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DIVERGING PATHS IN ENVIRONMENTAL PERFORMANCE: A COMPARATIVE ANALYSIS OF INNOVATION, GROWTH AND RENEWABLE ENERGY IN OECD AND BRICS COUNTRIES

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ABSTRACT:

Combating global climate change requires urgent and differentiated strategies to reduce carbon dioxide (CO_2) emissions. The environmental performance trajectories of developed (OECD) and emerging (BRICS) economies represent a critical area of research, as they account for a significant portion of global emissions. This study aims to comparatively analyze the key determinants of CO_2 emissions in OECD and BRICS countries, focusing on 2021, which reflects the unique conditions brought about by the post-COVID-19 economic recovery. Using 2021 data obtained from the World Bank, a cross-sectional "snapshot" analysis was conducted using multiple regression methods. In the model, the dependent variable is total CO_2 emissions (kt); the independent variables are defined as 'renewable energy consumption', 'GDP', 'urbanization', and 'total patent applications' (innovation proxy). Empirical findings confirm that renewable energy consumption has a statistically significant and negative effect on CO_2 emissions. In contrast, GDP and urbanization were found to have a positive effect on emissions. It is noteworthy that innovation, measured by 'total patent applications', shows a weak or statistically insignificant effect on emission reduction. The study contributes to the literature by presenting an analysis of a critical period such as 2021 and highlighting the structural differences between the OECD and BRICS blocs. The results indicate that emission reduction policies should be designed according to countries' levels of development and the specificity of their innovation policies (specifically targeting green technologies), rather than a "one-size-fits-all" approach.

Keywords: CO_2 Emissions, Green Innovation, Renewable Energy, Environmental Performance, Multiple Regression, OECD and BRICS.

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Research Paper

1. INTRODUCTION

In recent years, the acceleration of globalization, industrialization, and urbanization has led to a sharp increase in global energy demand and carbon dioxide (CO_2) emissions. A particularly large portion of these emissions originate from a limited number of economies that combine high income, production, and trade integration with significant energy consumption. OECD and BRICS countries account for a large share of global GDP, population, and primary energy use, and therefore occupy a central position in the global carbon budget. At the same time, these countries exhibit heterogeneous development paths. OECD members are generally characterized by mature industrial structures, high urbanization rates, and stricter environmental regulations, while BRICS economies have experienced rapid economic and demographic growth, often accompanied by energy-intensive industrialization and expanding urban agglomerations. This structure makes joint analysis of the OECD and BRICS crucial for understanding the drivers of global CO_2 emissions and the possibilities for low-carbon transitions.

Sustaining economic growth alongside industrialization has become a priority at the global level; however, this process has also brought significant externalities, such as environmental degradation and, in particular, increased CO_2 emissions. OECD countries have long accounted for a large share of global emissions due to their high energy consumption and production volumes. On the other hand, BRICS countries have also attracted attention in recent years with their rapidly growing economies, increasing populations, and energy demand, making them central actors in global climate change discussions. Indeed, although per capita carbon emissions in BRICS countries are relatively low, the environmental impact of these countries is increasing in terms of total volume. Therefore, examining the effects of economic growth, energy structure, and technological developments on CO_2 emissions in OECD and BRICS countries is critically important in terms of both environmental sustainability and policy-making. In this context, the question of whether variables such as the shift towards renewable energy sources and innovation capacity, measured by the number of patents, have a carbon emission-reducing effect is current and important (Setyadharma et al., 2024; Van & Sadradin, 2021).

The complex relationship between environmental performance, economic growth, urbanization, and energy consumption has been extensively examined in the econometric literature. In this field, renewable energy consumption and technological innovation are often highlighted as fundamental strategies for reducing CO_2 emissions. Empirical findings consistently support the role of renewable energy in reducing emissions, while the net effect of technological innovation shows significant uncertainty, largely depending on how innovation is measured (Dialchiev et al., 2023; Rainville et al., 2025; Sahoo et al., 2022; Van & Sadradin, 2021). For example, a panel cointegration analysis covering 37 OECD countries (1990–2019) reached the paradoxical conclusion that technological developments significantly increased CO_2 emissions when using "total number of patents" as an innovation indicator (Van & Sadradin, 2021). Similarly, another study on 14 developing Asian countries, despite using the more specific "environmental technology patents," found that these innovations played only a "modest role" in reducing emissions and that their effects were conditional on being supported by economic growth (Sahoo et al., 2022). These conflicting findings highlight the critical methodological weaknesses of patent indicators used in empirical analyses. Indeed, recent methodological studies comparing patent classification systems have shown that "green patent" systems that specifically label technologies combating climate change (such as the Cooperative Patent Classification- CPC Y02 class) provide a superior measure that is more comprehensive, detailed, and carries a lower risk of misclassification compared to general inventories (Rainville et al., 2025).

Climate change is an urgent global issue due to the continued increase in greenhouse gas emissions. The Intergovernmental Panel on Climate Change (IPCC) emphasizes that rapid and deep cuts in CO_2 emissions are necessary to achieve international targets. For example, roadmaps limiting warming to 1.5°C project a 35-51% reduction in CO_2 emissions from the energy system by 2030 and an 87-97% reduction by 2050. Achieving these targets requires a rapid transition to low-carbon technologies. Scenarios limiting warming to 2°C project that low-carbon sources will provide approximately 93-97% of global electricity by 2050 (Clarke et al., 2022). Technological innovation and renewable energy use are considered critical drivers of this transition. Indeed, while the IPCC notes that breakthroughs such as the widespread adoption of solar photovoltaics and LEDs would not be possible without focused innovation efforts, it also warns that innovation alone, if not guided by robust policies, could create undesirable “backlash” effects (Blanco et al., 2022).

In this context, OECD and BRICS countries require special attention. The five BRICS countries (Brazil, Russia, India, China, South Africa) currently account for approximately 42% of global CO_2 emissions due to rapid industrialization and intensive fossil fuel use (Erkılıç et al., 2025). OECD members, representing advanced economies, have historically contributed significantly to emissions but are also pioneers in clean technology research and applications. Analyzing these two blocs together allows us to understand their different levels of economic development and policy environments. For example, Iranmanesh (2025) found that OECD and BRICS financial markets are largely unintegrated and that there is no overall convergence due to differences in infrastructure, economic size, and regulatory factors (Iranmanesh, 2025). This implies that innovation systems and investment models are similarly differentiated. Nevertheless, most empirical research treats the OECD and BRICS separately. Studies either examine innovation–emission dynamics in OECD samples (e.g., Saqib et al., 2023) or individual BRICS countries; the number of studies directly comparing these two groups is quite limited. This study aims to fill this gap with a cross-sectional analysis focusing on 2021, which coincides with the post-COVID-19 recovery process. This year provides a unique context for understanding energy use and the innovation-emissions relationship.

Analyzing data from 2021, this study provides a global “snapshot” of the conditions that emerged after the initial shocks of COVID-19. 2021 was the first full year of recovery from the pandemic and was characterized by unique policy changes and challenges. Cross-sectional analyses provide “snapshot insights” into the composition of the population during this period, contributing to an understanding of the period's specific conditions (Wang & Cheng, 2020). For instance, the global distribution of vaccines in 2021 marked a significant turning point; however, Klobucista and Merrow (2021) noted that "persistent pressures on health systems" continued to prevail. Notably, the global economy was projected to grow by 5.9% in 2021 (following the sharp contraction in 2020), revealing that 2021 was a year of uneven recovery (IMF, 2021). This situation has also led to a noticeable rebound in global CO_2 emissions. Following the historic decline in 2020, 2021 is a critical turning point in understanding how the structural relationship between growth (ln_GDP) and emissions (ln_CO_2) is being reestablished. Furthermore, 2021 is the year when many countries began implementing their “Green Recovery” policies. In this context, concentrating on a single year allows for the evaluation, within the most current framework, of whether the new policy commitments have a measurable effect on "green sustainability" (Renewable) and "innovation" (ln_Patent). The single-year analysis approach ensures that the findings reflect these urgent phenomena (and are not overshadowed by pre- or post-pandemic changes) (Wang & Cheng, 2020; Yacoubian et al., 2025). Although this approach cannot directly track changes over time, it provides policymakers with a clear picture of the conditions in 2021.

