International Journal of Contemporary Economics and Administrative Sciences
ISSN: 1925 – 4423
Volume: XVI, Issue: 1, Year: 2026, pp. 764-787

A Panel Data Analysis of the Impact of Economic Growth, Population Change, Innovation, and Renewable Energy Policies on the Carbon Footprint in G-7 Countries

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Received: 07.11.2025, Accepted: 31.03.2026
DOI Number: 10.5281/zenodo.20800519

Abstract

This research aims to empirically analyze the environmental sustainability factors in G-7 countries. The study reveals the dynamic interactions between carbon footprint (dependent variable) and economic growth, population change, renewable energy consumption, and technological innovation (independent variables). The study examines the causality relationship between carbon footprint and macroeconomic variables using a panel data set covering the period 1991-2023. In this context, the Panel VAR model and the Granger Causality test are applied to the dataset as methodology. The results of the analysis show that renewable energy consumption and technological innovation have a negative impact on carbon footprint. On the other hand, economic growth and population change have positive effects on carbon footprint. These findings suggest that G-7 countries should prioritize renewable energy transition and R&D investments in their climate policies. Given the increasing importance of carbon footprint, especially with the Paris Climate Agreement, it is thought that this research will contribute to the literature in terms of identifying the underlying causes of the problems and providing a solution. In addition, it is important that the transformation is initiated and supported by the countries with the strongest economies.

Key words: CO_2 Emissions, Renewable Energy, Innovation, Population Change, Carbon Footprint.

JEL Code: Q53, O44, Q42

1. Introduction

The world's average temperature is rising due to the increase in CO_2 (Jang et al., 2014; Liu et al., 2021). Global temperature records first began in 1850. The year 2024 has been recorded as the hottest year since 1850. All of the hottest years

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recorded over the 175-year period have occurred in the last decade (2015–2024) (National Centers for Environmental Information (NCEI), 2025). The change in the amount of CO_2 is one of the most important factors triggering climate change and global warming. The number of events that damage the environment and increase the carbon footprint, such as the development and growth of countries, population growth, industrialization, people's use of more means of transportation, natural disasters, destruction of forests, concreting, etc., has increased significantly in the last 30-40 years (Özekenci, 2023).

Carbon footprint is a concept that refers to the amount of gases released directly or indirectly into the atmosphere by the activities of individuals and organizations (Fakher, 2019). The concept of carbon footprint has been explained with CO_2 emissions in the literature. However, carbon footprint is a broader concept that also includes CO_2 emissions. The reason for this is related to the calculation of the carbon footprint. In this calculation, CH4 (Methane), NO2 (nitrous oxide), and small amounts of other greenhouse gases are also included, converted into CO_2 equivalents (Uzunali and Yazıcı, 2023). This calculation is preferred in academic studies over the carbon footprint because CO_2 emissions are more standardized and directly measurable. In the carbon footprint calculation, the CO_2 ratio is around 90%. The actual proportion of CO_2 in the gases that make up greenhouse gases is only 62%, and other gases are included in the 28% section (Eslamidoost et al., 2022). This difference in carbon footprint calculations stems from the fact that all greenhouse gases are converted by taking into account their global warming potential (GWP). Focusing only on the amount of CO_2 emissions underestimates the total impact on climate change (Fasanya and Arek-Bawa, 2025). For this reason, the carbon footprint concept should be evaluated with a more holistic approach, taking into account the impact of other greenhouse gases (Patrick Arnold et al., 2025).

Although countries have participated in many environmental treaties, such as the Kyoto Protocol, under the leadership of the United Nations, it is seen that the desired results have not been achieved (Asaloko et al., 2025). In the case of the Kyoto Protocol, although it is aimed at reducing carbon emissions, many factors, such as the strict conditions, weak implementation mechanism, ineffective management of the process, and the exclusion of industrialized countries with large populations, such as China and India, contribute to the failure to meet the targets. Although the Protocol continues, global CO_2 emissions continue to increase (Aichele and Felbermayr, 2013; Böhringer, 2003; Mor et al., 2024). With the Paris Climate Agreement and the creation of the 2030 and 2050 visions, it is evident that the concept of carbon footprint has gained increased prominence (Akrofi et al., 2022; Duscha et al., 2019). To reduce the effects of global warming and climate change, and to take measures, the carbon footprint is becoming a phenomenon. In this respect, carbon footprint is seen as a symbol and a target (Imandojemu et al., 2025).

One of the biggest obstacles to reducing the carbon footprint is the perception that countries' welfare and economies will shrink (Umair et al., 2025).

In the literature, the relationship between economic growth and CO_2 emissions has been the subject of many studies. Economic growth is associated with more production and consumption. For this reason, economic growth leads to increased CO_2 emissions, which in turn exacerbate environmental degradation (Boutabba, 2014; Dağ and Kızılkaya, 2021; Özekenci, 2023). A theoretical framework for economic growth, known as the Kuznets curve, was proposed by economist Simon Kuznets. The Kuznets curve defines an inverted U-shaped relationship between economic growth and income inequality (Leal and Marques, 2022; Martínez-Navarro et al., 2020; Nielsen and Alderson, 1997; Roy Chowdhury and Moran, 2012). According to this theory, income inequality tends to increase in the early stages of economic development, but then declines as the economy matures (Kuznets, 1985). The current theoretical framework is often used to study the relationship between economic growth and environmental quality.

The study, based on extensive literature on economic growth and environmental dynamics, uses panel data techniques to analyze the impact of changes in economic growth, population, annual innovations, and the proportion of renewable energy in total energy consumption on carbon footprints in G-7 countries. To establish the study's place in existing literature, its main contributions can be summarized in three dimensions. First, theoretically, the study adopts a holistic approach by evaluating CO_2 emissions within a carbon footprint framework alongside a more up-to-date model, rather than focusing solely on CO_2 emissions. Second, empirically, it provides up-to-date evidence on G-7 countries for the period 1991-2023, offering a long-term and comprehensive assessment of environmental pressures in advanced economies. Third, from a methodological perspective, the study applies the Panel VAR model to capture the dynamic relationship between variables and supports the findings with the Granger Causality Test and the Generalized Method of Moments Estimation (GMM) to address potential endogeneity issues, thereby enhancing the robustness of the results.

Findings from the study reveal the main drivers of carbon footprint dynamics in advanced economies, offering important insights for policymakers. Understanding these relationships is crucial for designing effective and sustainable environmental and energy policies in G-7 countries.

