Decarbonise without compromise: Exploring the nexus between the energy transition and economic performance

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Executive Summary

This study investigates the relationship between energy production and economic performance, measured by gross domestic product (GDP), across a panel data set of 52 countries from 1990 to 2021. The research employs a fixed effects model and Granger-causality testing. The central hypothesis is that low-carbon energy sources, including renewables, will demonstrate a stronger and more significant positive correlation with GDP compared to combustible fuels. The findings confirm this hypothesis, revealing a statistically significant negative correlation between combustible fuels and GDP across the entire sample and within both higher and lower-income country subgroups. Conversely, renewable sources such as hydroelectric, pumped hydroelectric, wind, and solar power exhibit a statistically significant positive effect on GDP. Nuclear power also shows a particularly strong positive correlation with GDP, demonstrating the economic benefits of low-emission energy sources beyond renewables alone. Granger-causality testing revealed that certain low-carbon energy production methods had a causal effect on GDP beyond mere correlation. These results suggest that countries can confidently pursue policies to increase investment in domestic, low-carbon energy production while reducing reliance on fossil fuels. Such a strategy serves a dual purpose: it not only aids in meeting climate goals but also acts as a robust stimulus for economic performance. This research provides a basis for pro-growth macroeconomic strategies that are compatible with carbon reduction, positing that the energy transition is not a compromise on economic performance but a driver of it.

AI Statement

I acknowledge the use of generative AI in the literature search and code development in this paper. However, the work reported remains my own.

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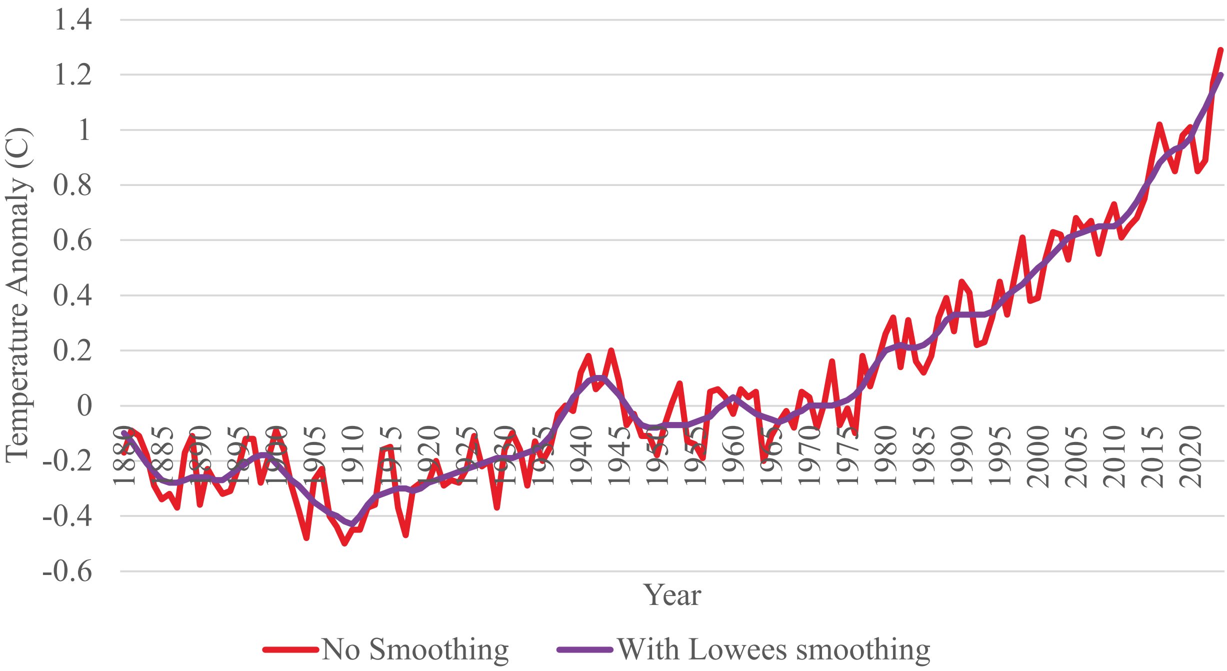
1. Introduction

The effects of global warming have long been established by researchers. Rising global temperatures, caused by greenhouse gas (GHG) emissions, are threatening human life by causing the sea level to rise, increased droughts and wildfires, more destructive hurricanes and a plethora of other negative impacts (Gibbens, 2025). 2024 was the warmest year on record since record keeping began in 1880, approximately 1.47ºC warmer than the pre-industrial period in the late 19th century (NASA/GISS, 2024). Governments understand that to mitigate the effects of global warming, we will need to undertake a global energy transition.

Figure 1 - GLOBAL LAND-OCEAN TEMPERATURE INDEX



Data source: NASA's Goddard Institute for Space Studies (GISS). Credit: NASA/GISS

The energy transition refers to the pathway via which countries will aim to achieve the targets of the Paris Agreement and mitigate the environmental and health impacts of global warming (IRENA, 2021). The Paris Agreement is a legally binding treaty created by the United Nations Framework Convention on Climate Change (UNFCCC) which aims to keep global warming to below 2ºC compared to pre-industrial levels (UNFCCC, 2015). This process will involve reducing reliance on fossil fuels and replacing them with low or no carbon energy sources to reduce GHG emissions. Countries are signalling the importance of this topic by developing their own strategies for meeting these emission goals such as the UK government's Net Zero Strategy. This involves reducing the UK's emissions to as close to zero as possible (DENZ and DBEIS, 2021).

The UN’s Sustainable Development Goals (UNSDG) underscore the enduring significance of the global energy transition for all nations. The goals “Affordable and Clean Energy for All”, “Responsible Consumption and Production” and “Climate Action” are particularly connected to the energy transition (UNDESA, 2023). The UNSDGs highlight the key hypothesis of this study, that energy and growth are inherently linked. Every industry in an economy relies on energy, and alterations to energy production can significantly impact economic performance and growth. This is important to understand as countries plan to decarbonise their own energy production capabilities in a manner that will encourage confidence and support strong economic performance (IEA, 2021).