2. THEORETICAL FRAMEWORK

Fundamental debates in environmental economics offer various theoretical frameworks aimed at explaining the complex relationship between economic activities and environmental degradation.

The Environmental Kuznets Curve (EKC) assumes an inverted U-shaped relationship between per capita income and environmental degradation. Inspired by Kuznets' income inequality curve, Grossman and Krueger (1991) and Panayotou (1997) argued that as economies grow, pollution first increases (scale effect) and then decreases after a certain income threshold is crossed (due to composition and technology effects). In other words, low-income growth increases pressure on the environment, but higher income eventually reverses this trend by encouraging cleaner technologies and demand for environmental quality (Bousnina et al., 2025; Ertaş & Uysal, 2014). The inverse U-shaped relationship between per capita income and environmental pollution is generally explained through three fundamental mechanisms: economies of scale, structural change, and technological development. When income levels are low, economic growth intensifies environmental pressures by increasing production volume; this process is defined as economies of scale and explains the rising part of the curve. However, once income levels exceed a certain threshold, the economy's structure shifts toward less polluting sectors (structural effect), and cleaner production techniques and environmentally friendly technologies become more widespread (technology effect). This transformation leads to a decrease in environmental degradation and forms the descending part of the curve (Ertaş & Uysal, 2014, p. 7).

In recent literature, this approach has been frequently tested in the context of CO_2 emissions in both developed and developing countries. For example, (Mirziyoyeva & Salahojaev, 2023) provide a detailed theoretical definition of the EKC in one study, while (Bousnina et al., 2025) examine the relationship between economic growth and carbon emissions from an EKC perspective in another study. Similarly, another study (Gieraltowska et al., 2022) analyzes different dimensions of this relationship through the variables of industrialization and energy consumption. However, empirical findings vary from country to country and depending on the methods used, which makes the universal validity of the ECF hypothesis debatable.

The Porter Hypothesis (PH) argues that well-designed, stringent environmental regulations can encourage innovations that offset compliance costs and even enhance competitive advantage. Michael Porter (1991) and Porter and van der Linde (1995) argued that strict but flexible regulations encourage firms to discover cost-saving clean technologies (an innovation trade-off) and thus the overall effect can be win-win. Porter and van der Linde describe this as a proactive environmental strategy that leads to increased profits in the long term despite short-term costs (Akdemir Ömür, 2021).

According to Porter and van der Linde, there is a multifaceted mechanism that explains how environmental regulations encourage innovation. According to this view, regulations primarily serve as a signal that reveals existing resource inefficiencies and potential technological opportunities for companies. This increased institutional awareness, driven by knowledge-based regulations, combines with a guarantee that reduces uncertainty about the future value of investments. The pressure created by regulations motivates firms to innovate while also triggering an industry-wide transformation on a level playing field by creating equal conditions for all competitors. However, the authors also acknowledge that these innovations may not always fully offset compliance costs in the short term (especially before learning curve costs are reduced) (Ambec et al., 2010).

There are different approaches in the literature that classify the Porter Hypothesis (PH).

In particular, the widely accepted typology developed by Jaffe and Palmer (1997) divides this theory into three main versions: weak, strong, and narrow. The weak Porter Hypothesis argues that environmental regulations encourage firms (especially green ones) to innovate, but it does not concern itself with whether this innovation results in a net economic gain. The focus is on the trigger effect of regulation on innovation.

The Strong Porter Hypothesis, on the other hand, makes a more assertive claim. The innovation triggered by regulations more than offsets compliance costs, providing the firm with a net competitive advantage and profitability; this is a true "win-win" scenario.

Finally, the Narrow Porter Hypothesis focuses on the type of regulation. According to this view, flexible, market-based policies (e.g., pollution taxes or emissions trading permits) are much more powerful and effective in encouraging innovation than rigid command-and-control rules. These theoretical distinctions are critical in determining which hypothesis (innovation incentives or net profitability) empirical tests target (Zhang et al., 2024).

Despite the optimistic "win-win" expectation of the Porter Hypothesis, the assumption that innovation will always be 'green' is theoretically debatable. At this point, the Directed Technical Change (DTC) theory offers a critical perspective.

This theory, developed by Acemoglu, formalizes that innovation is not random but is driven by economic factors. According to the model, the 'price effect' directs R&D towards inputs such as scarce resources that become more expensive, while the market size effect favors sectors with larger outputs (such as the still dominant fossil fuel sector). In short, the DTC theory implies that policies (taxes, subsidies) and relative factor supply can actively steer innovation toward dirty or clean directions (Acemoglu, 2002).

In an environmental context, Acemoglu et al. (2012) extend the model to dirty (fossil fuel-based) and clean (renewable) technologies, showing that when left to its own devices (if dirty technology is more profitable), the market can lock innovation into the dirty direction. They argue that active policy interventions, such as carbon taxes and green R&D subsidies, are necessary to break this lock and redirect innovation toward clean inputs.

This theoretical framework is directly related to the empirical findings of this study. If dirty technologies are still more profitable than clean technologies in the sample of OECD and BRICS countries, firms will direct their innovation efforts (ln_Patent) towards the "gray" area, as predicted by DTC theory. This situation provides a theoretically strong explanation for why a general innovation indicator such as total patents could have a positive (+) effect on CO_2 emissions (ln_CO_2).

Gray innovation refers to innovations that increase the efficiency of existing (dirty) technologies rather than developing entirely new clean technologies. In low-carbon innovation research, academics distinguish between 'clean' innovations (new renewable or zero-carbon technologies) and 'gray' innovations, which are incremental improvements in the energy efficiency or pollution reduction of existing industrial processes. For example, Yan et al. (2017), by categorizing patented low-carbon technologies into clean and gray categories, found that clean innovations significantly reduce CO_2 emissions, while gray innovations have an uncertain effect. They explain this with rebound effects: increases in energy efficiency (gray innovation) lower the effective price of energy and may encourage greater use, partially offsetting the direct savings (Yan et al., 2017).

The rebound effect (or "recovery" effect) describes the phenomenon where improvements in energy efficiency typically result in less-than-expected reductions in energy use. This is because the saved resources are partially recovered through increased consumption. In other words, more efficient devices or vehicles reduce the cost of energy services, so consumers use them more (like driving longer distances when gasoline is cheaper). This idea dates back to Jevons (1865), who warned that increases in coal efficiency could backfire and increase coal use. Khazzoom (1980) and Brookes (1990) later applied this idea to modern economies. They argued that overall efficiency gains could increase total energy consumption at the macro level (the Khazzoom–Brookes paradox) (Gillingham et al., 2015).

The modern literature classifies the rebound effect as follows:

Direct rebound: A sudden increase in usage due to the cheapening of energy services (e.g., increased car usage after purchasing a fuel-efficient model). Efficiency increases demand by lowering the implicit price of energy services.

Indirect rebound: Additional consumption of other goods thanks to the income saved (e.g., taking a plane trip with the money saved on fuel). Increases in efficiency raise real income, and part of this income is spent again on goods whose production requires energy.

Macroeconomic feedback: The sum of direct and indirect effects across the economy. This includes macroeconomic price adjustments and growth effects. In the overall balance, efficiency can increase overall economic growth and energy demand, making macroeconomic feedback significant (Kavaz, 2023).

Finally, the Energy Substitution Hypothesis proposes that the widespread adoption of renewable energy will replace fossil fuel use and thus reduce carbon emissions. In other words, as economies shift from non-renewable to renewable sources, the carbon intensity of energy decreases. Replacing fossil fuels with renewable energy sources reduces humanity's ecological footprint (Kılınç, 2023). In practice, most econometric studies empirically demonstrate that renewable energy consumption has a reducing effect on CO_2 emissions, while fossil fuel consumption increases emissions (Shafiei & Salim, 2014; Bölük & Mert, 2014). This substitution effect is the 'technology effect' mechanism of the Environmental Kuznets phenomenon (Panayotou, 1997). At higher stages of development, economies invest in clean energy and reduce emissions by eliminating dirty inputs (Jie and Khan, 2024).