2. Literature Review

The empirical analysis of this study is conducted using carbon footprint as the primary indicator, while the literature review primarily includes studies based on CO_2 emissions. The rationale is that CO_2 constitutes the largest share of total greenhouse gas emissions and forms the basis for carbon footprint calculations through CO_2 equivalent conversion factors. Furthermore, CO_2 emissions are traditionally more widely accepted and systematically analyzed in academic literature due to data consistency and methodological comparability. Therefore, CO_2- based studies provide a robust and theoretically consistent reference framework for the current analysis.

2.1. The Impact of Economic Growth on Carbon Footprint

The relationship between economic growth and carbon footprint is a complex issue that has been widely researched in the environmental economics literature. According to the Environmental Kuznets Curve, economic development initially leads to environmental degradation. Still, after a certain level of economic growth is reached, it shifts towards improving society's relationship with the environment. According to the traditional Environmental Kuznets Curve, the relationship between economic growth and environmental pollution is assumed to be in the form of an inverted letter U (Bilgili et al., 2016). There are three basic mechanisms underlying this relationship: the low-income stage, the middle-income stage, and the high-income stage. Although no direct studies have been found on the impact of carbon footprint and economic growth in less developed countries, Jiying et al. (2023) demonstrated a direct relationship between CO2 emissions and economic growth. There is a direct correlation between growth figures and environmental pollution in developing countries. It has been determined that the carbon footprint increases as growth increases. Mazlum's 2023 study examined the relationship among the E-7 countries (Brazil, China, Indonesia, India, Mexico, Russia, and Turkiye) from 1992 to 2008. It was observed that a 1% increase in economic growth in these countries led to a 0.12% increase in the ecological footprint (Mazlum, 2023). In a study using the US as an example, the effects of economic complexity, globalization, and energy consumption on environmental pollution (CO_2 emissions and ecological footprint) were examined over the period 1980-2016. The study's results support the Kuznets Curve, indicating that renewable energy reduces pollution, while non-renewable energy increases it. Additionally, globalization is found to be effective in reducing CO_2 emissions (Pata, 2021). Similarly, while there is a negative relationship between economic growth and CO_2 emissions in developed countries, CO_2 emissions increase with growth in low-income countries (Almeida et al., 2024). These findings support the validity of the Environmental Kuznets Curve for countries at different levels of development.

As developed economies with high income levels, the G-7 countries are located in the third stage of the Environmental Kuznets Curve. Therefore, the relationship between economic growth and carbon footprint in these countries is theoretically expected to be negative. However, globalization, technological diffusion, and international trade dynamics complicate this relationship.

2.2. Impact of Population Change on Carbon Footprint

Population changes are recognized as one of the most fundamental determinants of environmental pressures. Population growth creates multidimensional impacts on carbon footprint through resource consumption and waste management. The impact of population on carbon footprint can be explained by the direct consumption effect, urbanization effect, and scale effect models. Numerous scientific studies have investigated the relationship between population growth and environmental degradation (Grossman and Krueger, 1995). Studies have found a positive relationship between population density and CO_2 emissions (Arı and Zeren, 2011; Damırova and Yayla, 2021). Especially in developing countries, the slowdown or stagnation of the population growth rate creates a different formation. While less developed countries seek ways to meet their basic needs and achieve a healthy and quality life, developed countries struggle with the abundance of resources they possess and the challenges that arise in managing them (OECD, 2015). This situation shows that it will be different in developing countries. In general, although population growth supports economic growth, it also brings along overconsumption and environmental threats (Gül and Shipman, 2021). These two factors play a balancing role in determining sustainable development policies. Since people, economic systems, and living areas are directly related to each other, sustainable development can only be achieved by addressing society, economy, and environment in an integrated manner. By balancing the opportunities and risks brought about by population growth, a more inclusive, fair, and environmentally friendly policy can be created.

2.3. The Impact of Innovation on Carbon Footprint

Technological innovation plays a critical role in achieving environmental sustainability goals and has significant potential in reducing carbon footprints. Innovation can generally be defined as the development of new ideas, products, and processes that are different from the status quo, making them more efficient (Maranville, 1992). Porter (1991) suggests that appropriately designed environmental regulations can stimulate innovation, resulting in energy efficiency that can fully or partially offset the costs of the regulation. Environmental innovation is either process innovation or product innovation. Modern growth theories suggest that innovation is the primary driver of economic growth. In the study conducted by Altintas (2020) for G-20 countries, the positive cycle between innovation and economic growth as a result of the investments made by states in science, technology, and industry was demonstrated by using structural equation modeling. In another study by Tokal (2022), it was stated that increasing the innovation capacity of developing economies contributes to sustainable growth.

Innovation increases productivity while simultaneously accelerating the transition to low-carbon energy. There is empirical evidence on the positive effects of environmental innovation practices. Long et al. (2017) observed that Korean-owned firms in China have a positive impact on both environmental and economic performance. Environmental innovation is achieved through increases in energy efficiency, the development of clean technologies (including renewable energy), the implementation of circular economy solutions (such as waste reduction and recycling technologies), and the deployment of carbon capture systems. Many researchers in the environmental-economic literature have used the number of patents as a measure of innovation. The G-7 countries are leaders in global innovation ecosystems. They account for around 60% of total global R&D spending and generate the vast majority of green technology patents. The performance of innovation leaders, such as those in the G-7 countries, in this area influences the achievement of global climate goals (Albino et al., 2014; Popp et al., 2011; Raiser et al., 2017). Furthermore, their production of the vast majority of green technology patents not only increases their economic competitiveness but also plays a significant role in the transition to a low-carbon economy. The performance of G-7 countries in the field of innovation both drives technological transformation and supports international cooperation by setting an example for other countries in achieving global climate goals.

2.4. Impact of Renewable Energy Policies on Carbon Footprint

The impact of renewable energy sources on carbon footprint is one of the widely researched topics in the sustainable development literature. Energy is one of the main determinants of economic growth and welfare for countries. The energy demand of countries in the process of economic development tends to increase as their level of development increases. This energy manifests itself in critical sectors, including meeting basic human needs, industrial production activities, electric power generation, and transportation services (Sadorsky, 2009).

The impact of energy resources on countries shows a multidimensional structure. These resources have direct impacts on countries' development processes, social welfare levels, sustainability policies, economic performance indicators, and geopolitical power balances. Renewable energy sources reduce the carbon footprint through the direct substitution effect, the technological diffusion effect, and the structural transformation effect. Diversification of energy sources and increasing the share of renewable energy sources in the energy mix create positive results in terms of economic growth (Yilanci et al., 2021). Studies conducted in emerging economies have revealed a positive relationship between the diffusion of renewable energy technologies and energy diversification, as well as improved economic growth performance (Le et al., 2017).

Energy experts state that energy production based on renewable resources will contribute to reducing greenhouse gas emissions and achieving environmental sustainability goals (Aslan et al., 2014; Danish et al., 2017). The amount of CO_2 emissions generated during electricity generation using different energy sources varies significantly.

