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Article

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Amfiteatru Economic Journal

Provided in Cooperation with:

The Bucharest University of Economic Studies

Suggested Citation: Mecu, Andra-Nicoleta; Chitu, Florentina; Marin, Georgiana-Ionela; Hurduzeu, Gheorghe (2023) : Analysis of the Impact of Energy Efficiency and Renewable Energy on Greenhouse Gas Emissions and Economic Growth in EU Member States, Amfiteatru Economic Journal, ISSN 2247-9104, The Bucharest University of Economic Studies, Bucharest, Vol. 25, Iss. Special Issue No. 17, pp. 1149-1163, <https://doi.org/10.24818/EA/2023/S17/1149>

This Version is available at:

<https://hdl.handle.net/10419/281754>

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ANALYSIS OF THE IMPACT OF ENERGY EFFICIENCY AND RENEWABLE ENERGY ON GREENHOUSE GAS EMISSIONS AND ECONOMIC GROWTH IN EU MEMBER STATES

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<p>Please cite this article as: Mecu, A.N., Chițu, F., Marin, G.I. and Hurduzeu, G., 2023. Analysis of the Impact of Energy Efficiency and Renewable Energy on Greenhouse Gas Emissions and Economic Growth in EU Member States. <i>Amfiteatru Economic</i>, 25(Special No. 17), pp. 1049-1163.</p> <p>DOI: https://doi.org/10.24818/EA/2023/S17/1149</p>	<p>Article History Received: 15 August 2023 Revised: 3 September 2023 Accepted: 20 September 2023</p>
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Abstract

The European Union has set ambitious goals for both energy efficiency and renewable energy use as part of its strategy to combat climate change. Using a panel data regression model that spans from 2012 to 2021, this study aims to evaluate how energy efficiency and the use of renewable energy sources impact greenhouse gas emissions and economic growth in the member states of the European Union. The findings confirm that energy efficiency and renewable energy production effectively reduce greenhouse gas emissions while also positively influencing economic growth. However, it is important to note that the impact of renewable energy production on economic growth is limited. Therefore, it is crucial to emphasise the role of energy efficiency policies for sustainable development within the European Union. In addition, these findings support the implementation of policies that promote responsible energy consumption and encourage economically and environmentally sustainable development.

Keywords: climate change, renewable energy, economic growth, energy efficiency.

JEL Classification: O44, Q01, Q42, Q50, Q56.

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Introduction

The global effort to address climate change is led by the European Union (EU). The EU has recognised the urgent need to address climate change by establishing ambitious goals for energy efficiency and renewable energy use. However, the effectiveness of these measures in mitigating greenhouse gas emissions and promoting sustainable economic development remains a topic of debate.

The EU's biggest climate target is to reduce greenhouse gas emissions by at least 40% below 1990 levels by 2030. By 2030, the EU wants to have 32% of its energy mix made up of renewable sources (European Parliament, 2023). These targets reflect the EU's commitment to reducing its carbon footprint and promoting sustainable economic growth.

Under the Paris Agreement, The Council of the European Union (2023) argues that the EU and its member states will stimulate global action on climate change, demonstrating that a path to climate neutrality is not only essential, but also feasible and desirable. The transition to climate neutrality presents enormous opportunities, including new business models, growth potential for markets, new jobs, and technological developments (Ministerul Mediului, 2023).

The use of renewable energy sources and the improvement of energy efficiency are essential to achieving these goals. Energy efficiency involves optimising energy use in buildings, transportation, and industrial processes to reduce energy consumption and emissions. Reduction in overall energy consumption is achieved by incorporating energy-efficient technologies and processes. Energy-efficient practises must be adopted by both businesses and individuals if sustainability is to be achieved, as doing so allows the reduction of ecological footprints, which in turn promotes an environmentally conscious attitude toward energy use (Clodnițchi and Tudorache, 2022).

