OLSZTYN ECONOMIC JOURNAL
2024, 19(2), 201–221
ISSN 1897-2721 e-ISSN 2083-4675 DOI: 10.31648/oej.10984

ORIGINAL PAPER

IMPACT OF GDP AND RES SHARE ON CO_2 EMISSIONS, ENERGY EFFICIENCY AND ECONOMIC GROWTH IN EUROPEAN UNION MEMBER STATES

Grzegorz Szczubełek
Faculty of Economic Sciences
University of Warmia and Mazury in Olsztyn
ORCID: https://orcid.org/0000-0002-2511-7278
e-mail: grzegorz.szczubelek@uwm.edu.pl

Daniel Rzeczkowski
Faculty of Economic Sciences
University of Warmia and Mazury in Olsztyn
ORCID: https://orcid.org/0000-0002-8458-5987
e-mail: daniel.rzeczkowski@uwm.edu.pl

JEL Classification: Q43, Q56, O13, C39, R11, O44.

Key words: CO_2 emissions, renewable energy sources (RES), structural equation modelling (SEM).

Abstract

Economic growth and CO_2 emissions are closely linked to energy consumption. Energy transition towards renewable energy sources (RES) and improving energy efficiency are crucial to combating global warming. EU member states are striving to reduce CO_2 emissions while supporting economic growth. However, it is necessary to develop an understanding of how both gross domestic product (GDP) level and RES share affect energy efficiency and CO_2 emissions. The purpose of this paper is to analyse the impact of the GDP level and the renewable energy sources (RES) share on CO_2 emissions, energy efficiency, and economic growth in European Union states. The study employs structural equation modelling (SEM) using the partial least squares (PLS) method. The analysis is based on data collected from Eurostat, the OECD and other sources covering the period 2004-2023.

The paper constitutes a substantial contribution to the body of literature by providing a comprehensive analysis of the impact of GDP level and the share of renewable energy sources (RES) on CO_2 emissions, taking into account energy efficiency and urbanisation as key factors. The study revealed that a high level of GDP combined with a high share of RES in the energy mix is conducive to a more effective reduction of CO_2 emissions. Furthermore, urbanisation has a varying impact on economic growth depending on the level of GDP and the share of RES. This points to the

How to cite: Szczubełek, G., & Rzeczkowski, D. (2024). Impact of GDP and RES Share on CO_2 Emissions, Energy Efficiency and Economic Growth in European Union Member States. *Olsztyn Economic Journal*, *19*(2), 201-221. https://doi.org/10.31648/oej.10984

need to take the state's specifics into account when developing energy policies. The findings may provide policymakers with some guidelines when shaping energy and environmental strategies in EU states.

WPŁYW PKB I UDZIAŁU OZE NA EMISJĘ CO_2, EFEKTYWNOŚĆ ENERGETYCZNĄ ORAZ WZROST GOSPODARCZY W PAŃSTWACH UNII EUROPEJSKIEJ

Grzegorz Szczubełek
Faculty of Economic Sciences
University of Warmia and Mazury in Olsztyn

Daniel Rzeczkowski
Faculty of Economic Sciences
University of Warmia and Mazury in Olsztyn

Kody JEL: Q43, Q56, O13, C39, R11, O44.

Słowa kluczowe: emisje CO_2, odnawialne źródła energii (OZE), modelowanie równań strukturalnych (SEM).

Abstrakt

Wzrost gospodarczy i emisja CO_2 są silnie powiązane z zużyciem energii. Transformacja energetyczna w kierunku odnawialnych źródeł energii (OZE) oraz poprawa efektywności energetycznej są najważniejszymi elementami w walce z globalnym ociepleniem. Kraje UE dążą do redukcji emisji CO_2 z jednoczesnym wsparciem wzrostu gospodarczego. Konieczne jest jednak zrozumienie, jak poziom PKB i udział OZE wpływają na efektywność energetyczną oraz emisję CO_2. Celem artykułu jest analiza wpływu poziomu PKB oraz udziału odnawialnych źródeł energii (OZE) na emisję CO_2, efektywność energetyczną i wzrost gospodarczy w krajach Unii Europejskiej. W badaniu zastosowano modelowanie równań strukturalnych (SEM) z wykorzystaniem metody najmniejszych kwadratów cząstkowych (PLS). Analiza oparta jest na danych pochodzących z Eurostatu, OECD oraz innych źródeł obejmujących lata 2004-2023.

Artykuł stanowi istotny wkład w literaturę ze względu na kompleksową analizę wpływu poziomu PKB i udziału odnawialnych źródeł energii (OZE) na emisję CO_2, z uwzględnieniem efektywności energetycznej i urbanizacji jako głównych czynników. Przeprowadzone badanie wykazało, że wysoki poziom PKB w połączeniu z dużym udziałem OZE w miksie energetycznym sprzyja skuteczniejszej redukcji emisji CO_2. Ponadto urbanizacja ma zróżnicowany wpływ na wzrost gospodarczy, w zależności od poziomu PKB i udziału OZE. Wskazuje to na potrzebę uwzględnienia specyfiki kraju podczas formułowania polityki energetycznej. Wyniki dostarczają decydentom politycznym wskazówek do kształtowania strategii energetycznych i środowiskowych w państwach Unii Europejskiej.

Introduction

Climate change is one of the greatest challenges the world faces today. CO_2 emissions are a major factor contributing to global warming and are closely linked to economic development and energy consumption. It is vital to understand how to continue economic growth without increasing the negative impact on the environment.

Studies by Liddle and Parker (2024) indicated that by reducing energy consumption and increasing the share of renewable energy sources (RES) it is possible to decouple economic growth from CO_2 emissions. Wang *et al*. (2024) confirmed the importance of RES, highlighting the efficiency of wind energy in reducing emissions and the role of hydropower in supporting economic growth.

Energy efficiency is of key importance. However, the rebound effect – an increase in energy consumption following the introduction of efficient technologies – may outweigh the benefits (Sorrell *et al*., 2009; Karakaya *et al*., 2024). This indicates the need for strategies that combine technology and behavioural change.

Urbanisation is affecting CO_2 emissions and economic growth. In rapidly developing countries, it leads to increased emissions due to industrialisation and the need for new infrastructure (Tian *et al*., 2024). RES integration and effective urban planning can mitigate these negative effects (Murshed *et al*., 2022).

Despite numerous studies, there is a shortage of analyses that simultaneously examine the impact of GDP level and RES share on CO_2 emissions, energy efficiency and economic growth in EU states. This is particularly relevant in the context of their economic and energy diversity.

