00	1.300e+00	-3.463	0.000802 ***
Re_Energy_India	-2.690e+00	1.078e+01	-0.249	0.803536
Re_Energy_U.S.	-1.063e-01	1.583e+00	-0.067	0.946588
Fossil_Fuel_China	-1.241e+01	3.317e+00	-3.742	0.000313 ***
Fossil_Fuel_Germany	-1.667e+01	4.543e+00	-3.669	0.000401 ***
Fossil_Fuel_India	-1.210e+01	3.643e+00	-3.321	0.001276 **
Fossil_Fuel_U.S.	-1.008e+01	3.376e+00	-2.986	0.003593 **
GFCF_China	-2.449e+02	3.870e+02	-0.633	0.528451
GFCF_Germany	-1.608e+01	5.837e+02	-0.028	0.978076
GFCF_India	-2.670e+02	3.065e+02	-0.871	0.385816
GFCF_U.S.	1.105e+02	4.299e+02	0.257	0.797667
Urban_Pop_China	1.872e+03	9.452e+02	1.981	0.050519
Urban_Pop_Germany	1.431e+04	1.815e+03	7.881	5.35e-12 ***
Urban_Pop_India	1.625e+03	1.774e+03	0.916	0.362111
Urban_Pop_U.S.	8.473e+03	1.666e+03	5.084	1.85e-06 ***

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 1599 on 95 degrees of freedom

Multiple R-squared: 0.996, Adjusted R-squared: 0.995

F-statistic: 980.8 on 24 and 95 DF, p-value: < 2.2e-16

The estimate of the intercept is 9.545e+04 (95,450), which is the baseline value of GDPPC when all the predictors (Re_Energy, Fossil_Fuel, GFCF, Urban_Pop) are zero for a country that isn't one of the four specified countries (China, Germany, India, US).

Main Effects

The estimate of Re_Energy is 3.121, suggesting that 1-unit increase in renewable energy increases GDPPC by 3.121 units, regardless of the country. The p-value (0.009650) indicates that this effect is statistically significant ($p < 0.01$). Fossil_Fuel estimate is 12.35, which means that on average, a 1-unit increase in fossil fuel consumption increases GDPPC by 12.35 units, regardless of the country. This effect is statistically significant ($p < 0.01$). The estimate of GFCF is 278.8, suggesting that on average, a 1-unit increase in GFCF increases GDPPC by 278.8 units. However, the p-value (0.319) suggests this effect is not statistically significant. Moreover, Urban_Pop has an estimate of -1591, meaning that a 1-unit increase in urban population decreases GDPPC by 1,591 units. The p-value (0.061676) indicates this is marginally significant ($p \approx 0.06$).

Country-Specific Effects

Country specific effects are included in this study to explicitly estimate and highlight the heterogeneous effects of the explanatory variables across different countries. While the FE model controls for country-specific intercepts, it does not directly present how the *slopes* of the explanatory variables differ across entities. The interaction terms serve to quantify these nuanced, country-specific relationships, providing richer policy-relevant insights that transcend average effects.

Brazil

A unit increase in Re_Energy is associated with a $3.12 increase in GDP per capita, which is significant and positive and a unit increase in Fossil_Fuel is linked with a $12.35 increase in GDP, surprisingly positive and significant—but this is just for Brazil, and we'll see that other countries behave differently. Moreover, Urban_Pop has a negative coefficient (-1,591), suggesting urbanization may hurt GDP in Brazil, but it’s marginally significant.

China

The negative interaction between Fossil_Fuel and China (-12.41) tells us that fossil fuel use hurts China’s GDP per capita significantly. It reverses the Brazil effect. So, in China, the net effect = 12.35 (Brazil) - 12.41 = ~0, i.e., fossil fuel use has no clear economic benefit. The interaction with Urban_Pop is positive (1,872) and marginally significant, meaning urbanization might actually help China’s economy, contrary to Brazil. No significant interaction for Re_Energy or GFCF is observed.