Renewable energy entails increasing the share of energy production from non-fossil fuels, such as solar, wind, and hydroelectric power. Compared to their equivalents that use fossil fuels such as coal, oil, and natural gas, renewable energy sources have substantially less of an impact on the environment (Streimikiene, 2022). As a result, this proactive shift towards renewable energy manifests itself as a crucial and persuasive strategy in ensuring the long-term sustainability of the planet, supporting the EU's objectives of reducing greenhouse gas emissions and stimulating sustainable economic growth.

EU countries have the capacity to develop national policies and strategies to mitigate climate change and to strengthen global decarbonisation efforts, while participating in and complying with the EU's joint processes. According to Bin Su et al. (2021) study, most of the work on energy consumption and energy efficiency focusses on trends and drivers in urban conglomerates, mainly because they are highly populated and allow for the concentration of activities that present considerable opportunities for optimising energy consumption and improving energy efficiency, such as the development of public transport systems, grid integration, and the deployment of large-scale energy storage systems.

Improvements in energy efficiency can lead to significant decreases in energy use if measures are taken to avoid rebound effects. The most economical strategy to reduce energy use while maintaining the same level of economic activity is to increase energy efficiency. Critical energy issues such as climate change, energy security, and competitiveness are also addressed by increasing energy efficiency.

The uniqueness of our study lies in introducing a new perspective by using energy consumption as an indicator of energy efficiency, recognising that increased energy consumption often means decreased efficiency and vice versa. Furthermore, we measure the adoption of renewable energy through renewable energy production, providing a new lens through which to examine the impact of these factors on greenhouse gas emissions and economic growth. This methodology allows us to provide information on the complicated relationship between energy strategies and sustainability goals.

The goal of this work is to conduct a comparative analysis of the effects of energy efficiency and renewable energy use on climate change and economic growth in the EU member states. By conducting a regression analysis of data from 2012 to 2021 for 27 EU member states, we seek to provide valuable insights on the relative effectiveness of these two approaches in achieving the EU's targets for fostering sustainable economic growth while lowering greenhouse gas emissions.

The introduction to the thematic area of our work is preceded by the section that presents the most important results from the scientific literature, followed by the research methodology, respectively, results obtained for each model made, and related discussions. The conclusions of our findings represent the final part of the article and are followed by proposed future research directions, such as the creation of more complex analysis models.

1. Review of the scientific literature

Several studies have examined the impact of energy efficiency and renewable energy on greenhouse gas emissions and economic indicators in the EU. A study by Apergis and Payne (2014) found a significant negative link between CO₂ emissions and the use of renewable energy in the EU countries.

The literature review can be analysed from two perspectives, namely, on the one hand, the literature that reflects the relationship between greenhouse gas emissions and the variables analysed in model 1 of our estimates: energy efficiency and renewable energy, and, on the other hand, the specialised literature that addresses the relationship between economic growth and the variables analysed in model 2: energy efficiency and renewable energy production.

1.1. The relationship between energy efficiency, greenhouse gas emissions, and renewable energy

In addition to these individual studies, several meta-analyses have synthesised the results of multiple studies to draw broader conclusions. A meta-analysis by Creutzig et al. (2017) found that renewable energy and energy efficiency measures are complementary and can be used to achieve both climate and economic objectives. They found that a combination of both measures can lead to significant reductions in greenhouse gas emissions while promoting sustainable economic growth.

A study by Wang et al. (2017) claims that the adoption of greenhouse gas emission reduction systems contributes to increasing energy efficiency. Furthermore, a similar result can be found in the study by Emir and Bekun (2019), who claim that energy efficiency is an important pillar to reduce global energy consumption and also global warming.

According to research conducted by Bayar and Gavriletea (2019), there exists a substantial positive correlation between carbon dioxide (CO₂) emissions and both economic growth and energy consumption within specific African nations. Furthermore, the study underscores the crucial role of renewable energy consumption in reducing CO₂ emissions, while the use of non-renewable energy sources is associated with an increase in CO₂ emissions.