The objective of this study is to analyse the impact of GDP and RES share on CO_2 emissions, energy efficiency and economic growth in EU states. The following hypotheses are being verified here:

1. A high level of GDP combined with a high share of renewable energy sources (RES) promotes a more efficient reduction of CO_2 emissions.
2. Increasing the share of RES in the energy mix leads to a significant reduction in CO_2 emissions.
3. Investment in research and development (R&D) has a greater impact on improving energy efficiency in countries where the share of renewable energy sources (RES) is low.
4. The link between urbanisation and CO_2 emissions and economic growth is determined by the level of economic development and the share of RES; a higher share of RES mitigates the negative effects of urbanisation.

The study applied structural equation modelling (SEM) using the partial least squares (PLS) method. The data used originated from Eurostat, OECD and other sources, covering the period 2004-2023.

The study makes a contribution to knowledge by comprehensively analysing the impact of GDP and RES on CO_2 emissions in EU member states, taking into account energy efficiency and urbanisation as central factors. The findings may provide valuable insight for policymakers when shaping effective energy and environmental strategies.

Literature Review and Identification of Key Factors

GDP and CO_2 emissions: towards sustainable growth

Contemporary studies on sustainable development concentrate on the complex relationship between economic growth, measured by GDP levels, and CO_2 emissions. The ambition to minimise the negative impact of the economy on the environment has led researchers to seek ways to decouple these two variables, enabling economic growth while reducing emissions.

A number of research papers have explored the role of renewable energy sources (RES) in decoupling economic growth from CO_2 emissions. Liddle and Parker (2024) identified 15 countries that successfully decoupled these variables, pointing to the key role of RES in decarbonising energy systems. Similar conclusions can be drawn from the study carried out by Wang *et al.* (2024), who highlighted the efficiency of wind energy in reducing emissions.

Barkat *et al.* (2024) demonstrated that foreign aid can reduce CO_2 emissions in developing countries by promoting green investment. Lu *et al.* (2024) emphasised the need to include emission factors in economic projections.

Gbadeyan *et al.* (2024) considered decoupling economic growth from CO_2 emissions as a fundamental element of the energy transition. While analysing the case of China, Shi *et al.* (2024) noted that the pursuit of rapid economic growth can lead to energy efficiency problems. In their examination of EU countries, Mohsin *et al.* (2024) found that despite the positive impact of green supply chains and the circular economy in reducing CO_2 emissions, economic growth can still generate increased emissions.

Amara *et al.* (2024) highlighted the positive impact of economic growth on the development of eco-innovation. Sikder *et al.* (2024) stated that the integration of green logistics and the circular economy has a positive impact on reducing CO_2 emissions in EU states. Zhang *et al.* (2024) stressed the importance of policies that support innovation and RES development in the context of adopting renewable energy. Dissanayake *et al.* (2023) noted the imperative of adapting energy policies to the specifics of each country.

In turn, Qin *et al.* (2024) proposed a spatial optimisation model of territorial functions that combines economic growth with CO_2 reduction in China. In their analysis of ASEAN (Association of Southeast Asian Nations) and GCC (Gulf Cooperation Council) countries, Naz *et al.* (2024) highlighted the importance of RES in GCC countries. Kinyar and Bothongo (2024) showed that eco-innovation in Great Britain had a stronger emission reduction effect than GDP growth alone.

Sikder *et al.* (2024) stressed that industrialisation and economic growth increase CO_2 emissions in developing countries. Onofrei *et al.* (2022) pointed to the need for appropriate policies and tools to manage climate risks in the EU.

The review of the literature presented above illustrates the complexity of the relationship between GDP and CO_2 emissions. In the context of this study focused on EU states, it is vital to understand how the combination of a high level of GDP and a high share of RES affects the efficiency of CO_2 reductions.

Hypothesis 1: A high level of GDP combined with a high share of renewable energy sources (RES) promotes a more efficient reduction of CO_2 emissions.

Role of RES in reducing CO_2 emissions

Contemporary scientific studies have clearly demonstrated the central role played by renewable energy sources (RES) in reducing carbon dioxide (CO_2) emissions and limiting negative environmental impacts.

Several studies have confirmed a direct link between RES use and CO_2 reduction. Dogan and Inglesi-Lotz (2024) found that increased use of biomass leads to reduced CO_2 emissions, and the environmental Kuznets curve (EKC) hypothesis[1] turned out to be true for countries using biomass. Ben-Ahmed and Ben-Salha (2024) found that both nuclear and renewable energy lead to reduced CO_2 emissions. Mehmood (2021) highlighted the considerable impact of renewable energy in reducing CO_2 emissions, noting the role of education in raising environmental awareness.

Zhang *et al.* (2024) observed that higher oil prices can make renewable energy more attractive and that technological innovation accelerates the transition to RES. Bakry *et al.* (2023) confirmed the significant impact green financing has on reducing CO_2 emissions. Acaravci and Ozturk (2024) found a long-term relationship between CO_2 emissions per capita, energy consumption per capita and GDP per capita in some European states, suggesting the veracity of the EKC hypothesis. Apergis and Payne (2024) concluded that renewable energy consumption is strongly related to GDP per capita, CO_2 emissions, as well as oil and coal prices.

Khan *et al.* (2022) proved that the relationship between renewable energy consumption and CO_2 emissions varies depending on the level of economic development. Naeem *et al.* (2024) reported that increased access to clean fuels and technologies is conducive to reducing CO_2 emissions while highlighting the need for improved environmental policies.

[1] The environmental Kuznets curve (EKC) is a hypothesis suggesting that during the initial stages of economic growth, environmental degradation accelerates, but after a certain level of income per capita is reached, it begins to decrease. This means that the correlation between economic growth and environmental pollution has the shape of an inverted "U".

A review of studies confirms the importance of RES in reducing CO_2 emissions. At the same time, it points to the need to consider a range of factors when assessing the effectiveness of RES in reducing emissions, such as the level of economic development, access to technology and environmental policies.

Hypothesis 2: Increasing the share of renewable energy sources (RES) in the energy mix leads to a significant reduction in CO_2 emissions.

Energy efficiency and climate policy: the paradox of the rebound effect

Energy efficiency is widely recognised as the key component of climate policy, enabling reductions in energy consumption and CO_2 emissions (Belaïd & Mikayilov, 2024). However, somewhat paradoxically, the introduction of energy-efficient technologies can lead to increased energy consumption, which is referred to as the rebound effect (Sorrell *et al.*, 2009).

The rebound effect means that energy savings resulting from the implementation of efficient technologies are partially or fully offset by increased consumption elsewhere (Karakaya *et al.*, 2024). This phenomenon can occur both at the microeconomic level (e.g., more frequently used appliances) (Dimitropoulos, 2007) and at the macroeconomic level (e.g., increased economic activity) (Bolat *et al.*, 2023).

Research shows that the rebound effect can have a significant impact on the effectiveness of climate policies. Yang and Li (2024) showed that the rebound effect for emissions in China is between 10% and 60%. Mongo *et al.* (2024) observed the short-term effect in 15 European states.