Oil-dependent countries that want to be minimally affected by price fluctuations invest in renewable energy sources. Especially after the 1973 oil crisis, many countries invested in renewable energy and supported investors to ensure energy supply security (Özbek, 2023). Germany's renewable energy and energy transition policies exemplify this issue (Erkök, 2022).

There are scientific studies in the literature on the subject covering the G-7 countries. In his study, Sadorsky (2009) employed a panel co-integrated FMOLS model to investigate the relationship between the increase in GDP per capita, renewable energy, CO_2 emissions, and oil prices, using data from the G7 countries. The dependent variable in the study is renewable energy. According to the results, a 1% increase in the country's GDP per capita is associated with an 8.44% increase in renewable energy use. In comparison, a 1% increase in CO_2 emissions results in a 5.23% increase in renewable energy use. At the same time, oil prices have a weak effect on renewable energy.

Wang et al. (2020) employed the CS-ARDL method in their study, which covered G-7 countries between 1990 and 2017. The study took ecological innovation, export diversification, and renewable energy consumption as variables, with CO_2 emissions as the dependent variable. As a result of the study, it was revealed that the variables significantly affect the dependent variable. Export diversification has an inverse effect on CO_2 emissions, while ecological innovation and renewable energy amounts help reduce CO_2 emissions.

Studies on other country groups yield similar results. The study by Aye and Edoja (2017) revealed the mitigating effect of renewable energy policies on CO_2 emissions in 31 developed countries. In a study published in 2024, Wei et al. investigated the effect of international digital trade, green technology innovation, gross national product, and renewable energy consumption on environmental sustainability (carbon footprint) in BRICST countries in the long and short term. In the study covering the years 1995-2022, they tried to explain the effect of variables on the dependent variable using various statistical methods (Wei et al., 2024).

In their study on the impact of air pollution in selected developing African countries, Jiying et al. (2023) found that the adoption of green innovation technologies would lead to a reduction in carbon and particulate matter emissions. According to the study published by Bilalli et al. (2024), research conducted in nine selected countries has revealed that energy from renewable sources contributes to the national economy, is beneficial in reducing CO_2 emissions, and supports a sustainable economy.

The literature review indicates that renewable energy policies have a significant and consistent impact on reducing carbon footprint. Studies on G-7 countries show that these policies are consistent with both environmental and economic objectives. This study contributes to the existing literature by analyzing economic growth, population change, technological innovation (as measured by the number of patents), and renewable energy variables simultaneously, and by comprehensively examining the carbon footprint dynamics of G-7 countries.

3. Method

This study empirically examines the relationships between carbon footprint and economic growth, population change, renewable energy consumption, and technological innovation using panel data from G-7 countries for the period 1991-2023. Unlike analyses in the literature that often focus on CO_2 emissions, this study uses the carbon footprint variable, employing a more comprehensive environmental impact measure that encompasses all greenhouse gases. Thus, other gases that contribute to global warming are also taken into account.

Another original aspect of the study is the use of patent count data to represent technological innovation. This variable, which is often represented in the literature by abstract innovation indices or dummy variables, is modeled in this study in a concrete and measurable way using annual patent counts for G-7 countries, thus analyzing the effect of innovation on the carbon footprint with an objective approach.

In the study, the ImPACT model was used as a basis to comprehensively analyze the determinants of environmental impacts. This model reveals the relationship between environmental impact and components of population (P), economic prosperity (A), consumption intensity (C), and technology (T). Details about the model are provided in section 3.2. Economic Modelling.

The ImPACT model, widely used in the analysis of environmental impacts, formed the basic framework of the study. This model covers population, economic prosperity, consumption intensity, and technological factors, providing the opportunity to examine the causes of environmental impacts in a comprehensive manner. Empirical analyses were conducted using Stata 17.0 software. This software was chosen because it provides more reasonable results in panel data analysis compared to other programs. The Panel VAR (Vector Autoregression) model was applied to identify dynamic interactions between variables. Furthermore, Granger causality analysis was performed to test the causal relationships between variables. The Generalized Method of Moments (GMM) was used to address potential endogeneity issues in the model.

Data were obtained from reliable and internationally valid sources. Carbon footprint data was obtained from Our World in Data, economic and demographic indicators from World Development Indicators (WDI), and patent data from the World Intellectual Property Organization (WIPO) database.

The methodological structure of this study ensures its originality in terms of both measurement and modeling. The consideration of a wide range of greenhouse gases in carbon footprint measurement and the quantification of the technological factor through the number of patents offers an innovative approach to environmental impact analysis. Furthermore, the combined use of Panel VAR, GMM, and Granger tests adds methodological depth by enabling the analysis of both the causal aspects and the lagged effects of interactions between variables.

3.1. Data

In this study, the relationships between the variables listed in Table 1 for the G-7 countries (Germany, France, Japan, Italy, Canada, the United Kingdom, and the United States) from 1991 to 2023 are analyzed. Variables prefixed with ‘d’(dgdp, drec, dfp, dpop) represent annual changes calculated relative to the previous year (year-on-year changes). Specifically, they are calculated as the percentage change of the corresponding variables compared to (t-1).

Table 1. Variables, abbreviations, and source.

Variables	Description	Source
dfp	Annual change in carbon footprint per capita.	Our World in Data (OWID, 2024)
dpop	Percentage change in population numbers of G-7 countries.	World Bank (2023)
dgdp	Change in Gross National Product per capita at current exchange rates for G-7 countries.	World Bank (2023)
patent	Annual number of patents obtained from G-7 countries.	World Intellectual Property Organization (WIPO) (2023)
drec	Annual change in the share of renewable energy in total consumption.	World Bank (2023)

Source: Authors' calculations (Our World in Data (OWID), (2024); World Bank, (2023); World Intellectual Property Organization (WIPO), (2023))

Statistical summaries of the data obtained from the sources mentioned in Table 1 are presented in Table 2.