Østergaard et al. (2022) provides an overview of research on renewable energy sources, covering their status, role in sustainable development goals, sustainability of systems, and integration into low-carbon energy systems.

Overall, these studies suggest that increasing energy efficiency and the degree of use of renewable energy can have a positive impact on both climate change and sustainable economic growth. To achieve these two goals, policy makers should think about establishing measures that stimulate the adoption of energy efficiency measures and the use of renewable energy sources.

1.2. The relationship between energy efficiency, economic growth, and renewable energy production

In Africa, economic development and energy consumption are significantly positively correlated, according to a study by Raihan and Tuspekova (2022). The study discovered that in some African nations, economic development and energy use significantly reduce CO₂ emissions. The study also discovered that while the use of non-renewable energy causes CO₂ emissions to increase, the use of renewable energy significantly reduces them, supporting previous research.

The effect of energy efficiency and renewable energy on economic development in OECD nations was evaluated in a meta-analysis by Wang and Wang (2022). The results showed that both energy efficiency and renewable energy had a positive impact on economic growth, indicating that they can promote sustainable economic development. Furthermore, the study found that energy efficiency had a greater impact on economic growth than renewable energy, indicating that it may be a more effective tool to promote sustainable economic development.

Ayres, Turton and Casten (2007) examined the impact of energy efficiency on sustainability and energy reduction. It finds that, while initial improvements lead to rebound effects, over time, they become counterproductive. Energy consumption is increasing due to increased efficiency, highlighting the need for a coordinated portfolio of energy policies to achieve environmental improvements.

There is an ongoing debate in the literature on the impact of renewable energy on economic growth, and these influences are due to multistate analyses where the share of renewable energy production is significant or not, compared to the EU average. The study by Xie et al. (2023) presents non-parametric estimates of the link between economic growth as a result of the expansion of energy production systems, finding that increasing energy consumption from renewable sources not only improves the gross domestic product of the country, but also improves the inclusive well-being of the population.

Based on the literature review presented earlier, this study formulates four testable hypotheses to investigate the relationships between key indicators:

1. Increasing energy efficiency in EU member states will lead to a significant reduction in greenhouse gas emissions.
2. Increasing renewable energy production in EU member states will lead to a significant reduction in greenhouse gas emissions.
3. The increase in energy consumption in EU member states will have a positive impact on economic growth.
4. The increase in renewable energy production in EU member states will have a positive impact on economic growth.

2. Research methodology

Based on the analysis of the literature provided and the aforementioned research purpose, the research objectives are the following:

- a. Quantifying the impact of energy efficiency policies implemented by EU states on the reduction of greenhouse gas emissions;
- b. Evaluation of the role of renewable energy production in stimulating economic growth in EU member states;
- c. Identifying an optimal mix of policies for the sustainable development of EU member states.

Using a fixed-effects panel regression model, we are trying to analyse the relationship between energy efficiency, renewable energy consumption, economic growth, and greenhouse gas emissions.

Despite the studies mentioned above, the relationship between energy efficiency, renewable energy consumption, economic growth, and greenhouse gas emissions in the EU remains an important research question. To address this gap in the literature, this study uses panel regression with fixed effects in SAS to examine the relationship between these variables in the 27 EU member states over the period 2012-2021.

Data for this study were obtained from the Eurostat database and include variables related to energy efficiency, renewable energy consumption, economic growth, and greenhouse gas emissions. The data is collected for each EU member state annually from 2012 to 2021, resulting in a panel dataset with 27 cross-sectional units and 10 time series observations.