Among the sources of the rebound effect is the "institutional trap" (Matraeva *et al.*, 2024), i.e., established social norms that lead to inappropriate use of energy-efficient technologies.

Successful mitigation of the rebound effect calls for comprehensive strategies that combine different policy mechanisms, such as economic incentives and regulatory actions. Ziaei (2024) notes that increased public spending on energy innovation can lead to reduced CO_2 emissions in the long term, though in the short term, it can stimulate economic activity and thus generate increased emissions.

Energy efficiency plays a key role in reducing CO_2 emissions, but its effectiveness can be hampered by the rebound effect. Further research into effective strategies to reduce this effect is necessary.

Hypothesis 3: Investment in research and development (R&D) has a greater impact on improving energy efficiency in countries where the share of renewable energy sources (RES) is low.

Urbanisation versus economic development and energy: complex interdependencies

Urbanisation plays an important role in shaping economic growth, energy consumption and CO_2 emissions. Studies demonstrate that the interdependencies between urbanisation, economic growth and emissions are complex and depend on many factors, such as the stage of development and the level of RES deployment (Zhang & Yang, 2024).

In rapidly developing countries, urbanisation is often associated with increased CO_2 emissions due to burgeoning industrialisation and demand for infrastructure (Tian *et al.*, 2024). However, RES integration has the potential to mitigate these effects (Murshed *et al.*, 2022). In high-income countries, the relationship between urbanisation and emissions is more nuanced. Grodzicki and Jankiewicz (2022) found that urbanisation in Europe leads to increased emissions, yet a high share of RES can significantly reduce them.

The effect of urbanisation on emissions is not linear. Zhu *et al.* (2024) observed in China that emissions increase in the early phase of urbanisation, but later stabilise and decrease with the implementation of energy-saving technologies and efficient transport systems.

Sikder *et al.* (2024) showed that improvements in energy efficiency in developing countries can reduce the growth of emissions associated with urbanisation.

Tong (2024) noted that the impact of urbanisation on energy and emissions varies at the subnational level in China, indicating the importance of local policies. Quan *et al.* (2024) showed that urbanisation can be more effective than RES in reducing ecological footprints, but economic development can negatively affect environmental quality. Zhang *et al.* (2024) emphasised the necessity to combine efficiency gains with policies that support the optimisation of industrial structures and environmental protection.

The correlation between urbanisation and CO_2 emissions is complex and is influenced by several factors. Strategic implementation of energy policies is essential to minimise the environmental impacts of urbanisation.

Hypothesis 4: The link between urbanisation and CO_2 emissions and economic growth is determined by the level of economic development and the share of RES; a higher share of RES mitigates the negative effects of urbanisation.

Empirical Research Methodology and SEM Model Construction

The study relied on empirical data collected from official statistical sources such as Eurostat, the OECD and other institutions providing information on the economy, energy and the environment in EU states. Eurostat provided key indicators such as gross domestic product (GDP) per capita, carbon dioxide (CO_2) emissions, the share of renewable energy sources (RES) and urbanisation rates. Data from the OECD were supplemented with information on innovation, and additional environmental statistics provided data on energy efficiency.

The analysis covers the period 2004-2022, allowing long-term trends in the economy, energy efficiency and CO_2 emissions in EU states to be observed over the past 18 years. The period chosen also makes it possible to consider the impact of key energy policies and macroeconomic developments.

The study used the following indicators, which were implemented as variables in the structural equation model (SEM) constructed in SmartPLS 4. These variables were divided into constructs and control variables.

Constructs:

– Renewable energy (RE): Energy consumption from renewable sources in EU states, measured as the percentage of energy from RES in total energy consumption. This includes sources such as wind, solar, biomass or hydropower. It allows the assessment of states' commitment to the energy transition.

– Research and development (R&D): R&D expenditure as a percentage of GDP, extracted from the Eurostat database, including investment in new energy technologies and the number of energy-related patents. It represents the level of innovation and the ability to implement new technological solutions.

– Energy efficiency (EE): Energy consumption in relation to economic growth, measured by final energy consumption per unit of GDP and final energy consumption per capita. The average indicator reflects the efficiency of energy use in the state's economy.

– Economic growth (EG): GDP per capita, serving as a measure of the level of economic development and prosperity. Values at fixed prices have been used, eliminating the impact of inflation and allowing the data to be comparable over time.

– CO_2 emissions (CO_2): Carbon dioxide emissions per capita, illustrating the environmental burden generated by individual states and allowing progress in reducing greenhouse gas emissions to be tracked.

Control variables:

– Urbanisation (URB): Percentage of population living in urbanised areas, taking into account indicators such as percentage of the urban population, urban density and urban population growth rate. It influences energy consumption, emission levels and economic structures.

– Degree of industrialisation (IND): Industry's contribution to GDP, representing the level of industrialisation of the economy. A higher share of industry can result in higher energy consumption and CO_2 emissions.

The SEM model takes into account both the measurement and structural parts, which allows for the simultaneous modelling of the relationship between latent variables (constructs) and observable variables.

In order to carry out a more precise analysis, EU states were divided into groups under two criteria: the level of GDP per capita and the share of RES in total energy consumption. This division helps to identify states representing different levels of economic development and commitment to the energy transition, which is crucial for the formulation of efficient energy and environmental policies.

Groups by GDP per capita:

– highest GDP level: Ireland, the Netherlands, Denmark, Sweden, Austria;
– high GDP level: Germany, Belgium, Finland, France, Slovenia;
– average GDP level: Italy, Spain, Czechia, Lithuania, Estonia;
– low GDP level: Portugal, Poland, Slovakia, Romania, Latvia;
– lowest GDP level: Hungary, Croatia, Greece, Bulgaria.

Groups by RES share:

– highest RES share: Sweden, Finland, Latvia, Denmark, Estonia;
– high RES share: Portugal, Austria, Lithuania, Croatia, Slovenia;
– average RES share: Romania, Greece, Spain, Germany, France;
– low RES share: Italy, Bulgaria, Czechia, Slovakia, Poland;
– lowest RES share**:** Hungary, the Netherlands, Belgium, Malta, Ireland.

This breakdown facilitates an analysis of the relationship between the level of economic development and the share of RES in the energy mix, which plays an important role in assessing the impact of these factors on CO_2 emissions and energy efficiency.

Model validation

The SEM model designed using SmartPLS 4 was validated, including an assessment of the relevance and reliability of the measurement model (Fig. 1):

– factor loadings: all indicators achieved values between 0.72 and 0.89, exceeding the acceptable threshold of 0.7;

– average Variance Extracted (AVE): For each latent variable, the AVE value was above 0.5, indicating adequate construct validity;

– construct reliability: Values exceeded 0.8, indicating high internal consistency;

– discriminant validity assessment: The Fornell-Larcker criterion and the HTMT coefficient were used; the values were below the threshold of 0.85, confirming good discriminant validity between the constructs.