This research aims to understand the relationship between energy production and GDP, focusing on 7 forms of energy production. It aims to establish which forms of energy production have the most statistically significant positive effect on GDP over a 31-year period from 1990 to 2021. This study aims to inform future policy shaping investment into energy production and forming an optimal energy mix which both reduces GHG emissions and supports GDP.

Previous studies empirically proved that energy production and GDP are strongly related, indicating it to be a significant driver of growth, beyond just a consequence of a growing economy. However, the majority of research surrounding this topic focuses on energy demand and uses small sample sizes and countries with similar attributes. This study aims to fill the gap in the research by focusing on the effects of energy production using a large panel data set of 52 countries at various levels of income. It performs detailed analysis across different types of energy production to analyse the effects of energy composition and examines the differing effects on two groups of countries at different levels of income.

2. Literature Review

This literature review aims to understand and communicate the theoretical foundations of energy economics, the impact and limitations of traditional economic models, empirical evidence on the relationship between energy and economic performance, as well as the causal and directional relationship between the two.

2.1 Theoretical foundations of energy economics

Some of the earliest research establishing a relationship between energy production and GDP was done by Yoichi Kaya (1997), who developed the Kaya Identity framework. This outlines how the amount of carbon dioxide emissions produced in a country are a product of four human factors, population, GDP per capita, energy intensity per unit of GDP (the amount of CO_2 emissions produced per unit of GDP), and carbon intensity of energy (emissions per unit of energy consumed). This framework, while focused on emissions, highlights the intrinsic relationship between GDP per capita, carbon intensity of GDP, and energy emission intensity. To reduce greenhouse gas emissions, which is the goal of the energy transition, one or more of these four human factors will have to decrease. Populations are forecast to continue growing across the world, particularly in developing nations, and governments want to keep raising their GDP per capita to raise living standards. Therefore, according to the Kaya Identity Framework, the energy intensity of GDP or the emission intensity of energy will have to decrease. The energy transition to decarbonised fuels and renewable energy technology aims to do exactly this. In previous decades, the energy intensity of GDP has decreased globally. However, the extent of this varies between developed and developing nations. The reduced energy intensity observed in developed economies is attributable to technological advancements in energy efficiency, robust policy frameworks, and a transition towards industries with lower energy demands (Hajiyev et al., 2023). Conversely, developing economies exhibit comparatively high energy intensity, primarily attributable to their industrial composition and dependence on energy-intensive industries. (Deichmann et al., 2019) As GDP per capita across the world begins to converge (Kerr et al., 1996/1960) their energy intensity of GDP is likely to do the same, bringing developing nations to a comparable level to their developed counterparts. Ultimately, the Kaya Identity framework identifies the intrinsic relationships that energy intensity of GDP, GHG emissions and the carbon intensity of energy production have on GDP per capita and the differing effect it has on nations at various levels of development.

2.2 Energy's role in GDP and limitations of traditional models for GDP

Kümmel (2010 and 2015) has argued that traditional economic models understate energy production's importance in economic output. He uses the Linear Exponential (LinEx) production function to integrate energy explicitly into the factors of production. In mainstream economic thought, models such as the Cobb-Douglas (1928) production function and neoclassical growth models establish a direct correlation between the output elasticities of production factors (capital, labour, and energy) and their corresponding cost shares, the proportion of total cost attributed to each of these specific inputs. Kümmel argues that, due to the difficulty of substituting energy for capital and labour, its output elasticity significantly outweighs its cost share. Kümmel's approach supports a methodology for integrating energy into a study of economic performance due to the limitations of traditional economic models and provides a theoretical basis for doing so.

2.3 Empirical evidence of the relationship of energy and GDP

While, Kümmel has provided a theoretical basis to the analysis of energy's impact on economic performance, Işık and Shahbaz produced empirical evidence to support this theory. Although their work focuses on energy consumption, their lessons learned are still valuable to a study focused on energy production. Shahbaz et al (2016) analysed a panel data set of 19 African countries from 1980 to 2009, implementing a fixed effects regression method within a simultaneous-equation framework. He determined that a significant positive influence exists between energy consumption and GDP, showing increased energy usage demonstrably contributes to GDP. A negative relationship between CO_2 emissions and GDP is also observed, suggesting that increased carbon emissions may be detrimental to sustainable economic development. Shahbaz suggests this data fits his Environmental Kuznets Curve hypothesis; in more developed economies, the adoption of cleaner technologies and stricter environmental regulations creates a negative correlation between GDP and CO2 emissions. This suggests that there are benefits of investing in low-emission renewable energy sources to foster economic performance and achieve broader sustainability goals. Following this, Işık and Shahbaz (2015) produced a similar study on countries from the Organisation for Economic Cooperation and Development (OECD) over the same period as before. Once more, employing a fixed effects regression model to determine the correlation between energy consumption while accounting for unobserved differences among countries and across time. This research employed panel causality tests, such as the Granger causality test (Granger, 1969), to ascertain the causal relationship between energy consumption and GDP. As before, this study revealed a statistically strong relationship between energy consumption and GDP. The panel causality tests identified a unidirectional relationship between energy consumption and GDP, supporting the idea that energy is an enabler of economic performance.

Işık & Shahbaz's work empirically linked energy and GDP. More recently, Nuiriyev and Demiroz (2024) proved that renewable energy, specifically, is directly linked to economic performance in both the long and short term. Identifying two groups, they discovered that 59% of nations showed a positive, significant elasticity and the other 41% showed a smaller but positive and significant elasticity. The first group showed a 1% increase in renewable energy consumption increases GDP by approximately 0.072%. The second showed 1% increase in renewable energy use would increase GDP by approximately 0.048%. The reliability of Nuiriyev and Demiroz's results was enhanced through the inclusion of additional explanatory variables—real GDP, capital stock, the Human Capital Index, and renewable energy consumption—and further tests for homogeneity, heteroskedasticity, and autocorrelation. This study's methodology provides valuable insights into handling country specific heterogeneity and other unobservable characteristics. Highlighting that countries respond differently to renewable energy investments, suggesting that economic and energy policies require customisation. The findings provide strong empirical evidence that renewable energy sources positively impact GDP growth internationally, and governments ought to facilitate the expansion of renewable energy sources to overcome financial hurdles and achieve maximum economic benefits.