The period selected for the study was marked by the COVID-19 pandemic, which had profound implications for energy consumption patterns around the world and could influence the results. The data from the International Energy Agency for 2020 indicated a sharp decrease in energy demand of 5.8% compared to the previous year (IEA, 2020). The global renewable energy supply chain has faced significant challenges with delays in the procurement of critical components that have hindered service progress, labour shortages, and logistical challenges that have led to the postponement of numerous renewable energy projects (IRENA, 2020). However, governments in several EU states have recognised the importance of renewable energy for economic recovery and sustainability, leading to increased investment in clean energy projects. The COVID-19 pandemic caused a transient reduction in global greenhouse gas emissions as industrial and transport activities were

temporarily stopped during the lockdowns; however, these reductions in emissions were often short-lived and there was a rapid recovery as economies reopened. It is essential to recognise that the impact of the pandemic has been temporary and that long-term trends may not align with short-term disruptions caused by COVID-19.

To determine energy efficiency, we used energy consumption as a proxy, assuming that if EU member states consume more energy, energy efficiency decreases and vice versa. This assumption is supported by the fundamental principle of thermodynamics, which states that energy cannot be created or destroyed, only transformed (Hammond, 2007). Therefore, if energy consumption decreases, it means that energy is used more efficiently. Energy intensity, defined as the energy consumption per unit of GDP or other relevant values, is commonly used as an indicator of energy efficiency. Numerous studies have shown that a decrease in energy consumption indicates an increase in energy efficiency in economies (Taylor et al., 2010; Zheng, Qi and Chen, 2011; Paramati, Shahzad and Doğan, 2022). Energy efficiency programmes led by government and industry have led to positive results in reducing energy consumption. A study by Allcott and Greenstone (2017) analysed the effectiveness of energy efficiency programmes and found that they consistently lead to reductions in energy consumption.

Table no. 1. The panel regression model with fixed effects

Indicator	Abbreviations	Period	Data Source	Assumption	Unit of measure
Energy Consumption	CONS	2012-2021	Eurostat	It indicates the efficiency of the energetic system. High consumption might lead to low energy efficiency.	Million tons of oil equivalent
Energy Production	PROD	2012-2021	Eurostat	The production of energy from renewable sources.	Thousand tons of oil equivalent
Gross Domestic Product	GDP	2012-2021	Eurostat	Indicator of economic growth.	Purchasing Power Standards (PPS)
Greenhouse Gas Emission	GHG	2012-2021	Eurostat	Indicator of pollution degree	Index, 1990=100

The fixed effects panel regression model is used to estimate the relationship between energy efficiency, renewable energy consumption, economic growth, and greenhouse gas emissions. The fixed effects model controls for time-invariant country-specific factors. The model is estimated using SAS, a statistical software package widely used in data analysis and modelling. The SAS PROC PANEL procedure is used to estimate the panel regression model with fixed effects.

We will check unit-root tests to confirm whether the variables are stationary or not. A number of unit root tests were considered: Levin-Lin-Chu test, Im-Pesaran-Shin test, ADF - Fisher test and PP - Fisher test. If the test results show that the series are stationary, then the analysis will proceed with the estimation of the fixed-effects model. Otherwise, we will analyse the co-integrity test proposed by Pedroni.

Diagnostic tests are performed to test the model assumptions, including the absence of serial correlation, heteroskedasticity, and multicollinearity. The results of the regression analysis are then used to draw conclusions about the relationship between energy efficiency, renewable energy consumption, economic growth, and greenhouse gas emissions in the EU.

Our primary objective is to determine how efficient energy (PROD) and renewable energy (CONS) affect greenhouse gas emissions (GHG). To do this, we will use a panel data fixed-effects regression model with the following general specification:

$$GHG_{it} = \beta_0 + \beta_1 CONS_{it} + \beta_2 PROD_{it} + \varepsilon_{it} \quad (1)$$

where:

β_0 is the intercept or constant term.

β_1, β_2 , are the coefficients for the independent variables of energy efficiency and renewable energy use, respectively, which show how much the dependent variable (greenhouse gas emissions) changes for a one-unit change in each independent variable.

ε is the error term, which accounts for the variation in the dependent variable that is not explained by the independent variables.

i is the subscript of states and t is the subscript of the time dimension. We have used a fixed-effects approach to get around the bias caused by omitted variables.