3. PREVIOUS EMPIRICAL STUDIES

The effects of economic growth (GDP), technological innovation (ln_Patent), and energy consumption (Renewable) on CO_2 emissions have been examined in considerable detail and comprehensively in the sustainability literature within the context of the Environmental Kuznets Curve (EKC), Porter's Hypothesis, or Energy Substitution theories. In this context, the main objective of this study is to analyze the combined effect of renewable energy consumption as a 'green sustainability' indicator and patent applications as a 'green innovation' indicator on environmental performance (ln_CO2) under the control variables of economic growth and urbanization (Urban). Despite the intense interest in these topics in the literature and the numerous empirical studies on the determinants of CO_2 emissions, there is a lack of research that simultaneously addresses the dynamics of both developed (OECD) and emerging (BRICS) economies, which represent a very large portion of the global economy and emissions, and examine the simultaneous effect of this specific set of variables (innovation, renewable energy, and growth) in this mixed group of countries (OECD+BRICS). This study aims to fill this gap using 2021 cross-sectional data.

Alam (2024) identified cointegration between CO_2, GDP per capita, GDP per capita squared, and energy consumption per capita using panel data for 24 OECD countries for the period 1971–2016 and found an inverse U-shaped relationship between income per capita and CO_2 based on Fully Modified Least Squares model estimates. The study confirmed the EKC hypothesis. Muratoğlu et al. (2024) tested the EKC for 38 OECD countries for the period 1990–2022 in four sectors—agriculture, industry, manufacturing, and services—using a panel nonlinear ARDL (PNARDL) model. The analysis revealed that the validity of the EKC varies across sectors, with the EKC being proven correct in all sectors except the industrial sector. Akar et al. (2025) examined the impact of economic growth and energy consumption on carbon emissions in OECD countries and some late-industrialized Asian economies between 1990 and 2020. The analysis, conducted using advanced panel methods, found a significant inverse-U relationship between per capita income and CO_2 for OECD countries, concluding that the EKC is valid for OECD countries but not for other late-developing Asian countries. Again, this study found a unidirectional causality from economic growth to emissions and energy consumption.

Furthermore, Kasperowicz (2015), in his study covering the years 1995-2012 and performing panel data analysis on 18 EU member countries, confirmed that while there is a negative relationship between GDP and CO_2 in the long term, there is a positive relationship in the short term. Alam et al. (2016), in their study covering the period 1970-2012 and the countries of India, Indonesia, China, and Brazil, found that CO_2 emissions increased with rising income and energy consumption in these four countries and that there was a positive relationship. Naimoğlu and Özbek (2022), in their study covering the period 1990-2019 for Turkey, confirmed that the EKC is valid for Turkey in both the short and long term.

Konya (2022) tested the existence of the EKC for 10 developing country economies using panel data models for the period 1992-2014. No clear result was obtained regarding the relationship between carbon emissions and economic growth in terms of the EKC. Ridzuan et al. (2022) conducted research using the ARDL approach with a data set covering the years 1971-2019 to test the CEC for Malaysia, a BRICS member country. The analysis found that in the short term, there is an inverted U-shaped CEC, while in the long term, there is a U-shaped CEC. Nica et al. (2025) examined the dynamic relationship between economic growth, technological innovation, and carbon emissions in BRICS countries during the period 1991-2023 within the scope of the EKC. The results confirmed the EKC hypothesis, showing that there is an N-shaped relationship between GDP and carbon emissions, i.e., there are two different turning points.

Cheng et al. (2021) used panel quantile regression for 35 OECD countries for the period 1996–2015 and found that innovation directly reduces CO_2 emissions, but the effect is heterogeneous across countries and upper quantiles of the distribution. Similarly, Saqib et al. (2023) reported that patent development reduces CO_2 using panel quantile analysis for 32 OECD countries (1996–2020). They also found that the effect varied across quantiles. In contrast, Van and Sadradin (2022) applied panel regression (including unit root tests such as CADF and ADF) in the OECD and concluded that patent development increased CO_2 emissions. Haq et al. (2024) found that an increase in intellectual capital significantly reduced CO_2 emissions in the OECD, whereas no similar reduction effect was observed in the BRICS countries. Studies conducted for BRICS countries (Brazil, Russia, India, China, South Africa) similarly use patent counts, R&D, and "green innovation" indicators. The findings are heterogeneous from the OECD. Haq et al. (2024) could not detect a significant CO_2 reducing effect of intellectual capital for BRICS. Xiaoyang et al. (2022), however, using a two-stage least squares and GMM (Panel Generalized Method of Moments) analysis on a panel of 36 OECD + 5 BRICS countries (2005–2018), found that innovation and R&D expenditures are positively related to CO_2 emissions, meaning that as innovation increases, so do emissions. On the other hand, Qamruzzaman et al. (2025) reported that technological and environmental innovations significantly reduced carbon emissions for BRICS countries (1995–2023) using panel ARDL analysis. Similarly, Mehta et al. (2025) used annual panel data for BRICS countries from 2000 to 2024 and found that an increase in technological innovation and renewable energy integration would lead to a reduction in emissions.

Empirical studies conducted for OECD countries generally emphasize the reducing effect of renewable energy consumption on CO_2 emissions. For example, Işık et al. (2024), using panel data from 27 OECD countries (2001–2020) in their quantile regression analysis, found a negative relationship between renewable energy consumption and CO_2 emissions; that is, they showed that renewable energy use has a reduction effect on emissions. Mirziyoyeva and Salahodjaev (2023), in their study examining the 50 most global countries, also found that an increase in renewable energy use reduces carbon emissions. The study found that a 1-point increase in the share of renewable energy in total energy consumption led to a 0.26 reduction in per capita carbon emissions. Setyadharma et al. (2024), using data from 1992-2020, found that a 1% increase in renewable energy use in BRICS countries resulted in a 0.029% reduction in CO_2. Sahoo et al. (2022), in an analysis using data from 14 developing countries in Asia between 1990 and 2018, found that renewable energy consumption and globalization play an important role in reducing carbon emissions. Similarly, Van and Sadradin (2021), using data from 37 OECD countries between 1990 and 2019, found that renewable energy reduces carbon emissions. Gieraltowska et al. (2022), in their study using data from 163 countries between 2000 and 2016, concluded that renewable energy consumption reduces carbon emissions and that there is an inverse U-shaped relationship between urbanization and carbon emissions.

There are conflicting findings in the literature regarding the effect of urbanization on carbon emissions. While there are findings that urbanization increases or decreases carbon emissions, there are also findings that its effect is limited. Voumik and Sultana (2022) showed in their CS-ARDL panel analysis that the urbanization rate increases environmental degradation (and therefore CO_2 emissions) in BRICS countries. On the other hand, Ma and Ogata (2024) concluded that urbanization reduces emissions in a group of developing countries including BRICS members. Furthermore, Vo et al. (2022) found that urbanization has a limited effect on carbon emissions in OECD countries. In summary, this empirical literature review reveals a lively and complex academic debate surrounding the key variables of our study (growth, innovation, renewable energy, and urbanization). In particular, theoretical and empirical uncertainties regarding the effects of innovation (green or gray) and growth (does the EKC hold?) increase the importance of the empirical test this study will conduct for the OECD and BRICS mixed group.

4. METHODOLOGY

In this study, the following Multiple Linear Regression model was established to test the relationship between the factors discussed in the Theoretical Framework (Growth, Innovation, Renewable Energy, and Urbanization) and environmental performance (CO_2).

$$\ln(CO_2)_i=\beta 0+\beta 1\ln(GDP)_i+\beta 2\ln(Patent)_i+\beta 3 Renewable_i+\beta 4 Urban_i+\varepsilon_i$$

Here, i represents each country, β0 is the constant term, β1….β4 are the coefficients, and ε is the error term.

The natural logarithm (ln) transformation was applied to the CO_2, GDP, and Patent variables included in the model. This transformation has two main purposes (Gujarati & Porter, 2009; Wooldridge, 2015).