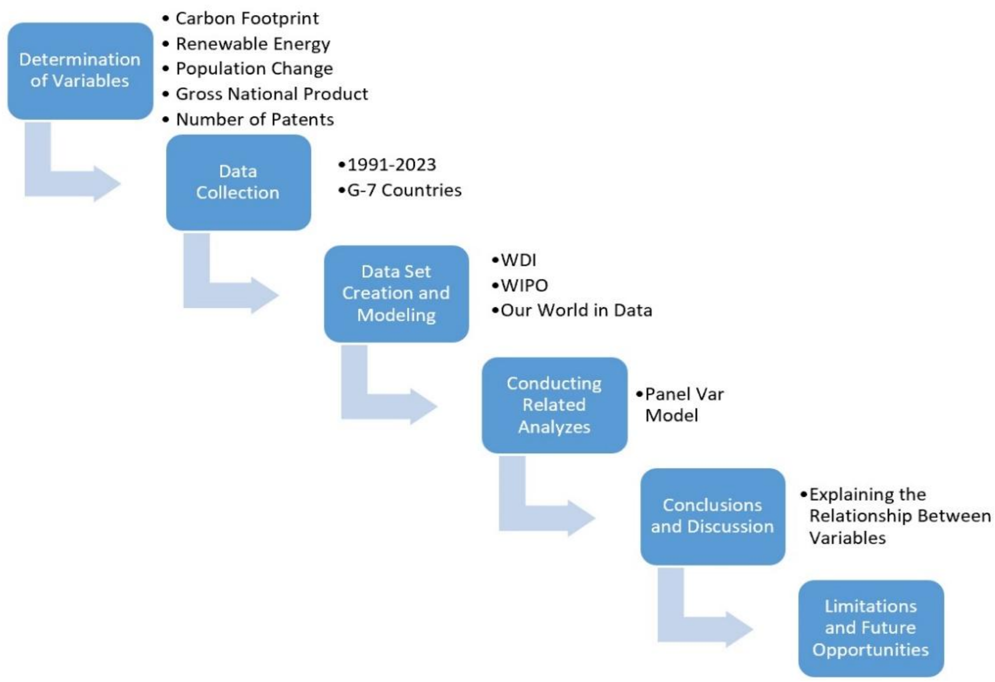
Table 2. Summary statistics.

Variables	**Number of observations**	**Mean**	**Standard deviation**	**Minimum**	**Maximum**
drec	231	.2844156	.6116403	-1.9	2,5
dgdp	231	875.80	2883.91	-8651,98	8959
dpop	231	.0031073	.3573418	-2.3	1.4
patent	231	149419.2	175238.8	2193	532000
dfp	231	-.0465368	.2945714	-1.06	1

Source: Authors' calculations.

When the variables in Table 2 are analyzed, the average of -0.047 for the carbon footprint variable indicates that G-7 countries tend to reduce their carbon emissions in general. The average of 0.284 for renewable energy consumption indicates that these countries have made progress in the energy transition process. A population change of 0.003 indicates that countries are developed economies that have completed their population transition process. The relatively high standard error values suggest that there are significant differences among G-7 countries. The process steps applied within the scope of the research are presented in Figure 1.

Figure 1. Process Steps.



Source: Created by authors.

3.2. Economic Modeling

This study is based on the IPAT (Impact = Population * Affluence * Technology) model, which is widely used in environmental impact analysis. The model was proposed by Ehrlich and Holdren (1971) and reformulated as the ImPACT model by Waggoner and Ausubel (2002). This model was used in the study "A framework for sustainability science: A renovated IPAT identity" and published in the Proceedings of the National Academy of Sciences (PNAS), one of the leading journals in the field (Waggoner and Ausubel, 2002). Original model:

I=P * A * T is. It has been transformed into a more comprehensive form by adding consumption intensity.

I = P × A × C × T (Impact modeli)

I=Environmental Impact, P=Population, A=Affluence Level, C=Consumption, T=Technological Factor represents. In this study, the ImPACT model has been adapted for carbon footprint analysis of G-7 countries, resulting in the following model.

$$dfp_{i,t} = f\left(dpop_{i,t}, dgdp_{i,t}, drec_{i,t}, patent_{i,t}\right) \quad (1)$$

$$dfp_{i,t} = \varphi 1 * dpop_{i,t} + \varphi 2 * dgdp_{i,t} + \varphi 3 * drec_{i,t} + \varphi 4 * patent_{i,t} + e_{i,t} \quad (2)$$

4. Implementation of Panel Var Model

Panel data econometrics is a method that integrates cross-sectional and time-series data in statistical analysis, facilitating the examination of complex relationships between different entities over time and allowing for a deeper understanding. The panel method has several positive features, including its appropriateness in interdependent structures, the ability to examine dynamic effects through impulse-response analysis, the determination of causal relationships between variables through causality tests, and the control of structural differences using the fixed effects model (Arellano and Bond, 1991; Blundell and Bond, 1998).

Investigating lag effects is crucial for both econometrics and statistical analysis. In particular, the appropriate lag length in unit root tests and cointegration analysis can significantly impact the results and may lead to erroneous conclusions if not appropriately handled (Wu, 2010).

Table 3. Lag values.

Number of lags	CD	J	J p-value	MBIC	MAIC	MQIC
1	.9858784	69.18066	.6675642	-326.6779	-80.81934	-180.3547
2	.997114	45.32922	.6610051	-218.5765	-54.67078	-121.0277
3	-.3565607	2.00e+17	0	2.00e+17	2.00e+17	2.00e+17
4	-3.345526	1.10e+15	0	1.10e+15	1.10e+15	1.10e+15

Source: Authors' calculations.

Table 3 shows lag (lags), CD (autocorrelation coefficient), J and J p-value (Johansen cointegration test), MBIC (modified Bayes Information Criterion), MAIC (Akaike Information Criterion), and MQIC (other variations). These ARIMA-type calculation criteria are used to determine the optimal number of lags for the model. When the values in the table are analyzed, it is seen that the first lag has the smallest values in terms of information criterion, and lag 1 is the best choice since it has smaller values than the second, third, and fourth lags.

The variance of each variable is explained by its own history and the contributions of other variables. Periods from 0 to 10 are considered. In the first period (period 0), the variance of the variable is explained by itself. During these periods, the contribution of other variables increases. The data related to this analysis are presented in Table 4.

Table 4. Analysis of Variance.