Second, using the same model, we will identify the effect of renewable energy (CONS) and efficiency energy (PROD) on gross domestic product (GDP).

$$GDP_{it} = \beta_0 + \beta_1 CONS_{it} + \beta_2 PROD_{it} + \varepsilon_{it} \quad (2)$$

3. Results

Table no. 2 provides the descriptive statistics of the variables for the 27 EU member states in the period 2012-2021. We note that the CONS and PROD variables have leptokurtic distributions, while the GHG variable has a platykurtic distribution and the GDP variable has a strongly leptokurtic distribution.

Table no. 2. Descriptive statistics of variables

	CONS	GHG	PROD	GDP
Mean	35.84851852	79.45777778	9240.506274	101.1740741
Median	16.45	79.9	4413.0615	90
Standard Deviation	49.49225896	27.87370339	13539.02666	43.96352064
Sample Variance	2449.483697	776.9433408	183305243	1932.791147
Kurtosis	4.660619297	0.163021357	4.384636598	6.343955648
Skewness	2.252925778	0.287213841	2.270310509	2.272124324
Minim	0.5	22.1	73.696	46
Maxim	221	156.5	56063.801	283
Sum	9679.1	21453.6	2494936.694	27317
Count	270	270	270	270

The issue of data instability is an important issue and a point to consider. As the data are panel-type, Levin, Lin & Chu, Im-Pesaran-Shin, ADF – Fisher, and PP – Fisher tests were used to determine the stability of the data over the period 2012 – 2021 and to ensure the robustness of the data. Table no. 3 shows the results:

Table no. 3. Results of panel unit root tests

Variable	Levin, Lin & Chu	Im-Pesaran-Shin	ADF - Fisher	PP - Fisher
CONS	-4.00333*	-2.42828*	-3.79590*	-8.10471*
PROD	-8.93587*	-4.96235*	-5.90346*	-8.31629*
GHG	-5.23088*	-2.36813*	-3.42944*	-7.24475*
GDP	-1.39838**	-1.25238**	-1.83824	-7.50397*

Note: *5% significance level; **10% significance level. The null hypothesis for all tests is that the series has a unit root.

The results of the stationarity assessments suggest that most variables can be considered stationary when observed at the level. When we calculate the first difference, we find that we can reject the unit root hypothesis with a significantly higher confidence level for CONS, PROD, GHG and GDP; thus all data are stationary, and we can proceed to the estimation of the fixed effects model.

3.1. Model 1: Fixed One-Way Estimates - Dependent Variable: GHG

The regression model estimates the relationship between greenhouse gas emissions (GHG) and two independent variables: energy efficiency (CONS) and renewable energy (PROD). The model uses fixed-effects panel regression to control for unobserved heterogeneity across EU member states.

Table no. 4. Fixed-effects model statistics

Fixed-effects model statistics	
SSE	19145.0228
MSE	79.4399
R ²	0.9084
DFE	241
R - Square	8.9129

Note: SSE = Sum of squares of errors; DFE = Number of degrees of freedom associated with errors: number of observations in the data set minus number of parameters; MSE = Mean squares of errors.

From Table 4 it can be seen that the value of R2 is 0.9084, which means that the model explains 90.84% of the variability in greenhouse gas emissions. The very high value of this indicator may show a false dependence due to the presence of heteroskedasticity and autocorrelation errors.

Table no. 5. Fixed effects model testing using F-test

F-statistic to test the occurrence of fixed effects			
Num DF	Den DF	F - Value	Pr > F
26	241	91.70	<.0001

The F-test for the fixed effects model has a p-value less than 0.0001. This suggests that a model with fixed effects fits better to the data than a model without fixed effects.