Statistical Reason (Data Normalization): These variables (GDP, emissions, and patent counts) exhibit very large-scale differences (outliers) across countries and tend to have a right-skewed distribution. The logarithmic transformation 'normalizes' the distribution of the data by softening the disproportionate effect of these extreme values on the regression results and ensures better compliance with OLS regression assumptions (particularly the normality of the error terms).

Reason for Interpretation (Flexibility): More importantly, the logarithmic transformation allows us to interpret the relationship between variables in ‘percentages’ rather than ‘units’ (e.g., dollars, tons). Thus, the coefficient of (for example) ln_GDP on ln_CO_2 can be interpreted as an elasticity coefficient showing how much a 1% increase in GDP changes CO_2 emissions. This provides a much more meaningful and powerful result for economic analysis.

In this study, 2021 was selected as the cross-sectional data year for analysis. Two main factors played a role in selecting this date. First, 2021 is the most complete and up-to-date data set (covering OECD and BRICS countries) for all five variables used in the study.

Second, and more importantly, 2020, the peak year of the COVID-19 pandemic, was considered an outlier year due to artificial declines in GDP and CO_2 emissions caused by global lockdowns. In order to analyze the structural relationship between the variables more accurately, data from 2021, when economic recovery began and the ‘new normal’ emerged, was preferred. In the 2021 data, missing data was found for only one country (Ethiopia), and this country was excluded from the analysis, resulting in a final sample size of n=47.

All data required for the variables examined in the study were obtained from the World Bank (World Bank World Development Indicators) database. The sample for the study consists of OECD and BRICS countries. These two country groups were selected for the study because they play a key role in the global economy and emissions and also have different positions and characteristics.

In this study, which examines the effects of country GDP, innovation, renewable energy, and urbanization on carbon emissions in OECD and BRICS countries, carbon emissions (ln_CO_2) are the dependent variable. GDP (ln_GDP), established patent applications (ln_Patent), which we define as innovation, renewable energy consumption (Renewable), and urbanization (Urban) are the independent variables. The expected results of the study are as follows:

As economic size (GDP) increases, production and consumption increase, which in turn increases carbon emissions (ln_CO_2).

H_1: There is a statistically significant and positive relationship between economic growth (ln_GDP) and carbon emissions (ln_CO_2).

H_2: As discussed in detail in the “Theoretical Framework” section of the study, the effect of innovation on CO_2 emissions constitutes one of the most important theoretical conflicts in the literature. Therefore, two competing hypotheses have been developed for this variable:

Hypothesis 2a: Porter Hypothesis (Green Innovation Effect)

According to this optimistic view (Porter & van der Linde, 1995), well-designed policies trigger innovation. This “eco-innovation” (green innovation) increases firms' resource efficiency, cleans up production processes, and reduces net CO_2 emissions.

H_{2a}: An increase in innovation capacity (ln_Patent) has a statistically significant and negative (-) (reducing) effect on CO_2 emissions (ln_CO_2).

Hypothesis 2b: Gray Innovation / Backlash Effect

According to an alternative (and more realistic) view, a general indicator such as ‘total patents’ may reflect ‘gray’ innovation (i.e., innovations that increase efficiency or consumption in dirty technologies) rather than ‘green’ innovation (Directed Technological Change theory; Acemoglu et al., 2012). Furthermore, efficiency gains can increase total consumption and thus emissions by creating a “Rebound Effect” (Sorrell, 2007).

H_{2b}: An increase in innovation capacity (ln_Patent) has a statistically significant and positive (+) (incremental) effect on CO_2 emissions (ln_CO_2).

H_3: An increase in the renewable energy consumption rate (Renewable) has a statistically significant and negative effect on carbon emissions (ln_CO_2).

The effect of urbanization on carbon emissions has different findings, as discussed earlier. There are two opposing views on the impact of urbanization on carbon emissions: the efficiency effect and the agglomeration effect (Voumik & Sultana, 2022; Ma & Ogata, 2024). Accordingly, two different hypotheses have been developed for the urbanization variable.

According to the Concentration Effect, urbanization leads to the geographical concentration of industrial activities, energy consumption, transportation networks, and consumption patterns. This “scale effect” increases environmental pressure (Voumik & Sultana, 2022).

H_{4a}: There is a statistically significant and positive relationship between the urbanization rate (Urban) and carbon emissions (ln_CO_2).

According to the Efficiency Effect, urbanization is a factor that increases resource efficiency. High population density facilitates the development of lower-carbon infrastructure, such as public transportation, more efficient heating/cooling systems (apartments), and an economy based on the service sector (Ma & Ogata, 2024).

H_{4b}: There is a statistically significant and negative relationship between the urbanization rate (Urban) and carbon emissions (ln_CO_2).

To estimate the parameters of the model established in this study (**β_1,β_2, β_3, β_4)**, a "Multiple Linear Regression" analysis based on the "Least Squares" (LS) method was performed. The ability of this method to produce reliable and unbiased results depends on the model meeting basic econometric assumptions. Therefore, along with the main regression analysis, a series of diagnostic tests were applied to test the statistical validity of the model.

First, the issue of "multicollinearity" was examined to measure the risk of high correlation between the independent variables. The correlation analysis, as expected, showed a high positive relationship (r = .894) between the ln_GDP and ln_Patent variables. To test whether this situation caused a bias in the OLS estimates, the VIF (Variance Inflation Factor) values, which are a more reliable indicator, were examined. As reported in the "Findings" section, the VIF values of all variables (e.g., ln_GDP=5.466, ln_Patent=5.109) were found to be below the critical threshold of 10 accepted in the literature. This confirms that there is no serious multicollinearity problem in the model.

Second, to test the assumption of constant variance (homoscedasticity), one of the OLS assumptions, the "Heteroscedasticity" (varying variance) situation was examined. This test was visually examined using a scatterplot plotting the standardized residuals (*ZRESID) against the standardized estimated values (*ZPRED). The graph presented in the "Findings" section shows that there is no distinct 'funnel' structure and that the residuals are distributed in a random "cloud" shape, indicating that this assumption is met.

Finally, the "Normality of Residuals" assumption was tested using the Histogram and Normal P-P Plot of the regression residuals. As will be shown in the "Findings" section, the close clustering of observations around the 45-degree diagonal line in the P-P plot and the reasonable fit of the histogram to a bell curve confirm that the normality assumption is also satisfied.

5. FINDINGS

This section presents the results of the econometric analyses conducted for the research model and their interpretation in light of the theoretical framework.

Table 1. Descriptive Statistics

Variable	N	Minimum	Maximum	Mean	Std. Deviation
Renewable	47	0.10	82.40	22.94	17.26
Urban	47	35.39	98.12	76.89	13.34
ln_CO_2	47	1.17	9.44	4.89	1.80
ln_Patent	47	2.71	14.17	7.38	2.49
ln_GDP	47	23.97	30.80	27.08	1.51

Table 1 confirms that the analysis covers the entire final sample of n=47 countries and that there is no missing data in the variables. According to 2021 data, the average renewable energy consumption rate (Renewable) of the sample consisting of OECD and BRICS countries is 22.94%, while the average urbanization rate (Urban) is 76.89%. The findings in the table reveal that the sample has a highly heterogeneous (diverse) structure.

This is critically important in terms of providing the variation necessary for regression analysis. For example, renewable energy consumption ranges from a very low value of 0.1% (almost entirely dependent on fossil fuels) to a very high value of 82.4% (providing most of its energy from renewable sources). Similarly, the high standard deviation values in the ln_CO_2 (Min: 1.17, Max: 9.44) and ln_Patent (Min: 2.70, Max: 14.17) variables confirm how different the countries in the sample are in terms of environmental performance and innovation capacity.

Before running the main regression model, a Pearson Correlation Matrix was created to examine the bivariate relationships between the independent variables and identify potential multicollinearity issues. Table 2 shows the correlation coefficients between the four independent variables.