Foresight-Error	Impulsive variable				
Variance Decomposition	dfp	drec	dgdp	dpop	patent

International Journal of Contemporary Economics and Administrative Sciences
ISSN: 1925 – 4423
Volume: XVI, Issue: 1, Year: 2026, pp. 764-787

dfp					
0	0	0	0		0
1	1	0	0	0	0
2	.7405478	2.23e-06	.0028515	.2540556	.0025429
3	.5386138	.0173084	.0037972	.438576	.0017046
4	.4825213	.0180151	.0033565	.4941716	.0019355
5	.4512208	.0224069	.0033247	.5212558	.0017918
6	.444144	.0224229	.0032559	.528316	.0018614
7	.4402021	.0232948	.003254	.5313976	.0018514
8	.4397753	.0232658	.0032527	.5318292	.0018768
9	.4394186	.0234302	.0032554	.5320108	.001885
10	.4394124	.0234475	.0032586	.5319864	.0018951
drec					
0	0	0	0	0	0
1	.4289156	.5710843	0	0	0
2	.3081609	.4368135	.0120393	.2393238	.0036625
3	.2847477	.3872774	.0109485	.3125369	.0044895
4	.2827547	.3695889	.0106857	.3297794	.0071913
5	.2731633	.3599175	.0103653	.3479733	.0085807
6	.2757764	.357669	.0103358	.345845	.010374
7	.2736752	.3562607	.0103518	.348209	.0115032
8	.274134	.3561748	.0104476	.3467263	.0125173
9	.2736714	.3561409	.0105273	.346434	.0132264
10	.2734759	.3563061	.0106145	.345828	.0137753
dgdp					
0	0	0	0	0	0
1	.3762251	.0073588	.616416	0	0
2	.3904975	.02996	.4359993	.1422067	.0013364
3	.3157464	.0658452	.340838	.2764487	.0011216
4	.3081473	.0626747	.3236443	.304435	.0010987
5	.3003225	.0657419	.3143125	.3184755	.0011476
6	.2987105	.0653701	.3124095	.3223563	.0011534
7	.2983053	.0654777	.3118347	.3231783	.0012039
8	.2981217	.0654895	.3116167	.323538	.001234
9	.2981417	.0654918	.3115892	.3235102	.0012671
10	.2981319	.0655348	.3115221	.3235186	.0012925
dpop					
0	0	0	0	0	0
1	.0294338	.1720079	6.30e-06	.798552	0
2	.0452192	.1661616	.0016041	.7870082	6.86e-06
3	.0614324	.1642944	.0015779	.7726187	.0000765
4	.0655979	.1620248	.0018283	.7704469	.0001021
5	.0673583	.1600056	.0018093	.7707134	.0001133
6	.0676016	.1593889	.0018248	.7710591	.0001256
7	.0676101	.1590716	.0018209	.771372	.0001254
8	.0676141	.158995	.0018205	.7714408	.0001295
9	.0675975	.1589727	.0018202	.7714795	.0001301
10	.0675999	.1589669	.0018201	.7714813	.0001318
patent					
0	0	0	0	0	0
1	.6922349	.0620045	.0001288	.0004552	.2451765
2	.3451391	.1592522	.0064614	.3209524	.1681949
3	.3653762	.1932624	.0094716	.2605246	.1713651

4	.3199938	.2272991	.0119005	.2859775	.1548291
5	.3147535	.2477607	.0137832	.2725588	.1511438
6	.3027629	.2629221	.0149953	.2739926	.1453271
7	.2975059	.2733529	.0159466	.2708111	.1423835
8	.2929164	.2807996	.0165856	.2698877	.1398107
9	.2898294	.286132	.0170674	.2688826	.1380886
10	.2876382	.289968	.017408	.2681822	.1368036

Source: Authors' calculations.

The variance decomposition results indicate that carbon footprint dynamics in G-7 countries are primarily driven by population growth. At the same time, the impact of renewable energy and technological innovation has not yet reached the expected level. Stricter environmental policies and more effective technological transformation are required to achieve sustainable development goals.

The Generalized Method of Moments Estimation attempts to estimate the equation by utilizing statistical information, such as the mean and variance of the model parameters. This model is preferred in panel data analyses, financial models, econometric studies, and models with endogenous variables. The structure of the GMM allows lagged variables to be integrated as instruments, providing a solution to the simultaneity problems in the data (Bera et al., 2010).

Table 5. Generalized method of moments estimation.

Items		**Coefficient**	**Standard Deviation**	**z**	**P>|z|**	**[95% Interval]**	**Confidence**
dfp	dfp L1.	-.5809053	.163718	-3.55	0.000	-.9017866	-.2600239
	rec L1.	.266114	.1044425	2.55	0.011	.0614104	.4708176
	gdp L1.	-.0000176	.0000204	-0.86	0.389	-.0000577	.0000224
	dpop L1.	-1.459459	.7188437	-2.03	0.042	-2.868367	-.0505516
	patent L1.	-2.15e-06	5.35e-07	-4.02	0.000	-3.20e-06	-1.10e-06
drec	dfp L1.	.5426939	.2240724	2.42	0.015	.1035201	.9818678
	rec L1.	.2297232	.118632	1.94	0.053	-.0027912	.4622376
	gdp L1.	.000048	.0000293	1.64	0.102	-9.47e-06	.0001055
	dpop L1.	1.888695	.9542263	1.98	0.048	.018446	3.758944
	patent L1.	3.44e-06	9.32e-07	3.69	0.000	1.61e-06	5.26e-06
dgdp	dfp L1.	-902.755	886.2146	-1.02	0.308	-2639.704	834.1937
	rec L1.	1917.072	506.8029	3.78	0.000	923.757	2910.388
	gdp L1.	.06976	.1017058	0.69	0.493	-.1295798	.2690997
	dpop L1.	-5046.765	3175.068	-1.59	0.112	-11269.78	1176.255

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	patent L1.	-.0072024	.0033373	-2.16	0.031	-.0137434	-.0006615
dpop	dfp L1.	.0759031	.0403099	1.88	0.060	-.0031028	.154909
	rec L1.	.0259757	.0324255	0.80	0.423	-.0375771	.0895286
	gdp L1.	5.15e-06	6.21e-06	0.83	0.407	-7.02e-06	.0000173
	dpop L1.	-.1451319	.078287	-1.85	0.064	-.2985715	.0083077
	patent L1.	-4.41e-08	1.63e-07	-0.27	0.786	-3.63e-07	2.75e-07
patent	dfp L1.	-24410.82	11239.47	-2.17	0.030	-46439.77	-2381.871
	rec L1.	1459.357	7019.872	0.21	0.835	-12299.34	15218.05
	gdp L1.	-2.168201	1.692992	-1.28	0.200	-5.486403	1.150002
	dpop L1.	-120386.4	61281.06	-1.96	0.049	-240495.1	-277.7015
	patent L1.	.8544765	.0487333	17.53	0.000	.758961	.9499921

Source: Authors' calculations.

GMM estimation results indicate that the dynamics of carbon footprints in G-7 countries exhibit a complex structure and are influenced by multiple factors. It can be clearly seen that the technological factor (patent) has a significant negative impact on carbon footprint ($p < 0.001$) and contributes to environmental sustainability, while the negative impact of the renewable energy process is limited.

The model is estimated using the two-step System GMM estimator. The Arellano-Bond serial correlation test indicates no evidence of second-order autocorrelation in first differences (AR(2), p=0.723), supporting the validity of the moment conditions. The AR(1) test is statistically insignificant (p=0.393), suggesting that residual serial correlation is not present in the transformed equation.