Table no. 6. Fixed effects model parameter estimates

Parameter Estimates						
Variable	DF	Estimate	Standard Error	t Value	Pr > t	Label
Intercept	1	-4.16147	13.1898	-0.32	0.7526	Intercept
CONS	1	0.819719	0.2742	2.99	0.0031	CONS
PROD	1	0.001361	0.00108	1.26	0.2074	PROD

The estimated coefficient for energy efficiency (CONS) is 0.82 and is statistically significant at the 0.05 level, suggesting that the increase in energy consumption in EU member states leads to a significant increase in greenhouse gas emissions. This means that a higher energy consumption suggests a decrease in energy efficiency. The estimated coefficient for Renewable Energy Production (REC) is 0.001 and is not statistically significant at the 0.05 level. This suggests that renewable energy production does not have a significant effect on greenhouse gas emissions.

3.2. Model 2: Fixed One-Way Estimates - Dependent Variable: GDP

The regression model estimates the relationship between economic growth (GDP) and two independent variables: energy efficiency (CONS) and renewable energy production (PROD). The model uses panel regression with fixed effects to control for unobserved heterogeneity across EU Member States.

Table no. 7. Fixed-effects model statistics

Fixed-effects model statistics	
SSE	12046.2075
MSE	49.9843
R²	0.9768
DFE	241
R - Square	7.0700

Note: SSE = Sum of squares of errors; DFE = Number of degrees of freedom associated with errors: number of observations in the data set minus number of parameters; MSE = Mean squares of errors.

From Table 7 it can be seen that the R-squared value is 0.9768, which means that the model explains 97.68% of the variability in economic growth. The very high value of this indicator may show a false dependence due to the presence of heteroskedasticity and autocorrelation errors.

Table no. 8. Fixed effects model testing using F-test

F-statistic to test the occurrence of fixed effects			
Num DF	Den DF	F - value	Pr > F
26	241	388.29	<.0001

The F-test for the fixed effects model has a p-value less than 0.0001. This suggests that the fixed effects model fits the data better than a random model.

Table no. 9. Fixed effects model parameter estimates

Parameter Estimates						
Variable	DF	Estimate	Standard Error	t Value	Pr > t	Label
Intercept	1	110.4266	10.4625	10.55	<.0001	Intercept
CONS	1	0.485213	0.2175	2.23	0.0266	CONS
PROD	1	-0.00011	0.000854	-0.13	0.8968	PROD

The estimated coefficient of energy efficiency (CONS) is 0.49 and is statistically significant at the 0.05 level. This suggests that the increased level of energy efficiency in EU member states has a positive impact on economic growth. The estimated coefficient for energy production (PROD) is -0.00011 and is not statistically significant at the 0.05 level. This suggests that renewable energy production does not have a significant effect on economic growth.

The fixed one-way effects model was evaluated for goodness of fit using several diagnostic graphs. The Q-Q plot of the residuals showed a long tail on the right, suggesting that the distribution of the residuals may not be perfectly normal. Although this may be a concern, it is important to note that the model still provides a good fit to the data overall. One potential explanation for the long tail could be the presence of outliers in the data, which can have a large impact on the distribution of the residuals. The histogram of the residuals showed a bell-shaped curve, which further supports the assumption of normality.