The results presented in Table 2 below reveal two main findings:

First, the Renewable variable has a statistically significant and negative correlation with ln_Patent ($r = -.367$, $p < .05$) and ln_GDP ($r = -.429$, $p < .01$). This finding provides a preliminary indication that wealthier and more innovative countries (at least as of 2021) may be *less* dependent on renewable energy (or that their fossil fuel consumption is still very high). Correlations between other variables (such as Urban and Renewable or Urban and ln_Patent) are statistically insignificant and quite low.

The second and most critical finding from a methodological perspective is the very high and strong positive correlation between the variables ln_Patent (Innovation) and ln_GDP (Economic Growth) ($r = .894$, $p < .001$). This coefficient is well above 0.80, which is accepted in the literature as a warning threshold for the risk of multicollinearity. This situation indicates that these two variables may carry similar information in the model and may affect the reliability of the regression coefficients (their standard errors).

However, the correlation matrix alone is insufficient to diagnose this issue; it serves only as a warning. The most reliable way to test whether this potential issue actually affects model estimates is to examine the VIF (Variance Inflation Factor) values in the main regression model results, which will be presented in the next section.

Table 2. Correlation Matrix Between Variables

Variable	1	2	3	4
1. Renewable	—			
2. Urban	0.08	—		
3. ln_Patent	-0.37*	-0.03	—	
4. ln_GDP	-0.43**	0.05	0.89**	—

Note. N = 47. * *p* < .05 (2-tailed). ** *p* < .01 (2-tailed).

5.1. Regression Model Results

A summary of the OLS regression results for the research model is presented in Table 3.

The "Adjusted R-Square" value, which indicates the model's overall explanatory power, was found to be .875. This high coefficient indicates that the four independent variables included in our model (ln_GDP, ln_Patent, Renewable, Urban) successfully explain 87.5% of the variation in the dependent variable, CO_2 emissions (ln_CO_2). The high explanatory power of the model proves that the econometric model established is statistically very strong and successful in showing determinants of CO_2 emissions in OECD and BRICS countries.

Table 3. Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.941	.886	.875	0.64

Note. Predictors: (Constant), ln_GDP, Urban, Renewable, ln_Patent. Dependent Variable: ln_CO_2.

The F-statistic (Table 4), which tests the overall significance of the model, also support this finding ($F(4,42) = 81.40$, $p < .001$), and shows that the established model is statistically highly significant in explaining CO_2 emissions.

Table 4. ANOVA Results Related to the Regression Model

Model	Sum of Squares	df	Mean Square	F	p
Regression	132.15	4	33.04	81.40	< .001
Residual	17.05	42	0.41		
Total	149.20	46			

Note. Dependent Variable: ln_CO_2. Predictors: (Constant), ln_GDP, Urban, Renewable, ln_Patent.

5.2. Regression Model Prediction Results and Hypothesis Tests

The estimation results of the main econometric model of the study are presented in Table 5. The table includes the coefficients (B), standard errors (SE), p-values, and multicollinearity statistics (VIF).

Multiple Linear Regression (VIF) Test: As highlighted in the correlation matrix, a strong correlation (r = .89) was detected between ln_GDP and ln_Patent. To determine whether this correlation undermines the regression estimates, Variance Inflation Factor (VIF) values were examined. As shown in the last column of Table 5, the highest VIF values correspond to ln_GDP (VIF = 5.47) and ln_Patent (VIF = 5.11). Although these values slightly exceed the conservative threshold of 5, they remain well below the widely accepted critical threshold of 10 (Hair et al., 2010). This finding indicates that multicollinearity is within acceptable limits and does not pose a severe threat to the reliability of the estimated coefficients (B) and significance levels.

Table 5. Regression Coefficients and Collinearity Statistics

Variable	B	SE	β	t	p	VIF
(Constant)	-12.455	3.389	—	-3.68	< .001	—
Renewable	-0.022	0.006	-.21	-3.58	< .001	1.25
Urban	-0.017	0.007	-.13	-2.37	.022	1.04
ln_Patent	0.222	0.085	.31	2.60	.013	5.11
ln_GDP	0.647	0.146	.54	4.44	< .001	5.47

Note. Dependent Variable: ln_CO_2. B: Unstandardized coefficient; SE: Standard error; β: Standardized coefficient.

5.3. Hypothesis Test Results

Upon examining the model's coefficients, the following results were obtained regarding the research hypotheses:

Economic Growth (H_1): The coefficient of the ln_GDP variable (B= **.647**) is positive as expected and is statistically highly significant (Sig. < .001).

Conclusion: H_1 IS SUPPORTED. This finding shows that, consistent with the "output branch" of the EKC hypothesis, as of 2021, economic growth still has a stimulating effect on CO_2 emissions in the OECD and BRICS groups. Holding all other variables constant, a 1% increase in GDP increases CO_2 emissions by an average of 0.647%.

Innovation (H_{2a} / H_{2b}): The coefficient of the ln_Patent variable (B= .222) is positive and statistically significant (Sig. = .013).

Conclusion: H_{2a} (Porter Hypothesis) is REJECTED, H_{2b} (Grey Innovation) is SUPPORTED. This is the most striking finding of the study. It was found that innovation (measured by total number of patents) does not reduce CO_2, but rather increases it. This finding is consistent with the theories of

"Directed Technological Change" (DTC), "Grey Innovation," and "Rebound Effect" in the theoretical framework and with similar findings in the empirical literature (e.g., Xiaoyang et al., 2022). Holding all other variables constant, a 1% increase in patent applications increases CO_2 emissions by an average of 0.222%.

Renewable Energy (H_3): The coefficient of the Renewable variable (B= **-**.022) is negative as expected and highly statistically significant (Sig. < .001).

Conclusion: H_3 IS SUPPORTED. This finding strongly confirms the "Energy Substitution Hypothesis" and the consensus in the empirical literature (e.g., Shafiei & Salim, 2014).

Holding all other variables constant, a 1-point increase in the share of renewable energy (e.g., from 22% to 23%) reduces CO_2 emissions by an average of 2.2**%** (i.e., -.022 * 100).

Urbanization (H_{4a} / H_{4b}): The coefficient of the Urban variable (B= **-**.017) is negative and statistically significant (Sig. = .022).

Conclusion: H_{4a} (Concentration Effect) is REJECTED, H_{4b} (Efficiency Effect) is SUPPORTED. This finding shows that, contrary to the "polluting" (positive) effect of urbanization, the "efficiency" (negative) effect (public transportation, efficient infrastructure, etc.) is more dominant in this sample group. This result is similar to the findings of Vo et al. (2022) and Ma & Ogata (2024).

Holding all other variables constant, a 1-point increase in the urbanization rate (e.g., from 76% to 77%) reduces CO_2 emissions by an average of 1.7**%** (i.e., -.017 * 100).

5.4. Tests for Changing Variance and Error Terms

As stated in the "Method" section, for the OLS regression results presented in the "Coefficients" table to be statistically valid and reliable (robust), the model must meet the basic assumptions. The results of the diagnostic tests performed to test these assumptions are presented in Figure 1 and Figure 2.