Other studies using similar panel data, including that of Aliev et al. (2023), have shown a positive and significant relationship between renewable energy consumption and GDP. Oil consumption and prices were also positively correlated with GDP, underscoring their sustained significance. Alternatively, GDP exhibited an inverse relationship with coal consumption, reflecting the observed trend of diminished reliance on coal due to environmental and regulatory restrictions. Aliev tested several regression models, including Ordinary Least Squares (OLS), Fixed Effects (FE), and Random Effects (RE) methodologies, on a panel data set of 10 EU countries from 2000 to 2020. They found the FE model most reliable because it controls for unobservable differences between the countries in the panel. These findings were supported by robust testing, such as the Fisher test for model significance, Hausman test for selection between RE and FE models, Durbin-Watson test for autocorrelation and Breusch-Pagan test for heteroskedasticity. Supporting the idea that FE models are most suitable for analysis of panel data pertaining to GDP and energy variables across various countries.

2.4 Causality and directionality in the energy-economic performance nexus

Much of the existing literature focuses on the impacts of energy consumption on GDP. Energy consumption and production are closely linked, and the conclusions of this research can reliably be used interchangeably due to the symbiotic relationship between energy demand and production (Garrett, 2020). However, in their research, Ozkan et al. (2012) examined whether energy production specifically has a direct and significant effect on economic performance, rather than economic performance primarily driving demand for energy production. He used cointegration analysis and error correction models to assess relationships, short-run dynamics and adjustments to long-term equilibrium states. Ozkan et al. used a Granger causality test (Granger, 1969) to test the relationship between energy production and GDP in Turkey over this period. The study finds strong evidence of a positive and unidirectional causal relationship running from energy production to GDP in both the short and long terms. It is argued that increased energy production capacity is a primary driver of GDP, rather than growth increasing demand for energy production. This research draws out three key implications. Firstly, that economies must expand their energy production capabilities if they wish to continue to stimulate economic performance. Secondly, government policy should target improving domestic energy production over importing energy to support GDP. Finally, Ozkan et al. warn that countries' economic performance may be constrained by inadequate investment in domestic energy supply.

Further research into the directional nature of the relationship between energy production and GDP was done by Tran et al. (2022). Tran employed a threshold regression analysis to detect a GDP per capita threshold of $48,170, that significantly influenced the relationship between energy consumption and GDP. Using a panel of 26 OECD countries over a 43-year period, they proved the existence of a unidirectional causality relationship running from energy consumption to GDP growth under the threshold. For nations over the threshold, there was no causal relationship in the short term and a unidirectional relationship running the other way from GDP growth to energy consumption in the long term. This shows a significant difference between developing countries, where energy consumption is a driver of growth, and developed countries, where energy demand is a consequence of growth. This demonstrates that policymakers should target their energy policies and investment differently depending on their development stage.

2.5 Summary of the literature

In summary, from the evidence outlined in this literature review, there is an inherent link between energy and economic performance. Whilst the relationship between energy and GDP runs both ways, it is apparent from the evidence outlined that energy production is a driver of GDP worldwide.

The literature in this study demonstrates the clear relationship between both energy production and consumption on economic performance. Whether it is measured as GDP, GDP per capita or other economic elasticities. The Kaya framework (Kaya, 1997) lays the foundations for this theory, which is then taken by Kümmel (2010) and others into new economic models such as the LinEx Function that improve on traditional economic models for growth by incorporating energy. It has then been the focus of many researchers over the last decade to establish an empirical link between both energy and renewables with growth across differing contexts. Through Granger-Causality testing, the literature has also been able to show that energy is a significant driver of economic performance and not just a consequence of demand from a growing economy.

This is still a relatively new focus within the field of economics and, at this stage, much of the academic literature focuses on energy consumption as a driver of GDP. The current study intends to fill this gap in the literature by examining the relationship between the composition of energy production and GDP in a 52-country panel. Moreover, most studies analyse a small number of similar countries (like OECD, EU, or African nations) over short periods. This research study aims to fill the gap in the research by taking a large panel data set covering 52 countries from across the globe at differing levels of development to identify the differing relationships between countries at various levels of economic prosperity. Additionally, existing literature has often used a single metric for energy consumption. This study will incorporate variables for 7 different forms of energy production, allowing the examination of the nuances between different energy sources and GDP. This study aims to bolster the research that has already taken place to establish a directional and causal relationship between domestic energy production and GDP whilst contributing to the field of energy economics by focusing on energy production from multiple sources and a large panel of countries at varying levels of development.

3. Data

3.1 Panel data collection

The energy production data is from the United Nations (UN) Energy Statistics Database published by the UN Statistics Division (UNSD, n.d). This study uses the Total Electricity data set to provide its independent variables, electricity in Kilowatt-hours (kWh) produced by 7 different forms of production; Combustibles, Hydroelectric, Nuclear, Pumped Hydroelectric, Solar, Wind, and Tide, Wave and Marine (TWM). Additionally, this study sources its dependent variable, GDP, in current US Dollar value, and population statistics from the World Bank (World Bank, n.d). For this study, these three data sets were combined to produce a comprehensive panel data set to capture the relationship between GDP and energy production over a 31-year period from 1990 to 2021, for 62 countries, totalling 1984 observations. The study period was determined by the years for which complete UNSD data were available.

Table 1 –Model Variables

Variable	Unit	Model role	Source
GDP	USD (current value)	Dependent	World Bank World Bank national accounts data
Population	People	Not directly in model	World Bank various sources
Combustibles	KwH	Independent	UN Energy Statistics Database
Hydroelectric	KwH	Independent	UN Energy Statistics Database
Nuclear	KwH	Independent	UN Energy Statistics Database
Pumped Hydroelectric	KwH	Independent	UN Energy Statistics Database
Solar	KwH	Independent	UN Energy Statistics Database
Wind	KwH	Independent	UN Energy Statistics Database
TWM	KwH	Independent	UN Energy Statistics Database