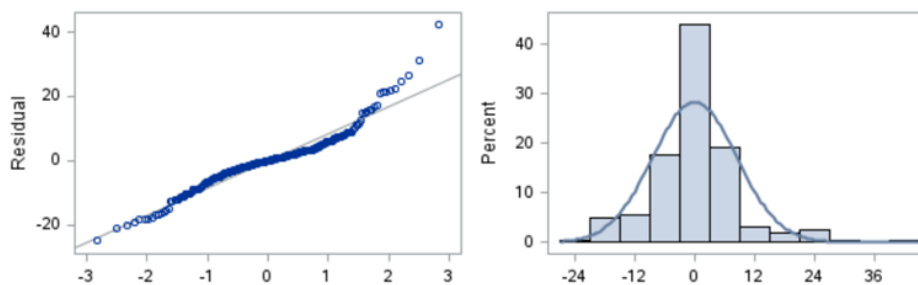


Figure no. 1. Fit Diagnostics Panel for GHG

The Fit Diagnostics Panel for GDP (Figure no. 2) highlights that the Q-Q plot of the residuals from the fixed one-way effects model showed a pattern where the left end of the points was above the line and the right end of the points was below the line, with a few points going above and below the line in each section. This suggests that the distribution of the residuals may not be perfectly normal, which can be a concern when interpreting the model results. One potential explanation could be violations of the assumption of constant variance, which can also cause deviations from normality in the residuals. To investigate this possibility, we examined plots of the residuals vs. predicted values and found some evidence of heteroscedasticity in the data. Despite these concerns, we believe that our fixed one-way effects model still provides a reasonable fit to the data and produces reliable results. However, it is important to be cautious when interpreting the results and to keep in mind the potential limitations of the model.

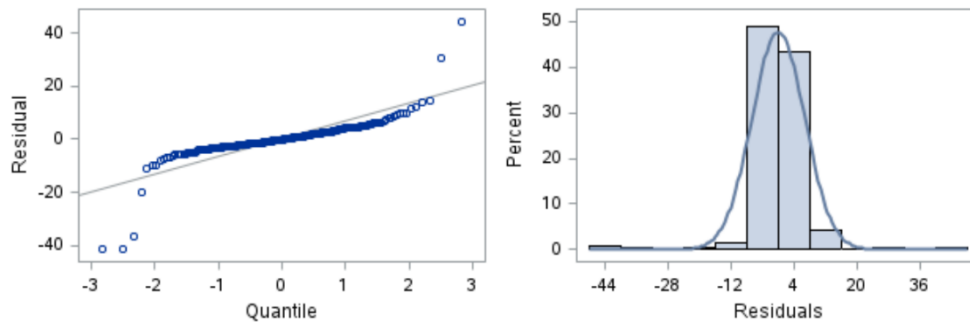


Figure no. 2. Fit Diagnostics Panel for GDP

4. Discussions

There is a significant and positive relationship between energy consumption and greenhouse gas emissions. As energy consumption increases, greenhouse gas emissions tend to increase. The positive and significant coefficient estimate for energy consumption suggests that policies aimed only at reducing energy consumption may not be sufficient to reduce greenhouse gas emissions. The link between sustainable development and the effective mitigation of environmental challenges is of primary importance to understand and address current sustainability concerns. In the pursuit of sustainability and the mitigation of climate change, a concerted effort is imperative to begin a transition to cleaner and more sustainable energy alternatives. In this context, an integral and comprehensive strategy to create a sustainable energy landscape is the convergence of energy-saving measures with the widespread integration of cleaner and renewable energy sources. Such an integrated framework promotes a sustainable trajectory for the well-being of both present and future generations by aligning with the overarching goals of climate change mitigation and long-term environmental health.

Considering increased energy consumption as equivalent to low energy efficiency, we can say that there is a significant and negative relationship between energy efficiency, renewable energy production, and greenhouse gas emissions. This means that when energy efficiency is low and renewable energy is limited, the result is higher greenhouse gas emissions. By adopting energy-efficient technologies, we can optimise energy consumption, thereby

reducing the overall environmental burden and promoting sustainability. The evidence presented validates hypothesis 1 based on the previous assumptions.

There is a significant and positive relationship between economic growth and energy consumption. As economic growth increases and energy consumption tends to increase, the third hypothesis is confirmed. However, the relationship poses challenges to long-term environmental sustainability. Increased energy use driven by economic expansion is a factor in the climate change crisis, air and water pollution, depletion of natural resources, loss of biodiversity, and waste production. It is important to create a resilient future that benefits society and the environment by incorporating sustainability into economic growth strategies.