Analysis of the path coefficients in the structural model showed values ranging from -0.602 to 0.517, indicating a diverse influence of the different variables on each other. The values of the coefficient of determination R^2 ranged from 0.341 to 0.713, suggesting a moderate to high explanatory power of the model. The Standardized Root Mean Square Residual (SRMR) value for the whole model was 0.057, indicating a good fit of the model.

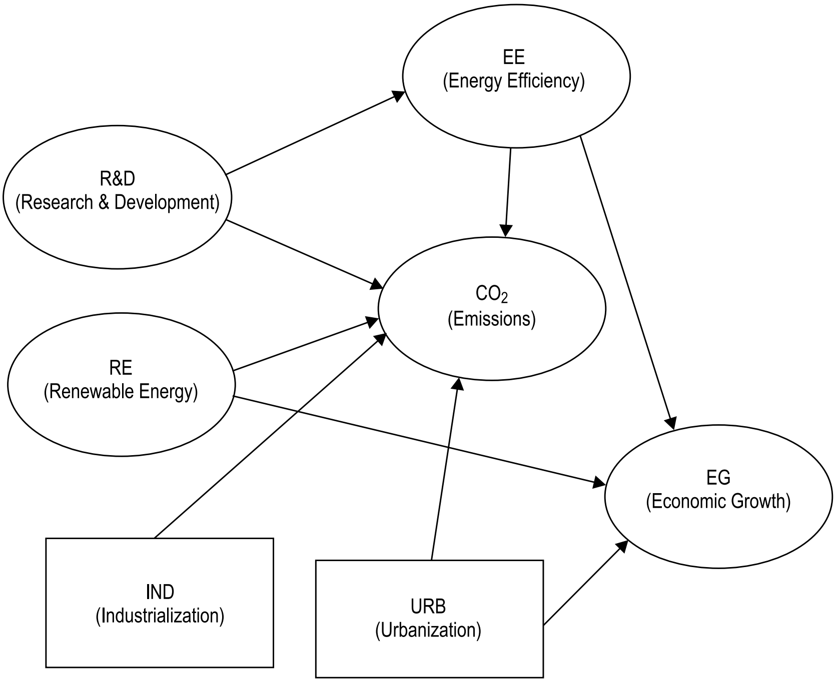

Fig. 1. Structural model of the SEM
Source: own study using SmartPLS4.

The PLS-SEM method was chosen for the following reasons:

– flexibility in the analysis of small samples: It allows reliable results to be obtained even with a limited number of observations;

– no requirement for normality of data distribution: Allows for the analysis of data that do not meet the assumption of normality;

– possibility to model complex structures: Ideal for studying complex relationships between latent and observable variables.

This is key to exploring the relationship between GDP, RES, CO_2 emissions and other factors, allowing the multidimensionality of these relationships to be addressed.

Empirical Results of the Analysis of the Impact of GDP, RES, and Other Factors on CO_2 Emissions and Economic Growth

This chapter presents the results of the empirical analysis of the impact of gross domestic product (GDP), renewable energy sources (RES) and other factors on carbon dioxide (CO_2) emissions and economic growth in EU member states. Each of the research hypotheses adopted has been verified against the results obtained and cross-referenced with existing literature. This provides a deeper understanding of the relationships and to compare the results with those of previous studies.

H1: A high level of GDP combined with a high share of renewable energy sources (RES) promotes a more efficient reduction of CO_2 emissions.

Table 1 shows the results of the analysis of the impact of GDP level and the share of renewable energy sources (RES) on CO_2 emissions in different groups of EU member states. These results clearly indicate a strong correlation between economic development, RES use and the effectiveness of pro-environmental efforts.

Table 1

Results of the analysis of the impact of GDP and RES share on CO_2 emissions in groups of EU member states

Group of states	GDP → CO_2	RES → CO_2	RES share	R^2 for CO_2
Highest GDP per capita	-0.602	-0.340	high	0.621
High GDP per capita	-0.285	-0.192	average	0.394
Average GDP per capita	0.104	-0.319	average	0.525
Low GDP per capita	0.022	-0.213	low	0.409
Lowest GDP per capita	0.341	-0.060	lowest	0.341

Source: own study using SmartPLS4.

The groups of states with the highest levels of GDP per capita recorded the highest value of the R^2 coefficient of determination for CO_2 emissions, with a value of 0.621. This suggests that countries with a high level of economic development and a high share of RES, such as Sweden, Germany and the Netherlands, are most effective in reducing CO_2 emissions. The path coefficient value for GDP → CO_2 was -0.602, confirming that economic growth in states with high GDP can contribute to emission reductions, especially when accompanied by the use of renewable energy sources. Similarly, the path coefficient value for RES → CO_2 was -0.340, indicating a positive impact of RES on emission reductions.

In states with average GDP levels, limited effectiveness of emission reduction efforts was observed. The value of the GDP → CO_2 path coefficient was 0.104, suggesting that the economic benefits of economic growth often outweigh the environmental benefits, leading to an increase in CO_2 emissions. This effect may be due to the occurrence of the so-called rebound effect, a situation in which economic growth and technological efficiency lead to increased energy consumption. The value of the path coefficient for the RES → CO_2 relationship was

-0.319, which indicates that despite the impact of RES on reducing emissions, this influence is not strong enough to completely offset the effects of economic growth.

States with the lowest levels of GDP per capita achieved the lowest R^2 value for CO_2 (0.341), indicating limited environmental performance. In these states, the path coefficient value for GDP → CO_2 was 0.341, suggesting that economic development is associated with increased emissions. Although the contribution of RES is beneficial, its impact on reducing emissions is limited (the RES → CO_2 ratio was -0.060).

These results are confirmed in the literature. A study by Grodzicki and Jankiewicz (2022) revealed that an increase in the share of RES leads to reduced CO_2 emissions, especially in northern European countries where the share of renewables is highest. The study by Mongo *et al.* (2024) suggested that the effects of introducing eco-innovation, including RES development, can be observed only in the long run, whereas in the short term, there may be a rebound effect related to the costs of adapting to new technologies and a temporary increase in energy demand. Conversely, studies by Kinyar and Bothongo (2024) showed that investments in eco-innovation and renewable technologies in highly developed countries such as the UK have stronger effects in reducing emissions than in countries with lower levels of development.