Germany

Very large negative intercept (-1.01 million!) indicates Germany's GDP per capita differs greatly in structure and level from Brazil’s. Re_Energy estimate in Germany is -4.50, suggesting renewable energy is less effective in Germany than in Brazil—possibly due to saturation or diminishing returns in a highly developed system. Fossil_Fuel estimate is -16.67, showing a strong negative impact of fossil fuels on GDP, reinforcing Germany’s shift away from them. Urban_Pop interaction is very strong (+14,310) and highly significant—urbanization strongly boosts GDP in Germany, possibly reflecting better infrastructure and high urban productivity.

India

No significant effects for Re_Energy, GFCF, or Urban_Pop—suggesting India may still be transitioning, and these factors haven’t yet matured in terms of GDP contribution. However, Fossil_Fuel: India is -12.10, meaning fossil fuel use is economically harmful, reinforcing the need for cleaner alternatives.

United States

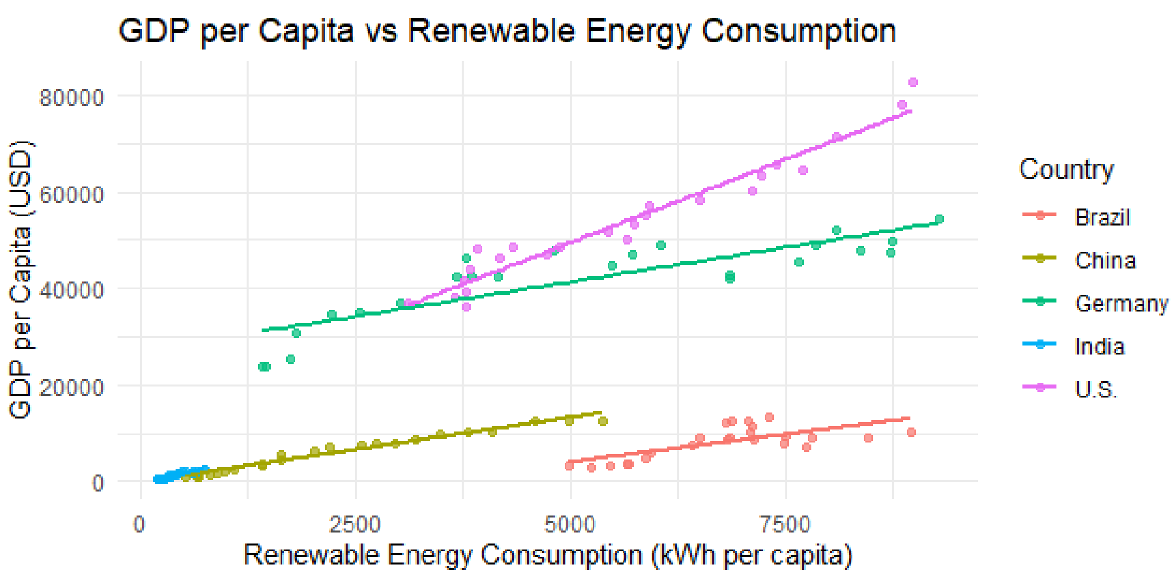
Fossil_Fuel estimate is -10.08, which is also significant, meaning fossil fuels reduce GDP here too (despite being a large fossil fuel producer). Urban_Pop interaction is positive and significant (+8,473), suggesting urbanization supports economic activity in the U.S. Renewable energy shows no significant interaction, suggesting a neutral economic effect—possibly because the U.S. already has diversified energy use.

Figure. 5 shows the relationship between GDP per Capita and Renewable Energy Consumption for five countries: Brazil, China, Germany, India, and the U.S. Each country is represented with a different color, and trend lines are included to indicate the general relationship for each. All countries show a positive correlation between renewable energy consumption and GDP per capita. This means that as renewable energy consumption increases, so does GDP per capita, though the strength and steepness of that relationship vary.