3.2 Selection of countries and grouping

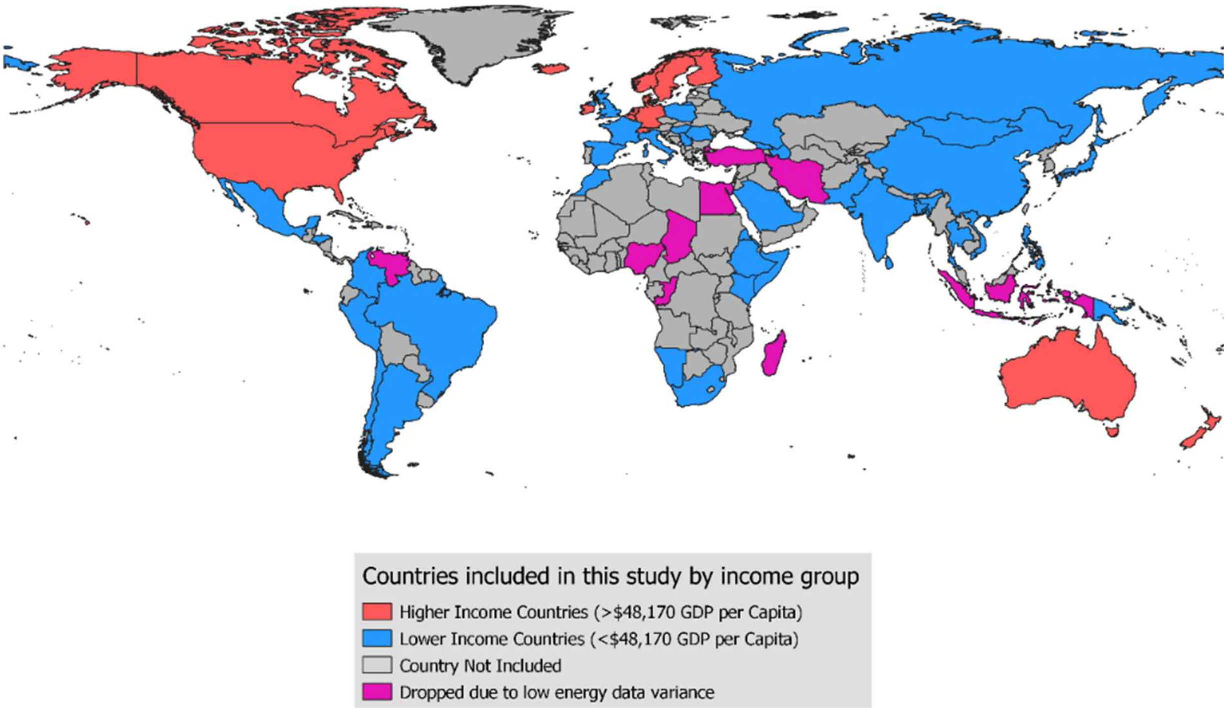
UNSD provides Total Electricity data for 244 different areas, countries, dependencies and self-governing zones. This study initially chose a sample of 62 countries as a representative sample of global data by including 20%-50% of the countries on a continent. Sensitivity testing reduced the final number of countries to 52 and 1664 observations to remove countries with low variation in their energy production variables. At least 4 variables had to have variation >0.01. This led to a possible underrepresentation of African countries in the data.

Table 2 - Selected countries

Continent	Countries in initial sample	Proportion of Continent (%)	Countries in refined sample	Proportion of Continent (%)
Africa	13	24.1%	7	13.1%
Asia	16	33.3%	13	27.1%
Europe	19	43.2%	19	43.2%
North America	5	21.7%	5	21.7%
South America	6	50.0%	5	41.7%
Oceania	3	21.4%	3	21.4%
Total	**62**	**31.8%**	**52**	**26.7%**

One objective of this study is to understand how energy's relationship with GDP changes with a country's level of income. The refined 52 country sample was then split into a 'higher-income' group of 14 countries and a 'lower-income' group of 38 countries. The countries were categorised based on a $48,170 GDP per capita threshold, a level Tran et al. (2022) suggest signals a change in the correlation between energy consumption and GDP. 2021 was the year it was decided which side of the threshold these countries were on to align with Tran's research. Therefore, the threshold does not need to be adjusted for inflation.

Figure 2 – Map of study area countries



3.3 Summary statistics

Table 3 shows the variable summary statistics. Combustibles clearly dominate the energy mix in this data, having a considerably higher mean than the other energy variables with hydroelectric and nuclear also high. The 25th percentile and median (50%) are zero for Nuclear, Pumped Hydro, Solar, Wind, and TWM. This implies at least 50% of countries produce no energy from these sources. This amplifies the high skewness of the energy variables that are highly skewed to the right, demonstrating a few countries produce large amounts from particular sources, while most produce little to none. The large standard deviations for population and GDP indicate the wide disparities in economy size and population across countries.

Table 3 - Summary statistics

Variable	GDP	Population	Combustibles (kWh)	Hydroelectric (kWh)	Nuclear (kWh)	Pumped hydroelectric (kWh)	Solar (kWh)	Wind (kWh)	TWM (kWh)
Count	1,664	1,664	1,664	1,664	1,664	1,664	1,664	1,664	1,664
Mean	881,516,525,763	92,038,246	179,528	49,882	42,712	1,329	1,919	7,098	10
Standard Dev	2,312,391,276,504	235,919,662	535,701	122,181	125,983	4,079	14,313	35,003	67
25%	35,447,436,934	7,281,390	3,934	1,292	0.0	0	0	0	0
50%	188,265,277,804	25,746,095	24,390	9,685	0.0	0	0	9	0
75%	589,104,165,500	67,343,180	126,651	35,157	17,117	480	7	1,035	0
Min	0	254,826	0	0	0	0	0	0	0
Max	23,594,031,000,000	1,412,360,000	5,335,013	1,355,210	843,330	32,900	325,760	656,100	522
Skewness	6	4	5	5	4	5	15	10	7
Kurtosis	36	20	33	46	22	26	275	130	47

3.4 Data limitations

There are several limitations associated with this data. The selection of countries in the UNSD Energy Data may introduce bias due to the omission of certain countries. Of the 244 options, many were not independent, UN-recognised, countries but territories or islands belonging to other nations. UN recognised nations were selected for this study rather than using the whole available dataset, leading to potential bias. Additionally, some countries lacked sufficient energy data. Although countries with available data were prioritised, many records began after 1990 or lacked complete energy information, e.g. landlocked countries naturally lacked tidal power data, and many nations do not use nuclear power. Therefore, data availability varied widely by country and energy type.