It is also worth referring to the environmental Kuznets curve (EKC) hypothesis, which assumes an inverse relationship between economic growth and environmental degradation beyond a certain level of income per capita. The findings of this analysis are consistent with this hypothesis, particularly for countries with the highest GDP per capita. Research by Acaravci and Ozturk (2024) also confirmed this relationship for developed countries, where investments in environmentally friendly technologies contribute to CO_2 reductions. Similar conclusions can be drawn from a study by Mirziyoyeva and Salahodjaev (2023), who found that growth in GDP per capita has an inverted U-shaped correlation with CO_2 emissions. Countries with high levels of globalisation and GDP are effective in reducing emissions due to investment in renewable technologies and better access to the capital needed to implement them.

H2: Increasing the share of RES in the energy mix leads to a significant reduction in CO_2 emissions.

Table 2 shows the results of the analysis of the impact of the share of renewable energy sources (RES) on CO_2 emissions in different groups of European Union member states. The analysis was designed to verify whether an increase in the share of RES contributes to a significant reduction in CO_2 emissions. The results clearly indicate that increasing the share of RES in the energy mix leads to significant emission reductions in countries with higher levels of decarbonisation.

Table 2

Impact of energy efficiency on CO_2 emission reduction in EU member states

Group of states	RES → CO_2	RES	R^2 for CO_2
Highest RES share	-0.340	high	0.621
High RES share	-0.192	average	0.394
Average RES share	-0.319	average	0.525
Low RES share	-0.213	low	0.409
Lowest RES share	-0.060	lowest	0.341

Source: own study using SmartPLS4.

The results for countries with the highest RES share show that the path coefficient value for the RES → CO_2 relationship was -0.340, suggesting that high investments in renewables contribute to effective CO_2 reductions. In countries with a high RES share, such as Germany and Sweden, these results are confirmed in the literature, showing the effectiveness of investments in eco-innovation and renewable technologies in reducing emissions. A study by Zhang *et al.* (2024) found that Germany, due to its high RES share, is able to achieve significant CO_2 reductions, especially in the power sector (Zhang *et al.*, 2024).

In states with an average RES share, the value of the RES → CO_2 path coefficient was -0.319, which also indicates significant benefits associated with the development of renewable energy sources. However, it is worth noting that the impact of RES on emission reductions in states with low RES share is less significant (-0.213). A study by Soytas *et al.* (2007) suggested that for states with lower levels of economic development and a lower RES share, infrastructure and investment constraints may limit the effectiveness of pro-environmental efforts, resulting in a lower impact on CO_2 reductions (Soytas *et al.*, 2007).

The countries with the lowest RES share, as shown by the results of the analysis, reached only a minimal impact on CO_2 reduction (path coefficient -0.060). This may be due to the lack of adequate tools to promote investment in renewables and insufficient policy support. Zhang *et al.* (2024) indicate that the development of renewable energy sources requires strategic support policies and increased investment in innovation, which is crucial to achieving long-term reductions in emissions (Zhang *et al.*, 2024).

These conclusions are supported by the literature, where the benefits of increasing the share of RES in the energy mix are repeatedly highlighted. Studies on the transition to renewable energy sources in developed countries show that an increased RES share leads to improved environmental quality and reduced CO_2 emissions, especially in the long term (Acaravci & Ozturk, 2024). Similarly, studies by Zhang *et al.* (2024) and Soytas *et al.* (2007) indicated that opting for renewable energy sources plays a key role in reducing emissions in countries that have introduced appropriate support policies.

In conclusion, the verification of hypothesis 2 proved that increasing the share of RES does indeed lead to significant reductions in CO_2 emissions, but the impact varies depending on the level of economic development and the policies implemented by each state. States with higher RES shares and more advanced support policies, such as Germany, are able to achieve greater CO_2 reductions, confirming the rationale for further investment in renewable energy sources.

H3: Investment in research and development (R&D) has a greater impact on improving energy efficiency in countries where the share of renewable energy sources (RES) is low.

Table 3 presents the results of the analysis of the impact of research and development (R&D) investments on energy efficiency (EE) in European Union member states, taking into account different levels of renewable energy sources (RES) participation. These results show that in countries with a low RES share, R&D investments had the highest impact on improving energy efficiency. The value of the R&D → EE path coefficient was 0.412, and the R^2 value reached 0.517. This confirms that R&D investments in countries with a low RES share are crucial for modernising energy systems and introducing innovative technological solutions.

Table 3

Impact of investments in research and development (R&D) on energy efficiency in EU member states

Group of states	R&D → EE_avg	RSE share	R^2 for EE_avg
Highest RES share	0.178	high	0.423
High RES share	0.215	average	0.398
Average RES share	0.301	average	0.452
Low RES share	0.412	low	0.517
Lowest RES share	0.389	lowest	0.489

Source: own study using SmartPLS4.

States with the lowest RES share reached an R&D → EE path coefficient value of 0.389 and an R^2 value for energy efficiency of 0.489. This means that R&D investments in states with the lowest RES share also have a significant impact on improving energy efficiency, albeit slightly lower than in states with a slightly higher, but still low, RES share.

In states with higher RES shares, the value of the path coefficient was noticeably lower. For the groups of states with the highest RES share, this value was 0.178, indicating that R&D had a limited impact on energy efficiency. The R^2 value for energy efficiency in the states with the highest RES share was 0.423. This may suggest that in these states, energy efficiency is already at such a high level that additional R&D expenditures do not have a significant impact on reducing energy consumption. Instead, these countries mainly focus on optimising the use of existing technologies.

Similar conclusions are confirmed in the literature. A study by Shi *et al.* (2024) indicates that developing countries with higher investment in R&D perform better in terms of energy efficiency and have a greater capacity to upgrade their energy systems. In contrast, a study by Liu *et al.* (2024) showed that in highly developed countries, energy efficiency is at such a high level that additional investment in R&D does not translate to significant benefits in terms of reducing energy consumption.

In states with a low RES share, investment in R&D is crucial, especially in the context of modernising existing energy systems and introducing innovative technologies. Research by Sikder *et al.* (2024) also confirmed that investment in R&D is instrumental in improving energy efficiency in developing countries, which can help reduce dependence on fossil fuels.

A study by Zhu *et al.* (2024) showed that in states with high RES shares, sustainable development policies and investments in sustainable urbanisation are more effective than additional R&D investments. This is because these countries are already equipped with advanced technologies, and additional investments in R&D may produce fewer benefits.

H4: The link between urbanisation and CO_2 emissions and economic growth is determined by the level of economic development and the share of RES; a higher share of RES mitigates the negative effects of urbanisation.