Figure 1. Test Distribution Graph for the Assumption of Changing Variance (Heteroscedasticity)

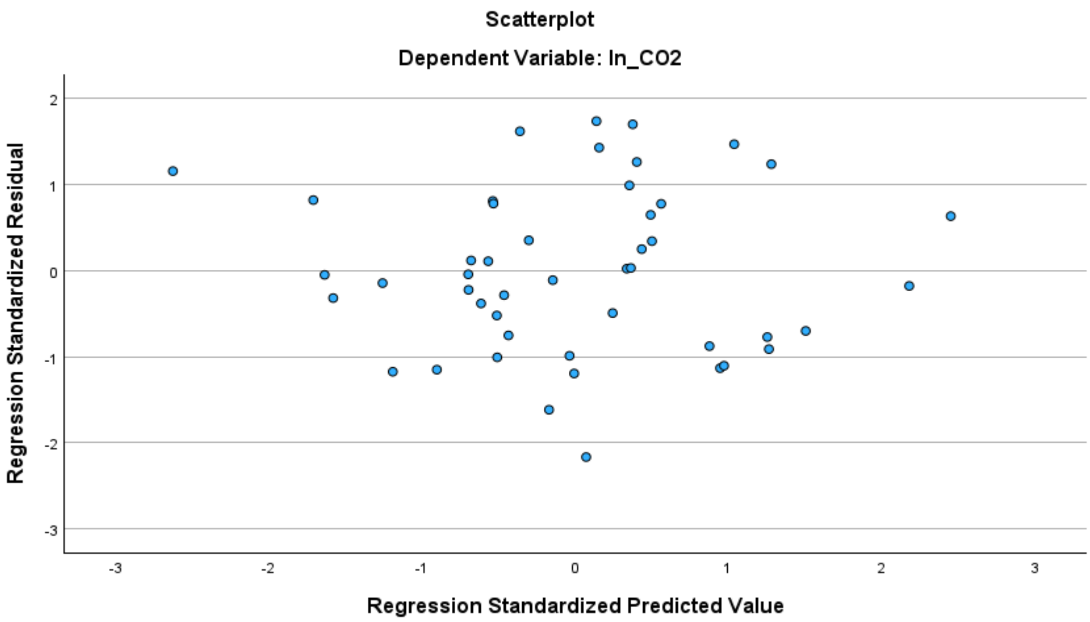


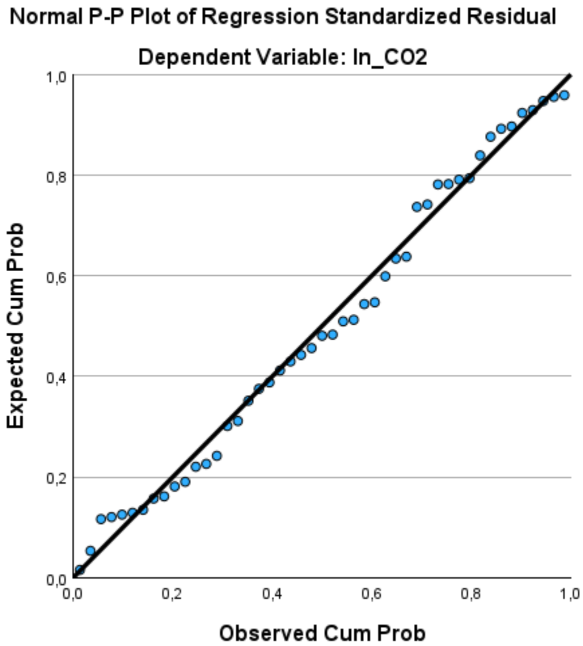
Figure 1 shows the scatterplot used to test the model's Heteroskedasticity assumption. The vertical axis of the graph represents the model's standardized errors (*ZRESID), while the horizontal axis represents the standardized predicted values (*ZPRED). For the OLS assumption to be met, the points in this graph should not form a distinct pattern (e.g., a 'funnel' shape) and should be scattered randomly around the '0' line in a 'cloud' pattern (Homoskedasticity).

Upon examining the graph, it is clear that the points do not form a distinct funnel shape and are scattered completely randomly around the center (0) line. This finding proves that there is no problem of Heteroskedasticity in the model and that the assumption of 'constant variance' (Homoskedasticity) is met.

One of the fundamental assumptions of the OLS model, the normality of residuals, was examined using the Normal P-P Plot presented in Figure 2.

This graph visually compares the observed cumulative probabilities of the model's standardized residuals with the expected cumulative probabilities of the theoretical normal distribution.

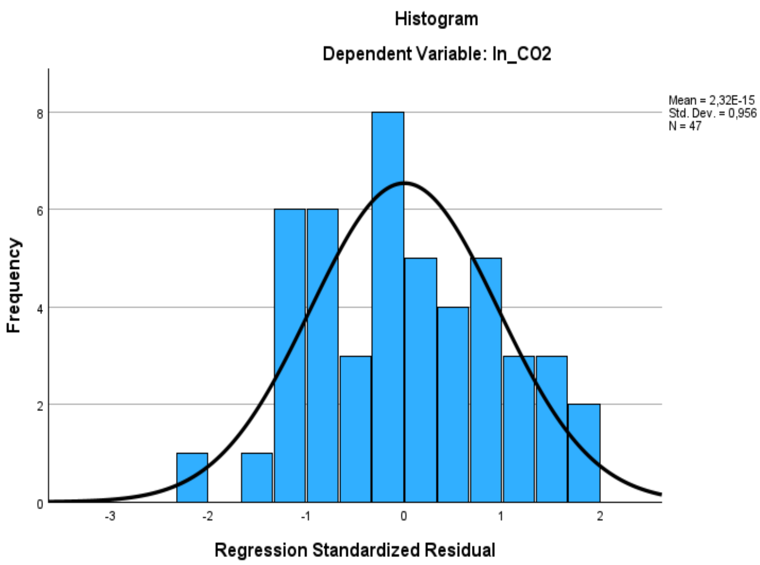
Figure 2. Error Term Normality Test



Upon examining Figure 2, it is observed that the data points representing the cumulative distribution of residuals are clustered closely on and around the 45-degree reference line. This observation demonstrates that the distribution of the model's error terms does not exhibit a statistically significant deviation from the theoretical normal distribution. This finding is also confirmed by the histogram analysis of the model residuals and strongly supports the statistical validity of the OLS estimators.

To support the visual inspection conducted for the normality assumption, Figure 3 presents the histogram of the model's standardized residuals. The graph shows the frequency distribution of the error terms (columns) and an ideal normal distribution curve (bell curve).

Figure 3. Histogram of Error Term Distribution



When examining Figure 3, it can be seen that the distribution of residuals is close to a symmetrical structure and centered around zero (0). The fact that the columns reasonably follow the ideal bell curve drawn over them indicates that there is no significant deviation from the normality assumption. This finding strongly confirms the result obtained with the P-P Chart (Figure 2).

CONCLUSION

This study aims to analyze the key determinants of CO_2 emissions in OECD and BRICS countries, which account for a large portion of global emissions and the economy, using 2021 cross-sectional data. The study tested the effects of the 'green sustainability' (renewable energy) and 'green innovation' (total patents) indicators on environmental performance under the control variables of economic growth (GDP) and urbanization using an EKK (OLS) regression model. The model results are largely consistent with the theoretical framework established but reveal some striking findings in certain key areas.

It was found that economic growth (ln_GDP) has a positive (+) and strong effect on CO_2 emissions (H1 supported), indicating that the sample continues to be in the "rising leg" of the Environmental Kuznets Curve (EKC). Renewable energy consumption (Renewable) has a negative (-) and statistically significant reducing effect on CO_2 emissions (H3 supported), proving that the "Energy Substitution Hypothesis" remains valid for the OECD and BRICS groups. It was found that urbanization (Urban), used as a control variable, has a negative (-) and significant effect on CO_2 emissions (H4b supported). This finding indicates that, in this mixed group of countries, the "efficiency" effects of urbanization, such as the development of public transportation and the service sector, are more dominant than its "concentration" (polluting) effects.

The most important and striking finding of the study emerged on the innovation variable (ln_Patent). Hypothesis H2a (Porter Hypothesis), which tested the "green innovation" expectation, was rejected; instead, hypothesis H2b (Grey Innovation / Rebound Effect), which predicted that innovation would increase CO_2 emissions in a positive (+) direction, was supported.

This "paradoxical" result is fully consistent with the theories of "Directed Technological Change" (DTC) (Acemoglu et al., 2012) and "Gray Innovation" (Yan et al., 2017) discussed in the "Theoretical Framework" section of the article. This finding strongly implies that, as of 2021, total innovation (total patent) activity in OECD and BRICS countries is still directed towards the "gray" area because dirty (fossil fuel-based) technologies are more profitable than clean technologies. Furthermore, as predicted by the "Backlash Effect" (Sorrell, 2007) theory, even productivity-focused innovations have a positive effect on net emissions by increasing total consumption.