The UNSD collects energy data through the UNSD ‘Annual Questionnaire on Energy Statistics’. This questionnaire is used to collect primary energy data on the production, transformation and use of energy products in physical and energy units (UNSD, 2022). This questionnaire relies on several assumptions including, data is reported in calendar year not financial year; data is recorded in the correct specified units; and the data is collected for the correct geographic coverage. The accuracy and honesty of the questionnaire data is also crucial. This assumption might be invalid for nations with poor data collection systems or those politically motivated to falsify their UN reports.

World Bank stipulates that GDP is not always the best indicator of economic performance, however, it is widely tracked and available. GDP calculation methods vary across countries, with differing approaches used based on production, income, or expenditure definitions. Many national statistical offices, particularly in developing countries, are under-resourced to compile reliable national accounts. A major hurdle to compiling national accounts is the substantial unrecorded economic activity within the informal sector. According to the World Bank (n.d), developing countries consume domestically or trade non-monetarily a considerable amount of agricultural production. The World Bank, however, reviews all data to ensure quality and consistency.

4. Methodology

4.1 Theoretical Framework

To establish the effect different forms of energy production have on GDP, this study utilises a panel fixed effects (FE) model. As per the recommendations in the research of Aliev et al. (2023) the FE model was selected for this research because of its ability to control for unobservable differences between countries and across time. FE controls for time-invariant effects affecting GDP and energy production as well as potential heterogeneity between countries, which will all have different economic systems. This avoids bias from OLS models, where correlated independent variables and errors violate Gauss-Markov assumptions (Gujarati & Porter, 2009). The Hausman test on the preferred FE specification failed to reject the null hypothesis and suggested RE may be suitable. This study continues to use the FE model as preferred because of its similarity of results to those of the RE model and its capacity to account for unobserved country-specific and time-varying effects; further supported by Aliev et al. (2023), who demonstrate FE's superior performance. The FE model's inclusion of the idiosyncratic term gives each country its own intercept, which accounts for cross-country differences and potential omitted variables. This improves the precision of the model's coefficients, better reflecting their impact on the dependent variable.

4.2 Preferred Model Specification

Below is the preferred FE model specification used in this study.

$$\mathrm{GDP}_{it} = \alpha_{\mathrm{i}} + \beta 1\ln(\mathit{Combustibles}_{it}) + \beta 2\ln(\mathit{Hydro}_{it}) + \beta 3\ln(\mathit{Pumped\ Hydro}_{it}) + \beta 4\ln(\mathit{Nuclear}_{it}) + \beta 5\ln(\mathit{TideWaveMarine}_{it}) + \beta 6\ln(\mathit{Wind}_{it}) + \beta 7\ln(\mathit{Solar}_{it}) + \varepsilon_{it}$$

In this instance:

- GDP_{it} is the gross domestic product of country *i* at time *t*.
- $\ln(\mathit{EnergyType}_{it})$ represents the natural log of energy production per million people in kWh for each energy source in country *i* at time *t*.
- β1 to β7 are the coefficients of interest, capturing the change in GDP (in USD) associated with a 1% change in each respective energy variable.
- α_i captures unobserved time-invariant country fixed effects (e.g., geography, institutional quality, etc.)

- ε_{it} is the error term.

This model uses a linear-log functional form. It was revealed through repeated testing that this specification provided the strongest model with the most explanatory power. This aligns with Kümmel's (2010) LinEx function that also utilised a linear-transformed model specification. The energy variables in this research represent kWh of energy produced per million residents and are used as the independent variables. Per million was used because per capita variables are frequently used to reduce variance and improve result reliability. However, log-transforming the per capita variables, however, resulted in errors and negative values. Dividing the energy variables by population often leads to values between 0 and 1, which produce negative values when transformed to natural logs. With per-million variables, the large variance in energy data between countries was reduced without introducing errors.

4.3 Robustness tests / assumptions and limitations

Stationarity tests

Meaningful fixed effects regression results require stationary data to avoid spurious correlations caused by non-stationary trends. Ignoring non-stationarity leads to biased and inconsistent estimates, breaking key FE model assumptions (homoskedasticity, no autocorrelation, uncorrelated zero-mean residuals), rendering the econometric results invalid. This research used the Augmented Dickey-Fuller (ADF) test to check for stationarity. Incorporating temporal and cross-sectional variation in a panel enhances the test's power to detect stationarity. Transforming variables into logs and per-million stabilised the variance, improving stationarity. The test for the preferred specification revealed a P value of 0.000, rejecting the null hypothesis, demonstrating that the data is stationary and confirming there is no unit root.

Autocorrelation and Heteroskedasticity

Autocorrelation is when the residuals in a regression are correlated with one another across time. If the errors aren't independent, it violates an OLS assumption and the model's significance is misinterpreted, with inflated t-values and underestimated standard errors. This study uses the Durbin-Watson (DW) test for first-order autocorrelation in the residuals. The preferred model had a DW value of 0.2477, which indicates severe problematic positive autocorrelation, which is common in panel data.

Another classical OLS assumption is homoskedasticity, where the error variance is constant across all observations. Heteroskedasticity suggests a non-constant error variance, leading to biased standard errors. This research employed the White's and Breusch-Pagan Tests for heteroskedasticity. Despite using log-transformed values, in this instance, the preferred model failed both tests. Heteroskedasticity is likely present, impacting the validity of the model's statistical indicators, including p-values and confidence intervals.

To address both issues, the model was run with robust standard errors. Robust standard errors adjust for heteroskedasticity by giving reliable standard errors, even when the error variance changes across observations. While coefficient estimates remain unchanged, robust standard errors ensure reliable hypothesis tests and confidence intervals, upholding the validity of econometric conclusions.

Multicollinearity

Multicollinearity occurs when independent variables are highly correlated, making it difficult to isolate the individual effect of each predictor. This leads to inflated standard errors, unstable coefficient estimates, and unreliable inference. To address this issue, the study examined the Variance Inflation Factors (VIFs) of the independent variables to identify those with the highest autocorrelation. VIF results <5 indicate a low correlation with others, 5-10 indicate a moderate correlation and VIFs higher than 10 have a high correlation and should not be used (James et al., 2021). Removing variables with high variance inflation factors (VIFs) leaves seven independent variables with acceptable VIFs for the final model. As VIFs for all variables in the regression were <5, there is no indication of multicollinearity amongst the independent variables.