Table 4 presents the results of the analysis of the impact of urbanisation (URB) on economic growth (EG) in different groups of European Union member states, taking into account the level of GDP per capita and the share of renewable

Table 4

Impact of urbanisation on economic growth in EU member states

Group of states	URB → EG	GDP per capita	RSE share	R^2 for EG_CST
Highest GDP per capita	0.432	high	high	0.498
High GDP per capita	0.284	high	average	0.276
Average GDP per capita	0.517	average	average	0.354
Low GDP per capita	0.205	low	low	0.319
Lowest GDP per capita	0.208	low	lowest	0.208

Source: own study using SmartPLS4.

energy sources (RES). These results reveal that the impact of urbanisation on economic growth varies according to the level of GDP and the share of RES.

States with an average level of GDP per capita achieved the highest impact of urbanisation on economic growth, with a URB → EG path coefficient value of 0.517 and an R^2 value of 0.354. This means that urbanisation in this group of states plays a central role in stimulating the economy, especially by improving access to services and infrastructure. These states benefit from urban development as an important factor in stimulating economic growth.

In states with the highest level of GDP per capita, the value of the path coefficient for the URB → EG relationship was 0.432, while the R^2 value reached 0.498. Although urbanisation still had a positive impact on economic growth, its importance was lower than in countries with average GDP. This may be due to the fact that urban infrastructure in developed countries is already advanced, which makes further urbanisation less significant as an economic driver. It can be assumed that investment is shifting to other areas, such as technological innovation.

In states with lower and the lowest levels of GDP per capita, urbanisation had a relatively weaker impact on economic growth, with URB → EG path coefficient values at 0.205 and 0.208, respectively. The R^2 value for these groups of states was 0.319 and 0.208, respectively, suggesting that urbanisation is not the main driver of the economy, with limited access to financial and infrastructural resources being a barrier to realising the full potential of urbanisation.

Similar findings are confirmed in the literature. A study by Zhang *et al.* (2024) indicated that in developed countries such as Germany and the US, the economic impact of urbanisation varies, depending on the level of technological development and policies supporting renewable energy sources. In countries with medium GDP, urbanisation contributed to increased economic activity, improving access to services and infrastructure. In contrast, in states with a high RES share, the development of green areas and sustainable urbanisation are more focused on reducing emissions rather than having a direct impact on economic growth.

A study carried out by Bakry *et al.* (2023) suggested that sustainable urbanisation policies and green financing can support economic development and CO_2 emission reductions, but their impact is limited in developing countries due to a lack of adequate financial and institutional resources. In addition, Ziaei (2025) suggested that in OECD countries, investment in energy innovation may be more effective in reducing emissions than developing urban infrastructure, which may also explain the lower impact of urbanisation on economic growth in high-GDP countries.

Summary of the Findings and Recommendations for EU Energy Policy

A study carried out among European Union states examined the impact of GDP and the share of renewable energy sources (RES) on CO_2 emissions, economic growth and energy efficiency using structural equation modelling (SEM). The use of RES and economic growth were found to be key factors shaping CO_2 emissions and had a significant impact on economic development and energy efficiency.

High GDP levels combined with high RES share were found to be the most effective in reducing CO_2 emissions. States with a developed economy and a high share of RES, such as Sweden, Finland and the Netherlands, saw significant reductions in emissions. This confirms the hypothesis of decoupling economic growth from CO_2 emissions. A study by Liddle and Parker (2024) suggested that countries with high GDP and advanced decarbonisation can effectively decouple economic growth from emissions.

RES share had a significant impact on CO_2 reductions in every group of states. Greater emission reductions were observed in the groups with the highest RES share, which is consistent with the findings of Wang *et al.* (2024) indicating the effectiveness of RES in decarbonisation, especially wind energy. In states with lower RES shares, the impact was lower, suggesting the need to intensify efforts to develop RES.

Energy efficiency had a different impact on CO_2 emissions depending on the country's GDP level. In states with high and average GDP, energy efficiency does not always lead to reduced CO_2 emissions, suggesting the presence of a rebound effect. This effect, described by Karakaya *et al.* (2024), involves the obtained energy savings being offset by increased consumption in other areas. Its presence has been confirmed in states with medium and low GDP, suggesting the need for more effective measures to minimise this phenomenon.

Urbanisation appeared to have a complex effect on CO_2 emissions and economic growth, depending on a state's level of economic development. In countries with higher GDP, urbanisation was managed more effectively, allowing emissions to be minimised. In contrast, in states at lower levels of development, urbanisation contributed to increased emissions, suggesting the need for better planning of urban infrastructure and integration of renewable energy sources.

The addition of the RES share criterion to the analysis substantially increased the value of the results compared to the analysis based on GDP alone. The analysis, including the RES share, showed a more pronounced impact on CO_2 reduction and economic growth, especially in the groups of states investing heavily in RES. Models that considered only GDP levels failed to fully capture the benefits of energy transition in states with high RES shares. For instance, in countries such as Sweden and Finland, the R^2 value for CO_2 emissions was much higher, indicating a better fitting of the model to explain emissions variability.

This suggests that RES can play a key role in the effective transformation of the economy, regardless of the level of economic development. This is further supported by the findings of Ben-Ahmed and Ben-Salha (2024), who observed that RESs significantly reduce CO_2 emissions.

Based on the findings of the analysis, the following recommendations are made to policymakers in the context of optimising EU energy policies:

1. Investment in RES: EU states should continue to invest heavily in the development of RES, such as wind, solar or biomass power. RES play a key role in reducing CO_2 emissions and contribute to economic growth, especially in countries characterised by high and average levels of development.

2. Reducing the rebound effect: Policies to reduce the rebound effect, such as regulating energy consumption and implementing advanced efficiency technologies, are necessary in countries with average and low GDP levels.

3. Sustainable urbanisation: For developing countries, urbanisation should be linked to the implementation of green technologies and RES. Urban planning needs to take environmental aspects into account in order to reduce the negative impact of urban development on CO_2 emissions.

4. Supporting the countries with low RES share: States with low RES shares need to receive financial and technological support to intensify their energy transition. Financial incentives, such as tax breaks or subsidies for RES investments, can significantly improve the energy situation of these states.

To build on the findings of the current study, future analyses should consider other factors affecting CO_2 emissions, economic growth and energy efficiency, such as geographical (e.g., climatic conditions) and political (e.g., level of environmental regulation) variables. Including these variables would provide a more complete picture of the impact of different aspects on the energy transition in different countries.

Furthermore, future studies could extend the analysis to include countries outside the European Union. This would allow a comparison of results between countries with different levels of economic development and at different stages of energy transition. This could be useful in understanding how external factors affect the efficiency of RES-related policies.

Translated by Joanna Jensen

References

Acaravci, A., & Ozturk, I. (2010). On the Relationship Between Energy Consumption, CO_2 Eemissions and Economic Growth in Europe. *Energy*, *35*(12), 5412-5420. https://doi.org/10.1016/j.energy.2010.07.009.