The validity of the instrument set is evaluated using the Sargan and Hansen tests of overidentifying restrictions. The Sargan test doesn't reject the null hypothesis of instrument validity ($X^2(30) = 36.15, p = 0.203$). Likewise, the Hansen J test, which is robust to heteroskedasticity, yields a p-value of 1.000, indicating that the overidentifying restrictions cannot be rejected. Overall, diagnostic results support the appropriateness of the model specification and the validity of the instrument set.

The eigenvalue roots of the variables are located within the unit circle. The absolute value of all eigenvalue roots must be less than 1. These roots must lie within the unit circle. Panel Var fulfills the stability condition. A stable Panel VAR system returns to its equilibrium in the long run. As a result of the analysis, the variance decomposition gives reliable results. In terms of the model, it shows that the model specification is chosen correctly, the lag length is chosen appropriately, and impulse-response analysis can be performed. Stability in Panel VAR should generally be checked before the Granger Causality test.

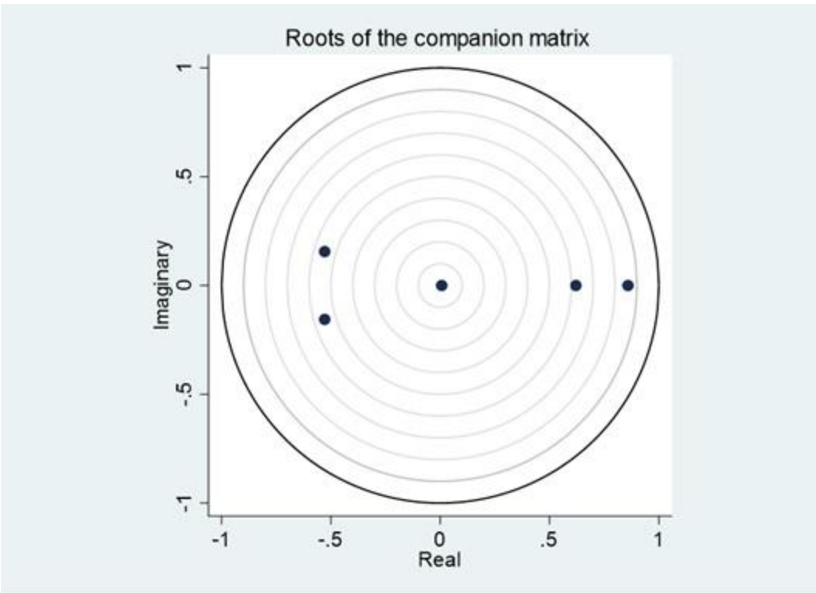
Table 6. Generalized method of moments estimation.

Eigenvalue		
Real	**Projection**	**Modules**
.8585059	0	.8585059
.6203457	0	.6203457
-.5287033	-.1558438	.5511937
-.5287033	.1558438	.5511937
.0064775	0	.0064775

Source: Authors' calculations.

The successful results of the stability test confirm that this dataset and method are an appropriate economic approach for Panel VAR analysis. Figure 2 shows that all eigenvalues are within the unit circle. In light of the obtained visualization, it is possible to say that the system is stable and resilient to shocks, returning to equilibrium in the long run.

Figure 2. Roots of a matrix.



Source: Authors' calculations.

Satisfying the stability condition guarantees the reliability of impulse-response analyses and Granger Causality tests between system variables. If one or

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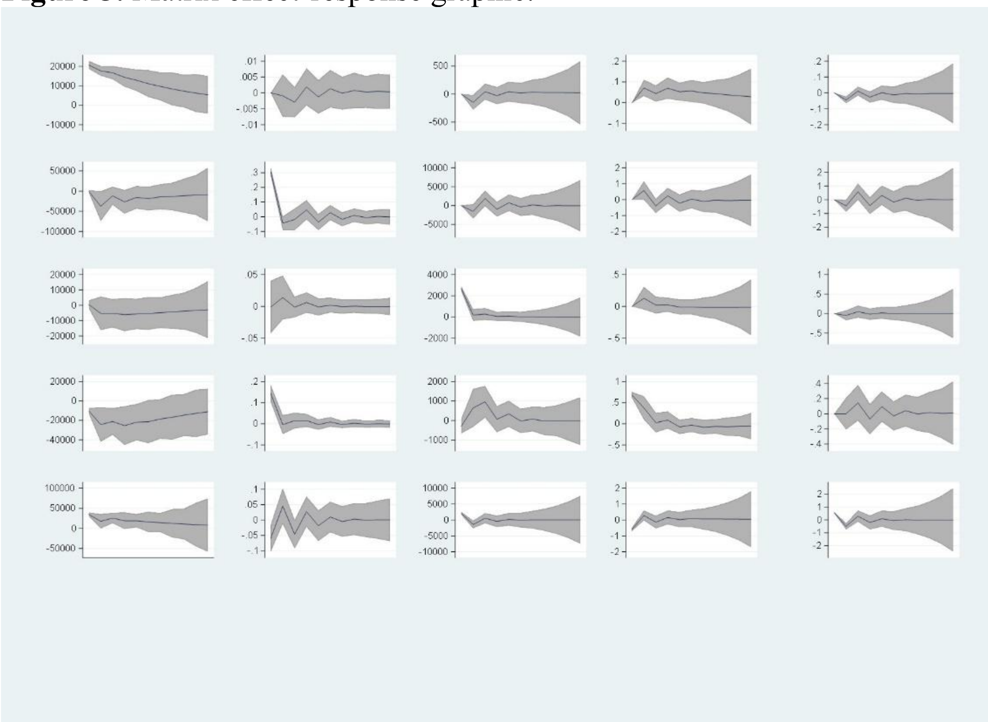
more of the roots were outside the system, the system would become unstable and deteriorate due to the widening of the gap between the system's roots over time.

Impulse response analysis is a primary method for understanding the dynamic relationships between variables in econometric models. The impulse-response function shows the effect of a one-unit shock in one variable on other variables over time. This analysis is conducted within the framework of VAR (vector autoregression) models. It is usually presented graphically, with the y-axis representing the magnitude of the response and the x-axis representing the time period. When analyzing the graph, the direction of the response, the magnitude of the response, the duration of the effect, and the pattern of change over time are examined. The graph is presented in Figure 3.

Figure 3. Matrix effect-response graphic.



Source: Authors' calculations.

The results of the impulse-response analysis indicate that the technological factor (patents) has a permanent negative impact on the carbon footprint in G-7 countries. In contrast, renewable energy shocks have a positive effect in the short term but an adverse effect in the long term, due to the costs associated with energy conversion. The positive impact of population growth on carbon footprint highlights the importance of effective population policies. Environmental policies should be considered more in the long term.