Table 4 – VIF results

Variable	VIF
ln_combustibles_pm	4.98
ln_hydro_pm	4.50
ln_Pumped_Hydro_pm	2.22
ln_nuclear_pm	2.40
ln_Tide_wave_marine_pm	1.16
ln_Wind_pm	2.72
ln_Solar_pm	1.73

Hausman Test

The Hausman test is used to decide whether FE or RE models are more appropriate for panel data. If the unique characteristics of each country/entity affect the model's regressors, use fixed effects. If not, RE could be more efficient (Hausman, 1978). In this test, the preferred specification fails to reject the null hypothesis of the Hausman test, suggesting that RE may be suitable. However, this study chooses to use the FE model as its preferred specification. This decision is supported by Aliev et al. (2023), who demonstrates FE's superior performance compared to RE and OLS models when modelling panel data of energy variables and GDP. FE model's inclusion of the idiosyncratic term gives each country its own intercept, which accounts for cross-country differences and potential omitted variables. This improves the precision of the model's coefficients, better reflecting their impact on the dependent variable. Nevertheless, the RE models were run, and their results demonstrated a strong degree of similarity, reinforcing the decision to proceed with the FE model.

Granger Causality Test

As the research of Işık and Shahbaz (2015) and Ozkan et al. (2012) did, this study uses the Granger Causality Test to test for the directional relationship between energy production and GDP. The Granger causality test checks whether past values of one variable can help predict the current value of another variable better than the information contained in past values of Y itself (Granger, 1969). Granger's approach begins with a regression of the dependent variable on its own past values, followed by the inclusion of lagged independent variables. If the variables lags are statistically significant, it demonstrates that X Granger-causes Y. This was done in both directions to see if energy Granger-causes GDP, or if GDP Granger-causes energy. Table 5 and 6 shows that hydroelectric, pumped hydroelectric and nuclear are significant to the 10% level on the 1-year lag. Demonstrating that these three energy types have a weak but demonstratable unidirectional impact directly on GDP. Whereas GDP only seems to have a Granger-causal effect on combustibles also to the 10% level for the 1-year lag. Longer lags were tested but did not yield any significant results.

Table 5– Energy production Granger-cause GDP

Variable	P-Value
ln_combustibles_pm	0.8944
ln_hydro_pm	0.0937
ln_Pumped_Hydro_pm	0.0530
ln_nuclear_pm	0.0910
ln_Tide_wave_marine_pm	0.4355
ln_Wind_pm	0.5152
ln_Solar_pm	0.9095

Table 6 – GDP Granger-cause Energy production

Variable	P-Value
ln_combustibles_pm	0.0979
ln_hydro_pm	0.4404
ln_Pumped_Hydro_pm	0.3491
ln_nuclear_pm	0.2218
ln_Tide_wave_marine_pm	0.6795
ln_Wind_pm	0.8053
ln_Solar_pm	0.6969

5. Results

Table 7 – Panel Fixed Effects Model Outputs

Significance codes: '*' =0.01, '**'=0.05, '*' 0.1**	**Measure**	**Panel Fixed Effects (FE) ($ billions)**	**FE Higher-Income ($ billions)**	**FE Lower-Income ($ billions)**
ln_combustibles_pm	Coefficient (P-Value)	-81.69*** (0.0030)	-427.8*** (0.0023)	-47.24** (0.0432)
ln_hyro_pm	Coefficient (P-Value)	48.76** (0.0377)	-871.1*** (0.0092)	22.24 (0.2897)
ln_pumped_hydro_pm	Coefficient (P-Value)	150** (0.0108)	1.744 (0.9896)	218.9*** (0.0010)
ln_nuclear_pm	Coefficient (P-Value)	308*** (0.0022)	1032*** (0.0006)	361.8*** (0.0013)
ln_tide_wave_marine_pm	Coefficient (P-Value)	418.8 (0.1507)	3124*** (0.0006)	-485.3 (0.1109)
ln_wind_pm	Coefficient (P-Value)	174.8*** (0.0018)	239.4*** (0.0000)	147.8*** (0.0000)
ln_solar_pm	Coefficient (P-Value)	244.9*** (0.0000)	611.9*** (0.0000)	136.4*** (0.0006)
Observations	Number	1664	448	1216
R-Squared	Number	0.1614	0.2541	0.1966
F-Statistic	Number	43.274	19.269	39.858
Durbin-Watson Test for Autocorrelation	Number	0.2463	0.1799	0.2714
Breusch-Pagan Test for heteroskedasticity	P-Value	<0.0000	0.0003	<0.0000
Augmented Dicky Fuller Test for Stationarity	P-Value	<0.0000	<0.0000	<0.0000
Hausman Test for Random Effects	P-Value	0.2461	0.9316	1.0000

6. Discussion

6.1 FE vs RE Model Interpretation

Table 7 displays the results from the preferred model specification. The FE model shows reasonable explanatory power. An R^2 Value of 0.1614 meaning that 16.14% of the variation in the data can be explained by this model. The coefficients demonstrate a negative relationship between GDP and combustibles and a positive relationship with all other forms of energy production. This model demonstrates stationarity of the data through passing the ADF test and the usage of robust standard errors addresses issues of heteroskedasticity and autocorrelation.

The RE model demonstrates a slightly stronger R^2 value of 0.2454 and a more significant F-statistic (76.917). RE passes and fails the same statistical tests as the FE model. The interpretation of the model's coefficients is also the same across both, demonstrating a negative impact from combustibles on growth and a positive impact from all other energy sources. The only difference being RE's coefficients are of a slightly smaller magnitude and show a negative effect from TWM; however, this variable is insignificant. Overall, the results from both models are very similar, meaning that the results from the FE model are robust even if the Hausman test suggests RE is an option.