Therefore, the results suggest that policies and measures aimed at increasing energy efficiency and renewable energy production could be effective in reducing greenhouse gas emissions in EU member states. However, efforts to promote economic growth must also take into account the potential increase in energy consumption and greenhouse gas emissions.

The estimated insignificant coefficient for renewable energy production suggests that policies aimed at increasing renewable energy production may not have a significant impact on greenhouse gas emissions or economic growth. The lack of visible impact on gas emissions indicates that simply expanding renewable energy production without considering the type of energy source used or its environmental effects may not be an effective way to combat climate change or reduce emissions. This suggests that other aspects of climate change mitigation, such as energy mix, energy efficiency, or the use of renewable energy sources, may be more important. Similarly, the insignificant effect on economic growth suggests that it is not just energy quantity that may be the sole factor in determining economic prosperity; other elements affecting economic growth include trade policy, labour skills, technological advances, and general economic conditions. As a result, the assumptions for the second and fourth hypotheses are not met.

From a political perspective, the study indicates that policy makers are of great importance to energy policy, focussing on energy efficiency and renewable energy to achieve the goals of climate change and economic development. These results support the adoption of policies that encourage responsible energy consumption and promote sustainable economic and environmental development. The EU can pave the way for a greener and more sustainable energy landscape in its member countries by adopting specific policies that encourage energy efficiency, promote renewables, and discourage overuse. These rules can also support economic stability, energy security, and a smaller carbon footprint.

Conclusions

This study has evaluated the relationship between energy efficiency, renewable energy consumption, economic growth, and greenhouse gas emissions for EU member states for the period 2012-2021. We use a panel regression to verify the assumptions.

Four assumptions were considered: (i) increasing energy efficiency in EU member states will lead to significant reductions in greenhouse gas emissions; (ii) increasing renewable energy production in EU member states will lead to significant reductions in greenhouse gas emissions; (iii) increasing energy consumption in EU member states will have a positive impact on economic growth; and (iv) increasing renewable energy production in EU member states will have a positive impact on economic growth.

Notable findings include a significant positive link between energy consumption and greenhouse gas emissions, highlighting the need for a holistic approach to reducing emissions beyond simple energy conservation. The importance of integrating cleaner and renewable energy sources into the energy landscape to achieve sustainable development and climate change mitigation is highlighted. Furthermore, the study validates the importance of promoting energy-efficient technologies and the adoption of renewable energy sources to reduce emissions, aligning with existing theoretical frameworks. The study suggests that economic growth strategies should incorporate sustainability principles to balance economic progress and environmental conservation. The insignificant impact of energy production on greenhouse gas emissions and economic growth underlines the need to consider the quality and environmental effects of energy sources. It points out that only the expansion of renewable energy production may not effectively combat climate change or promote economic prosperity.

The two models show that increasing energy efficiency or renewable energy consumption leads to a significant reduction in greenhouse gas emissions. The evidence presented not only validates Hypothesis 1 based on the previous assumptions, but also shows that there is a positive and significant relationship between economic growth and energy consumption. As economic growth increases, energy consumption tends to increase.

At the same time, the negligible estimate of the renewable energy production coefficient suggests that policies aimed at increasing energy production may not have a significant impact on greenhouse gas emissions or economic growth. Therefore, the assumptions of the second and fourth hypotheses are not satisfied.

In terms of the limitation of the study, there is no perfect indicator to match energy efficiency, and therefore we used the proxy variable of energy consumption. A notable limitation of our analysis is the observed correlation between the independent variables, energy efficiency, and renewable energy production, which could introduce multicollinearity issues in our models. Although steps have been taken to address this limitation by using fixed-effects models that account for unobserved time-invariant heterogeneity, the presence of correlated independent variables remains a concern. Future research could explore more advanced statistical techniques to better understand the effects of these factors and provide more precise estimates. Additionally, expanding the data set to include a more comprehensive set of control variables or exploring regional variation within the panel data could further enhance the robustness of our findings and contribute to a deeper understanding of the complex interaction between the variables analysed.

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