The Granger Causality test used in conjunction with the GMM model has been found effective in explaining collinearity and authentic causal relationships

(Zheng and Jiang, 2007). The Granger causality test is an econometric model used to examine the relationships between variables in time series analysis. Developed in 1969 by Clive Granger, this test aims to determine whether past values of another variable aid in predicting future values of a variable (Granger, 1969).

$$X_1(t) = \sum_{j=1}^{p} A_{11,j} X_1(t-j) + \sum_{j=1}^{p} A_{12,j} X_2(t-j) + E_1(t) \tag{3}$$

$$X_2(t) = \sum_{j=1}^{p} A_{21,j} X_1(t-j) + \sum_{j=1}^{p} A_{22,j} X_2(t-j) + E_2(t) \tag{4}$$

Null Hypothesis
H_0: $A_{12} = 0$ (X_2, X_1 is not the Granger cause.)
Alternative Hypothesis
H_1: $A_{12} \neq 0$ (X_2, X_1 Granger cause.)

Table 7. Granger causality test.

Equation	**Excluded**	**chi2**	**df**	**Prob> chi2**
dfp				
	rec	6.492	1	0.011
	gpd	0.744	1	0.389
	dpop	4.122	1	0.042
	patent	16.148	1	0.000
	ALL	8.089	3	0.044
drec				
	dfp	5.866	1	0.015
	gdp	2.680	1	0.102
	dpop	3.918	1	0.048
	patent	13.597	1	0.000
	ALL	14.921	3	0.002
dgdp				
	dfp	1.038	1	0.308
	gdp	14.309	1	0.000
	dpop	2.527	1	0.112
	patent	4.658	1	0.031
	ALL	16.467	3	0.001
dpop				
	dfp	3.546	1	0.060

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	rec	0.642	1	0.423
	gdp	0.688	1	0.407
	patent	0.074	1	0.786
	ALL	7.060	3	0.070
patent				
	dfp	4.717	1	0.030
	rec	0.043	1	0.835
	gdp	1.640	1	0.200
	dpop	3.859	1	0.049
	ALL	12.624	4	0.013

Source: Authors' calculations.

According to the Granger Causality test in Table 7, it is evident that the technological factor (patent) has a significant impact on carbon footprint, and a bidirectional causality relationship exists between carbon footprint and renewable energy.

5. Conclusion and Discussion

This study examines the dynamic relationships between carbon footprint as the dependent variable and the independent variables of renewable energy consumption (drec), gross domestic product (dgdp), change in population density (dpop), and number of patents (patent), using data from G-7 countries for the period 1991-2023. Empirical findings reveal that technological innovation has a significant and negative effect on carbon footprint ($ß = -2.15e-06$, $p < 0.0001$). This highlights that an increase in the number of patents supports environmental sustainability and that innovative technologies have a carbon footprint-reducing effect. In contrast, changes in renewable energy consumption exhibit a positive and statistically significant short-run effect on the carbon footprint ($ß=0.266$, $p < 0.05$). This result suggests that the transition process toward renewable energy may initially generate adjustment costs or structural transformation effects that temporarily increase carbon emissions. Granger causality analysis shows a bidirectional relationship between carbon footprint and renewable energy consumption. This finding suggests a dynamic interaction in which renewable energy policies influence environmental outcomes, while changes in conditions may also affect energy policy adjustments and renewable energy demand.

The effect of the population variable was found to be negative and statistically significant ($ß=-1.459$, $p <0.05$). This result suggests that the slowdown in population growth in G-7 countries may have a limiting effect on the carbon footprint. In contrast, the effect of economic growth on the carbon footprint was not statistically significant (p=0.389). This result indicates that the Environmental Kuznets Curve hypothesis has limited validity in the context of G-7 countries.

The research findings are consistent with studies in the literature examining G-7 countries, such as Sadorsky (2009) and Wang et al. (2020). It was concluded that technological innovation and renewable energy consumption positively affect environmental performance. This is consistent with studies supporting the Porter Hypothesis in the existing literature. From the perspective of policymakers, the strategic importance of increasing renewable energy investments and technological innovation in reducing the carbon footprint is emphasized.

The study has limitations. It is difficult to fully disentangle the effects of major shocks such as the 2008 global financial crisis and the COVID-19 pandemic that occurred during the 32-year data period. Economic and technological differences among G-7 countries may affect the model results. Furthermore, carbon pricing, environmental regulations, and international trade have not been included in the model. This may limit the generalizability of the results obtained.

For future researchers, it is recommended to include new variables such as energy efficiency, digitalization index, and green technology patents, and to apply the model to broader country groups such as G-20 or OECD countries. In conclusion, this study empirically demonstrates that technological innovation and renewable energy use are critical for reducing the carbon footprint in the context of G-7 countries. In this context, G-7 countries should more strongly embrace sustainable energy and innovation policies in line with their global climate leadership roles and set an example for developing countries in this area.

REFERENCES

Aichele, R., and Felbermayr, G. (2013). The Effect of the Kyoto Protocol on Carbon Emissions. *Journal of Policy Analysis and Management*, *32*(4), 731–757. https://doi.org/10.1002/PAM.21720

Akrofi, M. M., Okitasari, M., and Kandpal, R. (2022). Recent trends on the linkages between energy, SDGs and the Paris Agreement: a review of policy-based studies. *Discover Sustainability*, *3*(1), 1–17. https://doi.org/10.1007/S43621-022-00100-Y

Albino, V., Ardito, L., Dangelico, R. M., and Messeni Petruzzelli, A. (2014). Understanding the development trends of low-carbon energy technologies: A patent analysis. *Applied Energy*, *135*, 836–854. https://doi.org/10.1016/J.APENERGY.2014.08.012

Almeida, D., Carvalho, L., Ferreira, P., Dionísio, A., and Haq, I. U. (2024). Global Dynamics of Environmental Kuznets Curve: A Cross-Correlation Analysis of Income and CO_2 Emissions. *Sustainability 2024, Vol. 16, Page 9089*, *16*(20), 9089. https://doi.org/10.3390/SU16209089

Altintas, F. F. (2020). İnovasyonun ekonomik büyümeyi etkilemesine yönelik bir yapısal eşitlik modeli uygulaması: G20 grubu ülkeleri örneği. *Business and*

Management Studies: An International Journal, *8*(4), 723–763. https://doi.org/10.15295/BMIJ.V8I4.1582

Arellano, M., and Bond, S. (1991). Some Tests of Specification for Panel Data: Monte Carlo Evidence and an Application to Employment Equations. *The Review of Economic Studies*, *58*(2), 277–297. https://doi.org/10.2307/2297968