These empirical findings offer critical implications for policymakers regarding sustainability and combating climate change:

First and foremost, the widely accepted view that promoting innovation alone will reduce carbon emissions (Porter Hypothesis) is not supported by this analysis. The effect of innovation capacity, measured by total number of patents, on emissions was found to be statistically positive ($B = .222$, $p < .05$) and significant. This shows that policy frameworks based solely on quantitative increases, without focusing on the quality of innovation, cannot guarantee environmental sustainability. In this context, policymakers should take on the responsibility of "steering" innovation rather than merely "promoting" it. In line with the Directed Technology Change (DTC) approach, direct and targeted interventions such as carbon taxes, emissions trading systems (ETS), and subsidies for environmentally friendly R&D (green R&D) are required.

On the other hand, the clear and consistent reduction effect of renewable energy use on emissions makes accelerating investment in this area a priority policy goal. While indirect measures such as energy efficiency have the potential to create a rebound effect, directly replacing fossil fuels with renewable energy sources is the most reliable strategy for carbon reduction. Therefore, infrastructure investments, integration capacities, and production incentives should be restructured within this framework.

Finally, the fact that urbanization has a significant reduction effect on emissions in this mixed sample (OECD+BRICS) ($B = -.017$, $p < .05$) shows that rapid urbanization is not only an environmental threat but also a sustainability opportunity. In this context, it is possible to strengthen this positive efficiency effect through measures such as smart city planning, the widespread use of public transportation, and the improvement of energy-efficient building standards.

These findings emphasize the importance of coordinating multi-layered policies such as guiding innovation, accelerating renewable energy investments, and supporting urbanization with sustainable urban infrastructure to achieve carbon neutrality goals.

Limitations and Suggestions for Future Research

Despite the significant contributions of this study, some limitations exist. First, the study has a cross-sectional (2021) structure. While this snapshot reveals the relationship between variables, it cannot analyze causality or the evolution of this relationship over time (whether the EKC will reverse in the long term). Future studies should extend this analysis using panel data methods (such as Panel ARDL, GMM) to examine long-term dynamics.

Second, as highlighted in the "Introduction" section of this study, total patents were used as an indicator of 'innovation'. The positive (+) finding of this study supporting "Gray Innovation" has precisely revealed the weakness of this general indicator. Future research should use more specific and targeted innovation data, such as "green patents," to test the net effect of 'real' green innovation on CO_2 (whether it supports the Porter Hypothesis).

REFERENCES

Acemoglu, D. (2002). Directed technical change. *Review of Economic Studies, 69*, 781-809. https://doi.org/10.1111/1467-937X.00226

Acemoglu, D., Aghion, P., Bursztyn, L., & Hemous, D. (2012). The environment and directed technical change. *American Economic Review, 102*(1), 131-166. DOI: 10.1257/aer.102.1.131

Akar, G., Kaplan, E. A., Güler, İ., & Şahin, S. (2025). Has the Environmental Kuznets Curve hypothesis become stronger? A comparative analysis for OECD countries and selected late-industrializing Asian economies. *Journal of Environmental Management, 394*, Article 127575. https://doi.org/10.1016/j.jenvman.2025.127575

Akdemir Ömür, G. (2022). Yönetim yazınında Porter Hipotezinin bibliyometrik analizi. *Kafkas Üniversitesi İktisadi ve İdari Bilimler Fakültesi Dergisi, 13*(Kongre Özel Sayısı), 74-98. https://doi.org/10.36543/kauiibfd.2022.ozelsayi4

Alam, F. (2024). Environmental Kuznets Curve and sustainable development in OECD countries: A panel data analysis. *European Journal of Development Studies, 4*(6), 9-15. 10.24018/ejdevelop.2024.4.6.392

Ambec, S., Cohen, M. A., Elgie, S., & Lanoie, P. (2013). The Porter Hypothesis at 20: Can environmental regulation enhance innovation and competitiveness?. *Review of Environmental Economics and Policy, 7*(1), 2-22. RePEc:oup:renvpo:v:7:y:2013:i:1:p:2-22

Blanco, G., de Coninck, H., Agbemabiese, L., Mbaye Diagne, E. H., Diaz Anadon, L., Lim, Y. S., Pengue, W. A., Sagar, A. D., Sugiyama, T., Tanaka, K., Verdolini, E., & Witajewski-Baltvilks, J. (2022). Innovation, technology development and transfer. In P. R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, & P. Vyas (Eds.), *Climate Change 2022: Mitigation of climate change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press. https://doi.org/10.1017/9781009157926.018

Bousnina, R., Lajnaf, R., Mnif, S., & Gabsi, F. (2025). Economic growth, technological innovation and CO_2 emissions in developed countries: Is there an inverted U-shaped relationship? *Management of Environmental Quality: An International Journal, 36*(8), 2106-2126. https://doi.org/10.1108/MEQ-12-2024-0555

Bölük, G., & Mert, M. (2014). Fossil and renewable energy consumption, GHGs (greenhouse gases) and economic growth: Evidence from a panel of EU (European Union) countries. *Energy, 74*, 439-446. https://doi.org/10.1016/j.energy.2014.07.008

Cheng, C., Ren, X., Dong, K., Dong, X., & Wang, Z. (2021). How does technological innovation mitigate CO_2 emissions in OECD countries? Heterogeneous analysis using panel quantile regression. *Journal of Environmental Management, 280*, Article 111818. https://doi.org/10.1016/j.jenvman.2020.111818

Clarke, L., Wei, Y.-M., De La Vega Navarro, A., Garg, A., Hahmann, A. N., Khennas, S., Azevedo, I. M. L., Löschel, A., Singh, A. K., Steg, L., Strbac, G., & Wada, K. (2022). Energy systems. In P. R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, & P. Vyas (Eds.), *Climate Change 2022: Mitigation of climate change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press. https://doi.org/10.1017/9781009157926.008

Erkılıç, E., Gazeloğlu, C., & Özgören Ünlü, E. (2025). Renewable energy solution to carbon emissions: BRICS countries in the grip of globalization and economic growth. *Sustainability, 17*, Article 4117. https://doi.org/10.3390/su17094117

Gieraltowska, U., Asyngier, R., Nakonieczny, J., & Salahodjaev, R. (2022). Renewable energy, urbanization, and CO_2 emissions: A global test. *Energies, 15*, Article 3390. **https://doi.org/10.3390/en15093390**

Gillinham, K., Rapson, D., & Wagner, D. (2015). The rebound and energy efficiency policy. *Review of Environmental Economics and Policy, 10*(1), 64–83.

Grossman, G. M., & Krueger, A. B. (1991). *Environmental impacts of a North American Free Trade Agreement* (NBER Working Paper No. 3914). National Bureau of Economic Research. https://doi.org/10.3386/w3914

Gujarati, D. N., & Porter, D. C. (2009). *Basic econometrics* (5th ed.). McGraw Hill.

Hair, J. F., Black, W. C., Babin, B. J., & Anderson, R. E. (2010). *Multivariate data analysis* (7th ed.). Pearson.

Haq, W., Ahmad, I., Arshad, A., & Alvi, S. (2025). The role of human capital and innovation in reducing carbon emissions in OECD and BRICS countries. *Sustainable Futures, 10*, Article 101475. https://doi.org/10.1016/j.sftr.2025.101475

International Monetary Fund. (2021, Ekim). *World Economic Outlook, October 2021: Recovery during a pandemic*. https://www.imf.org/en/Publications/WEO/Issues/2021/10/12/world-economic-outlook-october-2021.