U.S. (Magenta) has the steepest slope, indicating a strong relationship between renewable energy use and high GDP per capita. The U.S. consistently has the highest GDP per capita across all levels of renewable energy consumption in this graph. Germany (Green) also shows a strong positive correlation, with a high GDP per capita that grows with renewable energy consumption. China (Yellow-Gold) and Brazil (Red) show a similar, more moderate upward trend, with Brazil having generally lower renewable energy use but somewhat comparable GDP trends to China. India (Blue) has the lowest GDP per capita, though it still shows a positive trend. Its renewable energy consumption is also on the lower end.

Figure.5. effectively highlights the economic disparities among these countries despite increases in renewable energy consumption. Developed nations like the U.S. and Germany are in the upper right, reflecting both high GDP and high renewable energy use. Developing nations, like India and Brazil, cluster towards the lower left, showing lower values in both metrics.

Figure 5. GDPPC vs Re_Energy by Country



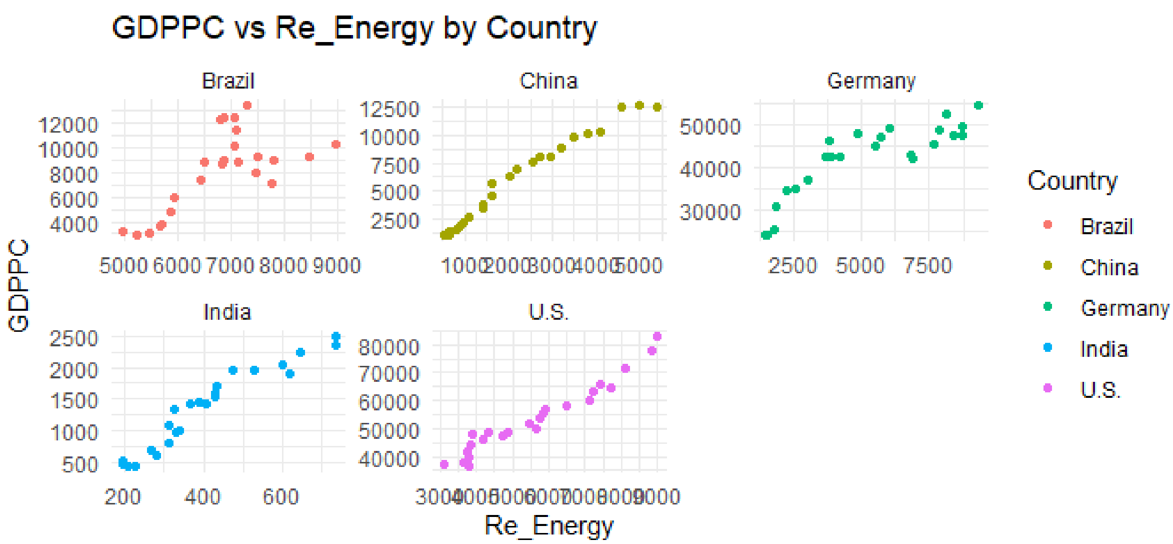
Key Takeaways from Country-Specific Model

The coefficients and interaction terms reveal the specific differences between countries in how these variables influence GDP. Countries like Germany, U.S., and China have significant deviations in how predictors affect

GDP compared to the reference country. Some effects, like GFCF and Urban Population in certain countries, are not statistically significant, which suggests that they may not be as relevant in explaining GDP for those countries.

Fossil fuels hurt economic performance in all four countries relative to Brazil, with especially strong negative effects in Germany and China. Urbanization helps GDP in Germany and the U.S., but not Brazil or India. Renewable energy's benefits are context-specific: It helps Brazil, but seems less impactful in Germany and China (likely due to saturation). India shows few significant interactions, pointing to structural and developmental transitions still in progress.