Amara, D., Qiao, J., & Zada, M. (2024). How to Reconcile the Climate Change Issue with Economic Growth? Spatial Dual Mediating Effects of Carbon Emissions and Foreign Investment. *Journal of Cleaner Production*, *411*. 137285. https://doi.org/10.1016/j.jclepro.2023.137285.

Apergis, N., & Payne, J.E. (2014). Renewable Energy, Output, CO_2 Emissions, and Fossil Fuel Prices in Central America: Evidence from a Nonlinear Panel Smooth Transition Vector Error Correction Model. *Energy Economics*, *42*, 226-232. https://doi.org/10.1016/j.eneco.2014.01.003.

Bakry, W., Mallik, G., Nghiem, X.-H., Sinha, A., & Vo, X.V. (2023). Is Green Finance Really "Green"? Examining the Long-Run Relationship Between Green Finance, Renewable Energy and Environmental Performance in Developing Countries. *Renewable Energy*, *208*, 341-355. https://doi.org/10.1016/j.renene.202.

Belaïd, F., & Mikayilov, J.I. (2024). Closing the Efficiency Gap: Insights Into Curbing the Direct Rebound Effect of Residential Electricity Consumption in Saudi Arabia. *Energy Economics*, *135*, 107647. https://doi.org/10.1016/j.eneco.2024.107647.

Ben-Ahmed, K., & Ben-Salha, O. (2024). Assessing the Spillover Effects of Various Forms of Energy on CO_2 Emissions – An Empirical Study Based on Dynamic Spatial Durbin Model. *Heliyon*, *10*(e31083). https://doi.org/10.1016/j.heliyon.2024.e31083.

Barkat, K., Alsamara, M., & Mimouni, K. (2024). Beyond Economic Growth Goals: Can Foreign Aid Mitigate Carbon Dioxide Emissions in Developing Countries? *Journal of Cleaner Production*, *471*, 143411. https://doi.org/10.1016/j.jclepro.2024.143411.

Bolat, C.K., Soytas, U., Akinoglu, B., & Nazlioglu, S. (2023). Is There a Macroeconomic Carbon Rebound Effect in EU ETS? *Energy Economics*, *125*, 106879. https://doi.org/10.1016/j.eneco.2023.106879.

Dissanayake, H., Perera, N., Abeykoon, S., Samson, D., Jayathilaka, R., & Jayasinghe, M. (2023). Nexus between Carbon Emissions, Energy Consumption, and Economic Growth: Evidence from Global Economies. *PLOS ONE*. https://doi.org/10.1371/journal.pone.0287579.

Dimitropoulos, J. (2007). Energy Productivity Improvements and the Rebound Effect: An Overview of the State of Knowledge. *Energy Policy*, *35*(12), 6354-6363. https://doi.org/10.1016/j.enpol.2007.07.028.

Dogan, E., & Inglesi-Lotz, R. (2024). Analyzing the Effects of Real Income and Biomass Energy Consumption on Carbon Dioxide (CO_2) Emissions: Empirical Evidence from the Panel of Biomass-Consuming Countries. *Energy*, *138*, 721-727. https://doi.org/10.1016/j.energy.2017.07.136.

Gershon, O., Asafo, J.K., Nyarko-Asomani, A., & Koranteng, E.F. (2024). Investigating the Nexus of Energy Consumption, Economic Growth and Carbon Emissions in Selected African Countries. *Energy Strategy Reviews*, *51*, 101269. https://doi.org/10.1016/j.esr.2023.101269.

Gbadeyan, O.J., Muthivhi, J., Linganiso, L.Z., & Deenadayalu, N. (2024). Decoupling Economic Growth from Carbon Emissions: A Transition Toward Low-Carbon Energy Systems – A Critical Review. *Clean Technologies*, *6*, 1076-1113. https://doi.org/10.3390/cleantechnol6030054.

Grodzicki, T., & Jankiewicz, M. (2022). The Impact of Renewable Energy and Urbanization on CO_2 Emissions in Europe: Spatio-Temporal Approach. *Environmental Development*, *44*, 100755. https://doi.org/10.1016/j.envdev.2022.100755.

Karakaya, E., Alataş, S., Erkara, E., Mert, B., Akdoğan, T., & Hiçyılmaz, B. (2024). The Rebound Effect of Material and Energy Efficiency for the EU and Its Major Trading Partners. *Energy Economics*, *134*, 107623. https://doi.org/10.1016/j.eneco.2024.107623.

Khan, M.K., Trinh, H.H., Ullah, I., & Ullah, S. (2022). Sustainable Economic Activities, Climate Change, and Carbon Risk: An International Evidence. *Environment, Development and Sustainability*, *24*, 9642-9664. https://doi.org/10.1007/s10668-021-01842-x.

Kinyar, A., & Bothongo, K. (2024). The Impact of Renewable Energy, Eco-Innovation, and GDP Growth on CO_2 Emissions: Pathways to the UK's Net Zero Target. *Journal of Environmental Management*, *368*, 122226. https://doi.org/10.1016/j.jenvman.2024.122226.

Liddle, B., & Parker, S. (2024). Another Look At 'Peak and Decline' Carbon Emissions Countries: Which Ones Have Decoupled Per Capita Emissions from GDP and How? *Global Environmental Change Advances*, *3*, 100012. https://doi.org/10.1016/j.gecadv.2024.100012.

Liu, H., Wong, W.-K., Cong, P.T., Nassani, A.A., Haffar, M., & Abu-Rumman, A. (2024). Linkage Among Urbanization, Energy Consumption, Economic Growth and Carbon Emissions. Panel Data Analysis for China Using ARDL Model. *Fuel*, *332*, 126122. https://doi.org/10.1016/j.fuel.2022.126122.

Lu, F., Ma, F., & Feng, L. (2024). Carbon Dioxide Emissions and Economic Growth: New Evidence from GDP Forecasting. *Technological Forecasting and Social Change*, *205*, 123464. https://doi.org/10.1016/j.techfore.2024.123464.

Matraeva, L., Vasiutina, E., Korolkova, N., Maloletko, A., & Kaurova, O. (2024). Identifying Rebound Effects and Formulating More Sustainable Energy Efficiency Policy: A Global Review and Framework. *Energy Research & Social Science*, *85*, 102402. https://doi.org/10.1016/j.erss.2021.102402.

Mehmood, U. (2021). Contribution of Renewable Energy Towards Environmental Quality: The Role of Education to Achieve Sustainable Development Goals in G11 Countries. *Renewable Energy*, *178*, 600-607. https://doi.org/10.1016/j.renene.2021.06.118.

Mongo, M., Belaïd, F., & Ramdani, B. (2024). The Effects of Environmental Innovations on CO_2 Emissions: Empirical Evidence from Europe. *Environmental Science & Policy*, *132*, 123-136. https://doi.org/10.1016/j.envsci.2024.12.004.