Iranmanesh, N. (2025). Analysis of financial convergence between the BRICS and OECD countries. *PLOS ONE, 20*(2), Article e0316410. https://doi.org/10.1371/journal.pone.0310950

Işık, C., Bulut, U., Ongan, S., Islam, H., & Irfan, M. (2024). Exploring how economic growth, renewable energy, internet usage, and mineral rents influence CO_2 emissions: A panel quantile regression analysis for 27 OECD countries. *Resources Policy, 92*, Article 105025. https://doi.org/10.1016/j.resourpol.2024.105025

Jaffe, A.B. & Palmer, K. (1997). Environmental regulation and innovation: A panel data study. The Review of Economics and Statistics, 79(4), 610-619. https://doi.org/10.1162/003465397557196

Jie, W., & Khan, R. (2024). Breaking the CO_2 gridlock: Can renewables lead the way for the OECD? *Energies, 17*, Article 4511. **https://doi.org/10.3390/en17174511**

Kasperowicz, R. (2015). Economic growth and CO_2 emissions: The ECM analysis. *Journal of International Studies, 8*(3), 91-98. https://doi.org/10.14254/2071-8330.2015/8-3/7

Kavaz, İ. (2023). Gelişmekte olan ülkelerde enerji verimliliği ve geri tepme etkisinin analizi. *Anadolu İktisat ve İşletme Dergisi, 7*(2), 49-73. https://doi.org/10.59293/anadoluiid.1363571

Kılınç, E. C. (2023). Yenilenebilir enerji ve fosil yakıt tüketiminin ekolojik ayak izi üzerindeki etkisi: Türkiye örneği. *Finans Ekonomi ve Sosyal Araştırmalar Dergisi, 8*(3), 731-749. https://doi.org/10.29106/fesa.1307807

Klobucista, C., & Merrow, J. (2021, 22 Aralık). *Seven charts that explain the COVID-19 pandemic in 2021*. Council on Foreign Relations. https://www.cfr.org/article/seven-charts-explain-covid-19-pandemic-2021

Konya, S. (2022). Panel estimation of the Environmental Kuznets Curve for CO_2 emissions and ecological footprint: Environmental sustainability in developing countries. *Folia Oeconomica Stetinensia, 22*(2), 123-145. DOI: 10.2478/foli-2022-0022

Ma, B., & Ogeta, S. (2024). Impact of urbanization on carbon dioxide emissions: Evidence from 136 countries and regions. *Sustainability, 16*(18), Article 7578. **https://doi.org/10.3390/su16187878**

Mehta, D., Patel, N., & Abdi, A. H. (2025). Nexus between carbon emissions, economic growth, renewable energy, and innovation of BRICS: Kuramoto dynamic synchronization approach. *Discover Sustainability, 6*, Article 987. DOI:10.1007/s43621-025-01799-1

Mirziyoyeva, Z., & Salahodjaev, R. (2022). Renewable energy, GDP and CO_2 emissions in high-globalized countries. *Frontiers in Energy Research, 11*, 1-8. https://doi.org/10.3389/fenrg.2023.1123269

Muratoğlu, Y., Songur, M., Uğurlu, E., & Şanlı, D. (2024). Testing the Environmental Kuznets Curve hypothesis at the sector level: Evidence from PNARDL for OECD countries. *Frontiers in Energy Research, 12*, Article 1452906. https://doi.org/10.3389/fenrg.2024.1452906

Naimoğlu, M., & Özbenk, S. (2022). Testing the Environmental Kuznets Curve hypothesis under structural breaks: The case of Turkey. *Alanya Akademik Bakış Dergisi, 6*(3), 3069-3084. https://doi.org/10.29023/alanyaakademik.992079

Nica, I., Georgescu, I., & Kinnunen, J. (2025). Economic growth, innovation, and CO_2 emissions: Analyzing the Environmental Kuznets Curve and the Innovation Claudia Curve in BRICS countries. *Sustainability, 17*, Article 3507. **https://doi.org/10.3390/su17083507**

Panayotou, T. (1997). Demystifying the environmental Kuznets curve: Turning a black box into a policy tool. *Environment and Development Economics, 2*(4), 465-484. DOI:10.1017/S1355770X97000259

Porter, M.E. (1991). America's green strategy. *Scientific American, 264*(168). http://dx.doi.org/10.1038/scientificamerican0491-168

Porter, M. & van der Linde, C. (1995). Toward a new conception of the environment-competitiveness relationship. *Journal of Economic Perspectives, 9*(4), 97-118. DOI: 10.1257/jep.9.4.97

Qamruzzaman, M., Almulhim, A. A., & Aljughaiman, A. A. (2025). Nexus between uncertainty, innovation, and environmental sustainability in BRICS: An analysis under the Environmental Kuznets Curve (EKC) framework. *Frontiers in Environmental Science, 13*, Article 1570150. https://doi.org/10.3389/fenvs.2025.1570150

Rainvelle, A., Dikker, I., & Buggenhagen, M. (2025). Tracking innovation via green patent classification systems: Are we truly capturing circular economy progress?

Journal of Cleaner Production, 486, Article 144385. https://doi.org/10.1016/j.jclepro.2024.144385

Ridzuan, N. H. A. M., Abdullah, A., & Ibrahim, M. A. (2022). Revisiting the environmental Kuznets curve hypothesis in Malaysia: An ARDL approach. *Environmental Science and Pollution Research, 29*(44), 66597–66611. https://doi.org/10.1007/s11356-022-20516-x

Sahoo, B., Behera, D., & Rahut, D. (2022). Decarbonization: Examining the role of environmental innovation versus renewable energy use. *Environmental Science and Pollution Research, 29*, 48704-48719. DOI:10.1007/s11356-022-18686-1

Saqib, N., Usman, M., Mahmood, H., Abbas, S., Ahmad, F., Mihai, D., & Mallek, R. S. (2023). The moderating role of technological innovation and renewable energy on CO_2 emission in OECD countries: Evidence from panel quantile regression approach. *Economic Research, 36*(3), 1-22. https://doi.org/10.1080/1331677X.2023.2168720

Setyadharma, A., Anawati, T., Sa'adah, N., & Sholikhatun Jamil, N. (2024). Analysis of the determinants of carbon dioxide emissions in BRICS countries: A panel dynamic ordinary least square (DOLS) estimation approach. *E3S Web of Conferences, 557*, Article 04010. DOI:10.1051/e3sconf/202455704005

Sorrell, S. (2007). *The rebound effect: An assessment of the evidence for economy-wide energy savings from improved energy efficiency*. UK Energy Research Centre (UKERC).

Van, M. H., & Sadradin, H. F. (2021). The effect of technological innovation on CO_2 emissions in OECD countries: Using panel regression. *International Journal of Contemporary Economics and Administrative Sciences, 11*(2), 438-453. https://doi.org/10.5281/zenodo.6582440

Vo, D. H., Ho, C. M., Thuong Le, Q. T., & The Vo, A. (2022). Revisiting the energy-growth-environment nexus in the OECD countries: An application of the CS-ARDL approach. *Energy, Sustainability and Society, 12*, Article 47. https://doi.org/10.1186/s13705-022-00375-z

Voumik, L. C., & Sultana, T. (2022). Impact of urbanization, industrialization, electrification and renewable energy on the environment in BRICS: Fresh evidence from novel CS-ARDL model. *Heliyon, 8*(11), Article e11340. https://doi.org/10.1016/j.heliyon.2022.e11457

Wang, X., & Cheng, Z. (2020). Cross-sectional studies strengths, weaknesses, and recommendations. *Chest, 158*(1), S65–S71. 10.1016/j.chest.2020.03.012

Wooldridge, J. M. (2015). *Introductory econometrics: A modern approach* (6th ed.). Nelson Education.

Xiaoyang, X., Balibae, M., & Epadile, M. (2022). The impact of technological innovation, research and development, and energy intensity on carbon emissions: An experience from BRICS and OECD countries. *International Journal of Sustainable Development & World Policy, 11*(1), 1-17. DOI:10.18488/26.v11i1.2898

Yacoubian, L. J., Garcia, D. S., Silva, B. N., Ferreira de Carvalho, G. H., & Ketenchian, G. (2025). Peace and prosperity: An empirical analysis using GDP and GDP per capita. *Revista JRG de Estudos Academicos, 8*(18), 1-15. DOI:10.55892/jrg.v8i19.2372

Yan, Z., Yi, L., Du, K., & Yang, Z. (2017). Impacts of low-carbon innovation and its heterogeneous components on CO_2 emissions. *Sustainability, 9*(4), Article 548. https://doi.org/10.3390/su9040548

Zhang, W., Zhu, B., Li, Y., & Yan, D. (2024). Revisiting the Porter Hypothesis: A multi-country meta-analysis of the relationship between environmental regulation and green innovation. *Humanities and Social Sciences Communications, 11*, Article 232. DOI: 10.1057/s41599-024-02671-9