6.2 Combustibles

Across all models, combustibles have a negative relationship with GDP. The results show a $816.9 million decrease in GDP for every 1% increase in combustible fuel production in the preferred FE model across all countries. Representing 0.092% of the mean GDP in this dataset. This result is significant at the 1% level, meaning this is highly statistically significant. Additionally, the results suggest that combustibles have a negative impact on GDP in both the higher and lower-income groups, where both are statistically significant to at least the 5% level. The results suggest a $4.278 billion decrease in GDP from a 1% increase in combustibles for higher-income groups. A 1% increase in combustibles in the lower-income group represents a $472.4 million decrease in GDP. This demonstrates that combustibles have a more significant negative effect on GDP in higher-income nations. These findings reinforce the literature suggesting higher-income countries are moving away from non-renewable sources; combustible fuels like coal are negatively correlated with GDP; and renewables play a larger role in developed economies' energy mixes. It also somewhat aligns with Tran et al. (2022) hypothesis that the relationship between GDP and energy differs on either side of the income threshold of $48,170 per capita. The Granger causality test yielded evidence of a causal link running from GDP to combustible power (10% significance), but not in the other direction. Suggesting GDP stimulates demand for combustible energy but may not act as a driver for GDP.

6.3 Hydroelectric

Hydroelectric power is shown to have a positive impact on GDP in the main FE model. In this model, a 1% increase in hydroelectric power supply reportedly represents a $479.6 million increase in GDP, significant to the 5% level. Approximately 0.054% of the dataset's mean GDP. Conversely, the model for the higher-income group suggests a negative relationship between GDP and hydroelectric power. It suggests an £8.7 billion decrease in GDP from a 1% increase in hydroelectric power. This result is significant at the 1% level. The model for lower-income groups shows positive impacts on GDP from hydroelectric power, ranging from $222 to $251 million. However, this result is statistically insignificant and cannot be interpreted reliably. The results of the preferred specification support the hypothesis that renewable power like hydroelectric has positive effects on GDP (Aliev et al., 2023). However, the negative results for the higher-income groups does cast some doubt on this conclusion. The Granger causality test results show a unidirectional relationship, with hydroelectric power exhibiting a weak but statistically significant positive impact (at the 10% level) on GDP.

6.4 Pumped hydroelectric

The preferred FE model suggests a significant positive impact on GDP from pumped hydroelectric power. A 1% increase in hydroelectric power supply creates a £1.5 billion contribution to GDP, significant at the 5% level. Representative of 0.17% of the dataset's mean GDP. Within the higher-income group, the results suggest a very marginal positive impact of $17.4 million in GDP for each 1% increase in pumped hydroelectric. However, this result is not statistically significant. The results for the lower-income group demonstrate a significant positive impact on GDP at the 1% significance level, resulting in an increase of $218.9 billion in GDP. Amongst the significant variables there is clear evidence of a positive impact on GDP from pumped hydroelectric. This supports the hypothesis that renewables will have a more significant effect on GDP than combustibles. Granger causality testing reveals a unidirectional relationship wherein pumped hydroelectric power exerts a statistically significant ($p<0.10$), positive influence on GDP.

6.5 Nuclear

The model shows nuclear energy as having the largest effect on GDP of any energy source. A $3.08 billion positive effect is anticipated from a 1% increase in nuclear power, significant to the 1% level. The higher income model suggests a $10.32 billion positive impact from a 1% increase in nuclear power, significant to the 1% level. Approximately 1.17% of the mean GDP in the dataset. The lower-income group shows similar results with a positive GDP impact of $3.62 billion. These results show a large, significant and positive impact that nuclear power seems to have on GDP that is extremely reliable. Greater than any other energy type seen in this study. Coefficients suggest that there is a slightly larger effect in higher-income nations. Although nuclear energy is not classified as renewable due to its reliance on finite fuel sources like uranium, it is widely regarded as a low-carbon energy technology. As such, it plays a significant role in clean energy policy despite not meeting the criteria to be renewable (International Energy Agency, 2022). Therefore, this result aligns with the hypothesis that low-carbon fuels contribute greatly to GDP. This seems to be the case regardless of renewable status. Nuclear power is also shown to have a Granger-causal effect on GDP, with 10% significance. Further indicating that this strong relationship is not only positively correlated but causal in nature.

6.6 Tide, Wave and Marine (TWM)

TWM is seemingly the least reliable energy source in this model due to the low significance of coefficients in the main model. The overall model suggests a $4.19 billion increase in GDP from a 1% increase in TWM. However, this result is not statistically significant therefore, these values are not important to this model's interpretation. The result for the higher-income group is statistically significant and suggests a positive impact on GDP of $31.24 billion, significant at the 1% level. Approximately 3.53% of the dataset's mean GDP. Conversely, the low-income model reveals a non-significant negative effect of TWM on GDP. This finding doesn't invalidate the positive impact observed in high-income countries, but the model is insufficient to explain the impact on low-income nations. This is possibly because of the relatively high expense associated with TWM, which is a developing technology less efficient than other means of energy generation (Chowdhury et al., 2021). Making TWM less cost effective than other methods, providing bad value for money to lower-income nations. Granger causality testing revealed no evidence of a causal relationship between TWM and GDP. A correlation is posited, but causality is not proven in this study.

6.7 Wind Power

Wind power also demonstrates significant positive influence on GDP in the preferred model. A 1% increase in wind power provision is positively correlated with a $1.75 billion increase in GDP, to the 1% significance level. 0.20% of the dataset's mean GDP. Similar correlations can be seen in the higher-income group, where the results indicate a $2.4 billion increase in GDP for every 1% increase in wind power, significant to the 1% level. The results demonstrate a $1.48 billion increase in GDP for each 1% increase in wind power for the lower-income group, which is also significant to the 1% significance level. These results all support the hypothesis that renewable energies, such as wind power, are positively correlated with GDP. We can see this is especially true in higher-income countries, where wind power seems to have a larger impact on GDP compared to lower-income nations. The extremely significant coefficients confirm that this hypothesis can be interpreted confidently. However, the Granger causality test did not reveal a direct causal relationship running in either direction.

6.8 Solar power

Solar power production also demonstrates significant positive impact on GDP. The results showed a $2.45 billion increase in GDP associated with a 1% increase in solar power, significant to the 1% level. Approximately 0.28% of the dataset's mean GDP. The results suggest that the higher-income countries experienced a greater impact on GDP with a 1% increase in wind power. Higher-income nations had a positive impact of $6.1 billion and lower-income nations had $1.36 billion, both to 1% significance. The results exhibited a significant positive impact of wind power on GDP, with higher-income nations experiencing greater impact from wind power. However, the Granger causality test did not reveal a causal relationship in either direction between solar power and GDP.