Mohsin, A.K.M., Gerschberger, M., Plasch, M., Ahmed, S.F., Rahman, A., & Rashed, M. (2024). Examining the Synergy of Green Supply Chain Practices, Circular Economy, and Economic Growth in Mitigating Carbon Emissions: Evidence from EU Countries. *Journal of Environmental Management*, *371*, 123109. https://doi.org/10.1016/j.jenvman.2024.123109.

Murshed, M., Apergis, N., Alam, M.S., Khan, U., & Mahmud, S. (2022). The Impacts of Renewable Energy, Financial Inclusivity, Globalization, Economic Growth, and Urbanization on Carbon Productivity: Evidence from Net Moderation and Mediation Effects of Energy Efficiency Gains. *Renewable Energy*, *196*, 824-838. https://doi.org/10.1016/j.renene.2022.07.012.

Naeem, M.A., Appiah, M., Taden, J., Amoasi, R., & Gyamfi, B.A. (2024). Transitioning to Clean Energy: Assessing the Impact of Renewable Energy, Bio-Capacity and Access to Clean Fuel on Carbon Emissions in OECD Economies. *Energy Economics*, *127*, 107091. https://doi.org/10.1016/j.eneco.2023.107091.

Naz, F., Tanveer, A., Karim, S., & Dowling, M. (2024). The Decoupling Dilemma: Examining Economic Growth and Carbon Emissions in Emerging Economic Blocs. *Energy Economics*, *138*, 107848. https://doi.org/10.1016/j.eneco.2024.107848.

Rajabi, M.M. (2022). Dilemmas of Energy Efficiency: A Systematic Review of the Rebound Effect and Attempts to Curb Energy Consumption. *Energy Research & Social Science*, *89*, 102661. https://doi.org/10.1016/j.erss.2022.102661.

Onofrei, M., Vatamanu, A.F., & Cigu, E. (2022). The Relationship Between Economic Growth and CO_2 Emissions in EU Countries: A Cointegration Analysis. *Frontiers in Environmental Science*, *10*, 934885. https://doi.org/10.3389/fenvs.2022.934885.

Qin, J., Ou, D., Yang, Z., Gao, X., Zhong, Y., Yang, W., Wu, J., Yang, Y., Xia, J., Liu, Y., Sun, J., & Deng, O. (2024). Synergizing Economic Growth and Carbon Emission Reduction in China: A Path to Coupling the MFLP and PLUS Models for Optimizing the Territorial Spatial Functional Pattern. *Science of the Total Environment*, *929*, 171926. https://doi.org/10.1016/j.scitotenv.2024.171926.

Quan, Z., Xu, X., Jiang, J., Wang, W., & Gao, S. (2024). Uncovering the Drivers of Ecological Footprints: A STIRPAT Analysis of Urbanization, Economic Growth, and Energy Sustainability in OECD Countries. *Journal of Cleaner Production*, *475*, 143686. https://doi.org/10.1016/j.jclepro.2024.143686.

Shi, B., Zhu, G., & Li, N. (2024). Does Economic Growth Targets Setting Lead to Carbon Emissions? An Empirical Study from China. *Journal of Environmental Management*, *368*, 122084. https://doi.org/10.1016/j.jenvman.2024.122084.

Sikder, M., Wang, C., Rahman, M.M., & Alola, A.A. (2024). Green Logistics and Circular Economy in Alleviating CO_2 Emissions: Does Waste Generation and GDP Growth Matter in EU Countries? *Journal of Cleaner Production*, *449*, 141708. https://doi.org/10.1016/j.jclepro.2024.141708.

Soytas, U., Sari, R., & Ewing, B.T. (2007). Energy Consumption, Income, and Carbon Emissions in the United States. *Ecological Economics*, *62*(4), 482-489. https://doi.org/10.1016/j.ecolecon.2006.07.009.

Sorrell, S., Dimitropoulos, J., & Sommerville, M. (2009). Empirical Estimates of the Direct Rebound Effect: A Review. *Energy Policy*, *37*(4), 1356-1371. https://doi.org/10.1016/j.enpol.2008.11.026.

Tian, J., Abbasi, K.R., Radulescu, M., Jaradat, M., & Barbulescu, M. (2024). Reevaluating Energy Progress: An In-Depth Policy Framework of Energy, Urbanization, and Economic Development. *Energy Policy*, *191*, 114196.

Tong, K. (2024). Urbanization Moderates the Transitional Linkages Between Energy Resource Use, Greenhouse Gas Emissions, Socio-Economic and Human Development: Insights from Subnational Analyses in China. *Journal of Cleaner Production*, *476*, 143776. https://doi.org/10.1016/j.jclepro.2024.143776.

Wang, Q., Guo, J., & Li, R. (2024). Better Renewable with Economic Growth without Carbon Growth: A Comparative Study of Impact of Turbine, Photovoltaics, and Hydropower on Economy and Carbon Emission. *Journal of Cleaner Production*, *426*, 139046. https://doi.org/10.1016/j.jclepro.2023.139046.

Wang, J.C., Qu, M., Xu, T.P., & Choi, S. (2024). The Dynamic Nexus Between Economic Growth, Renewable Energy Use, Urbanization, Industrialization, Tourism, Green Supply Chain Management, and CO_2. *Heliyon*, *10*(2024), e38061. https://doi.org/10.1016/j.heliyon.2024.e38061.

Yang, L., & Li, Z. (2024). Technology Advance and the Carbon Dioxide Emission in China: Empirical Research Based on the Rebound Effect. *Energy Policy*, *132*, 123-136. https://doi.org/10.1016/j.enpol.2024.11.020.

Zhang, Z., Karimi, M.S., Weerasinghe, N.M., Bilan, Y., & Shahzad, U. (2024). Interplay Between Economic Progress, Carbon Emissions and Energy Prices on Green Energy Adoption: Evidence from USA and Germany. *Renewable Energy*, *232*, 121038. https://doi.org/10.1016/j.renene.2024.121038.

Ziaei, S.M. (2025). Public Spending on Energy Innovations and CO_2 Impacts: Evidence from Selected OECD Countries. *Green Technologies and Sustainability*, *3*, 100137. https://doi.org/10.1016/j.grets.2024.100137.

Zhang, Y., & Yang, Y. (2024). Can the Resource and Environmental Dilemma Due to Water-Energy-Carbon Constraints Be Solved in the Process of New Urbanization? *Sustainable Cities and Society*, *114*, 105748. https://doi.org/10.1016/j.scs.2024.105748.

Zhu, H., Yue, J., & Wang, H. (2024). Will China's Urbanization Support Its Carbon Peak Goal? A Forecast Analysis Based on the Improved GCAM. *Ecological Indicators*, *163*, 112072. https://doi.org/10.1016/j.ecolind.2024.112072.