Figure 6. GDP per Capita vs Renewable Energy by Country



Conclusion

This study investigates the relationship between economic growth and key energy-related and demographic variables across five major economies: China, the United States, Germany, Brazil, and India, over the period from 2000 to 2023. The analysis employs panel data analysis to examine the influence of renewable energy consumption, fossil fuel dependence, population growth, gross fixed capital formation, and urbanization on GDP per capita. The panel data analysis, utilizing both fixed and random effects models, highlights the significance of renewable energy consumption and population growth in influencing GDP per capita. However, the results from the random effects model suggest that the effects of fossil fuel consumption, gross fixed capital formation, and urbanization on GDP per capita are not statistically significant, indicating that these factors may have varying impacts across the countries studied. Country-specific analyses further highlight the heterogeneous effects of these variables on GDP per capita. For instance, while renewable energy consumption generally has a positive impact on GDP per capita, this effect varies across countries, with Germany showing a significant negative interaction. Similarly, the impact of fossil fuel consumption and urbanization on GDP per capita also differs across the countries, reflecting the diversity in economic structures and policy environments. This study yields several important policy implications for the five countries in question and for other economies facing similar challenges and opportunities. Firstly, the consistent positive impact of renewable energy consumption on GDP per capita across the different models underscores the necessity for policies that promote and incentivize the development and deployment of renewable energy infrastructure. This could involve feed-in tariffs, tax credits, and subsidies, as well as the removal of barriers to grid integration and investment in research and development.

Secondly, the negative relationship between fossil fuel consumption and GDP per capita suggests that policies aimed at reducing dependence on fossil fuels, such as carbon pricing, emissions trading schemes, and stricter environmental regulations, are crucial for fostering sustainable economic growth. Thirdly, the findings highlight the complex role of urbanization in economic development, indicating that policies must address the challenges of rapid urbanization, including infrastructure deficits, housing shortages, and social inequalities, to fully harness its economic potential. Moreover, the significant negative impact of population growth on GDP per capita implies that policies addressing population dynamics, such as family planning and education, particularly for women, can play a vital role in promoting sustainable development.

This study can be extended in several directions. Firstly, future research could expand the scope to include a larger set of countries, particularly those with diverse economic and energy profiles, to enhance the generalizability of the findings. Secondly, incorporating additional variables such as technological innovation, energy efficiency, and policy stringency could provide a more nuanced understanding of the energy-growth nexus. Thirdly, employing dynamic panel data techniques, such as vector autoregression (VAR) models, could help to explore the causal relationships and feedback effects between the variables. Moreover, investigating the sectoral impacts of energy consumption and urbanization on economic growth could offer valuable insights for targeted policy interventions.

The findings of this study should be interpreted within the context of several limitations. First, despite employing panel data methods, the models do not fully account for potential endogeneity and reverse causality that may exist between GDP per capita and key explanatory variables such as renewable energy consumption, fossil fuel use, and gross fixed capital formation. These variables are often jointly determined with economic growth, and while the fixed effects approach addresses time-invariant unobserved heterogeneity, it does not correct for endogeneity arising from simultaneous causality or time-varying omitted variables. More advanced econometric techniques, such as instrumental variable (IV) methods or dynamic panel models, would be necessary to establish stronger causal inferences.

Second, while the two-way fixed effects model controls for unobserved time-invariant country-specific factors and common time trends, it may not comprehensively capture all time-varying omitted variables. Factors such as changes in national policy regimes, fluctuations in global commodity prices, or unique patterns of technological adoption that vary over time and across countries could potentially confound our estimates. Although incorporating time fixed effects mitigates some of this concern, fully accounting for all such time-varying confounders remains a challenge.

Furthermore, the relatively small sample size of five countries, though analyzed over a considerable 24-year period, inherently limits the external validity and generalizability of our results to a broader set of economies. A smaller sample size can also reduce the statistical power of tests, particularly when incorporating interaction terms to capture heterogeneous effects. Future research should aim to expand the country sample to enhance the generalizability and robustness of the findings.

Declaration

Acknowledgment: N/A

Funding: N/A

Conflict of interest: N/A

Ethics approval/declaration: N/A

Consent to participate: N/A

Consent for publication: N/A

Data availability: Data available upon request

Authors contribution: The author independently conducted all phases of the research, including the conceptualization and design of the study, data collection, analysis and interpretation of findings, as well as the writing and revision of the manuscript.

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