6.9 Robustness

The results of the preferred model should be interpreted with caution. Although the R^2 and f-stats are reasonable and the data passes the ADF test demonstrating stationarity, it fails the Durbin-Watson Test for autocorrelation and the Breusch-Pagan Test for heteroskedasticity. Autocorrelation can lead to potentially inflated t-values and significance levels. Heteroskedasticity biases standard errors, making coefficient significance unreliable. However, using robust standard errors mitigated this issue, allowing interpretation of significance levels, but with caution. This isn’t a major concern given the highly significant results. Considering this, the results of this model should be interpreted with some caution. While it can be used as an indication in policy decisions around energy mix and investment, it should not be used as the sole evidence.

7. Policy implications

This research is important for all countries committed to the energy transition. As nations move toward achieving collective climate goals — such as Net Zero (DENZ and DBEIS, 2021), the Paris Agreement (UNFCCC, 2015), and the UN Sustainable Development Goals (UNDESA, 2023) — macroeconomic policy will play a central role in shaping the future energy mix. The findings of this study provide strong evidence of a positive correlation between low-carbon energy sources, including renewables and nuclear power, and GDP from 1990 to 2021. This suggests that investment in domestic, low-carbon energy infrastructure not only serves climate objectives but also has an enhancing effect on national economies.

Notably, the findings highlight a strong correlation between nuclear energy and GDP, suggesting that strategic investment in nuclear power plants could foster long-term economic stability and energy security. Similarly, wind and solar power also demonstrated positive impacts, reinforcing the case for expanding capacity in these sectors. Governments could use macroeconomic policy tools, such as targeted subsidies, tax credits, and public-private partnerships, to encourage investment into these areas (OECD, 2023). By offering price protection against fluctuating wholesale energy prices to developers of renewable energy projects with high initial costs and long lifespans, the UK’s Contracts for Difference (CfD) scheme incentivises investment into renewables while safeguarding consumers from rising costs during periods of high electricity prices.

Conversely, the negative relationship between combustible fuels, like coal and oil, and GDP, suggests the need for policies that disincentivise fossil fuels. This could involve carbon pricing, ending fossil fuel subsidies, and investing in clean energy. Such policies have the potential to mitigate environmental externalities, enhance productivity, and bolster long-term fiscal sustainability. Policies such as these are already happening on a global scale. The EU's Carbon Border Adjustment Mechanism (CBAM) addresses carbon leakage, where EU companies relocate carbon-intensive production overseas to avoid stricter EU climate policies, or where EU goods are substituted with higher-carbon imports (European Commission, 2025).

Importantly, these trends hold for both higher and lower-income nations on either side of the $48,170 GDP per capita threshold, implying that the economic benefits of clean energy investment broadly apply. High-income countries see greater effects, possibly because of better infrastructure, more developed capital markets, and a greater ability to manage large-scale projects. This suggests that developed nations should prioritise clean energy deployment to support economic performance. Developing economies may also benefit from international financial support, technology transfer, and capacity-building initiatives to facilitate their own transitions (OECD, 2024).

8. Limitations and recommendations

Results from this research need to be interpreted with some caution, having failed the Durbin-Watson Test for autocorrelation, Breusch-Pagan Test for heteroskedasticity and Ramsey's RESET Test for misspecification. This is likely to lead to over-inflated significance values in the model, meaning interpretation of the coefficients should not be relied on for meaningful inference. As a result, it is suggested that additional research be conducted to replicate this study. Firstly, this could be achieved using the full dataset available via UNSD, with all 244 locations, to provide greater explanatory power as well as avoiding potential bias from this study's selection of countries. This may also solve omitted variable bias that could be related to this model's misspecification. Variables like capital stock and the Human Capital Index (Aliev, 2023) could improve the explanatory power of future models. Adding energy types, such as biomass, hydrogen, geothermal as well as splitting up the types of combustibles, e.g.

coal, oil, gas etc, should add greater explanatory power and nuance to the model's interpretation. Future researchers may want to consider using dynamic panel models such as the Arellano-Bond model (Arenello and Bond, 1991), trying additional specifications, or using Generalised Least Squares to improve the model's specification and address issues of heteroskedasticity and autocorrelation.

9. Conclusion

This research set out to discover whether energy production has been a genuine driver of GDP over the three decades from 1990 to 2021 and which forms of energy production were particularly correlated with GDP. It continues the research of Ozkan et al. (2012), Işık and Shahbaz (2015) and Nuiriyev and Demiroz (2024), who established an empirical link between energy and economic performance. This study used a larger data set from a spectrum of countries across the world as well as country groupings informed by the research of Tran et al. (2022). Their research established the income threshold where the relationship between energy and GDP changes, to establish if energy production specifically had a measurable impact on GDP at all levels of development.

The current research suggests clear empirical evidence of a link between energy production and GDP on a global scale. Analysis reveals substantial positive effects from low-carbon and renewable energy sources, including nuclear, wind, and solar power, with more modest, yet positive, effects observed for hydroelectric, pumped hydroelectric, and TWM energy. Prioritising investment in low-carbon energy generation serves a dual purpose: advancing environmental protection and sustainability goals while simultaneously stimulating economic performance at all income levels. Furthermore, it illustrates a demonstrably adverse effect stemming from combustible fuel provision. Fossil fuel reliance may be a constraint on economic performance in certain economies. Policymakers ought to implement policies that discourage the generation of energy from combustible fossil fuels if they wish to meet sustainability goals and unlock future economic potential.

Overall, this research provides a starting point for understanding the complex relationship between energy production and GDP. It provides important policy suggestions for global governments during the energy transition to low-carbon fuels. Renewable and low-carbon fuels could provide a route to a more sustainable future for the environment and unlock future economic potential. This research demonstrates the possibility of a pro-growth macroeconomic strategy compatible with carbon reduction, wherein energy transition policies are viewed as essential drivers of GDP. It may provide a useful basis for future research on the topic.

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