Arı, A., and Zeren, F. (2011). CO_2 Emisyonu ve Ekonomik Büyüme: Panel Veri Analizi. *Yönetim ve Ekonomi Dergisi*, *18*(2), 37–47. https://dergipark.org.tr/tr/pub/yonveek/issue/13695/165744

Asaloko, P. P., Asongu, S., and Zogo, T. E. (2025). Does peak technology combat energy poverty in developing countries? *International Journal of Energy Sector Management*. https://doi.org/10.1108/IJESM-12-2024-0028

Aslan, A., Apergis, N., and Yildirim, S. (2014). Causality between energy consumption and GDP in the U.S.: Evidence from wavelet analysis. *Frontiers in Energy*, *8*(1), 1–8. https://doi.org/10.1007/S11708-013-0290-6

Aye, G. C., and Edoja, P. E. (2017). Effect of economic growth on CO_2 emission in developing countries: Evidence from a dynamic panel threshold model. *Cogent Economics and Finance*, *5*(1). https://doi.org/10.1080/23322039.2017.1379239

Bera, A. K., Montes-Rojas, G., and Sosa-Escudero, W. (2010). General specification testing with locallymisspecified models. *Econometric Theory*, *26*(6), 1838–1845. https://doi.org/10.1017/S0266466609990818

Bilalli, A., Gollopeni, K. S., Beka, A., and Gara, A. (2024). The Relationship Between Renewable Energy Consumption, Carbon Dioxide Emissions, Economic Growth, and Foreign Direct Investment: Evidence from Developed European Countries. *International Journal of Sustainable Development and Planning*, *19*(1), 375–384. https://doi.org/10.18280/IJSDP.190136

Bilgili, F., Koçak, E., and Bulut, Ü. (2016). The dynamic impact of renewable energy consumption on CO_2 emissions: A revisited Environmental Kuznets Curve approach. *Renewable and Sustainable Energy Reviews*, *54*, 838–845. https://doi.org/10.1016/J.RSER.2015.10.080

Blundell, R., and Bond, S. (1998). Initial conditions and moment restrictions in dynamic panel data models. *Journal of Econometrics*, *87*(1), 115–143. https://doi.org/10.1016/S0304-4076(98)00009-8

Böhringer, C. (2003). The Kyoto Protocol: A Review and Perspectives. *Oxford Review of Economic Policy*, *19*(3), 451–466. https://doi.org/10.1093/OXREP/19.3.451

Boutabba, M. A. (2014). The impact of financial development, income, energy and trade on carbon emissions: Evidence from the Indian economy. *Economic Modelling*, *40*, 33–41. https://doi.org/10.1016/J.ECONMOD.2014.03.005

Dağ, M., and Kızılkaya, F. (2021). Türkiye için sağlık harcamaları, CO_2 emisyonları ve ekonomik büyüme ilişkisinin incelenmesi. *Yönetim ve Ekonomi Araştırmaları Dergisi*, *19*(3), 211–229. https://doi.org/10.11611/YEAD.917255

Damırova, S., and Yayla, N. (2021). Çevre kirliliği ile makroekonomik belirleyicileri arasındaki ilişki: Seçilmiş ülkeler için bir panel veri analizi.

Uluslararası İktisadi ve İdari İncelemeler Dergisi, *30*, 107–126. https://doi.org/10.18092/ULIKIDINCE.804787

Danish, Zhang, B., Wang, B., and Wang, Z. (2017). Role of renewable energy and non-renewable energy consumption on EKC: Evidence from Pakistan. *Journal of Cleaner Production*, *156*, 855–864. https://doi.org/10.1016/J.JCLEPRO.2017.03.203

Duscha, V., Denishchenkova, A., and Wachsmuth, J. (2019). Achievability of the Paris Agreement targets in the EU: demand-side reduction potentials in a carbon budget perspective. *Climate Policy*, *19*(2), 161–174. https://doi.org/10.1080/14693062.2018.1471385

Ehrlich, P. R., and Holdren, J. P. (1971). Impact of population growth. *Science*, *171*(3977), 1212–1217. https://doi.org/10.1126/SCIENCE.171.3977.1212

Erkök, B. (2022). Almanya'nın Enerji Dönüşümü Politikaları: Türkiye İçin Bir Örnek. *Fiscaoeconomia*, *6*(2), 294–324. https://doi.org/10.25295/FSECON.1056335

Eslamidoost, Z., Arabzadeh, M., Oskoie, V., and Dehghani, S. (2022). Carbon footprint calculation in one of the largest Gas Refinery Companies in the Middle East. *Environmental Science and Pollution Research*, *29*(54), 81609–81623. https://doi.org/10.1007/S11356-022-21482-6

Fakher, H. A. (2019). Investigating the determinant factors of environmental quality (based on ecological carbon footprint index). *Environmental Science and Pollution Research*, *26*(10), 10276–10291. https://doi.org/10.1007/S11356-019-04452-3/METRICS

Fasanya, I. O., and Arek-Bawa, O. (2025). Connection between urbanization and CO_2 emissions in South Africa: does global uncertainty matter? *International Journal of Energy Sector Management*, *19*(2), 412–428. https://doi.org/10.1108/IJESM-03-2024-0020

Granger, C. W. J. (1969). Investigating Causal Relations by Econometric Models and Cross-spectral Methods. *Econometrica*, *37*(3), 424. https://doi.org/10.2307/1912791

Grossman, G. M., and Krueger, A. B. (1995). Economic Growth and the Environment. *The Quarterly Journal of Economics*, *110*(2), 353–377. https://doi.org/10.2307/2118443

Gül, İ., and Shipman, D. (2021). Aşırı Turizm, Nüfus Teorisi ve Turizme Katılım. *Ahi Evran Üniversitesi Sosyal Bilimler Enstitüsü Dergisi*, *7*(3), 993–1006. https://doi.org/10.31592/AEUSBED.827987

Imandojemu, K., Osabohien, R., Sule, A., and Al-Faryan, M. A. S. (2025). Quantile analysis of the role of renewable energy technology on carbon neutrality in organization for economic co-operation and development countries. *International Journal of Energy Sector Management*. https://doi.org/10.1108/IJESM-10-2024-0046

Jang, W. S., Kim, J. S., Kong, B. S., Lee, D. C., and Kim, B. S. (2014). Experimental Analysis to Characterizing CO_2 Emission of Roller. *Advanced Materials Research*, *898*, 452–455. https://doi.org/10.4028/WWW.SCIENTIFIC.NET/AMR.898.452

Jiying, W., Beraud, J. J. D., and Xicang, Z. (2023). Investigating the impact of air pollution in selected African developing countries. *Environmental Science and*

Pollution Research, *30*(23), 64460–64471. https://doi.org/10.1007/S11356-023-26998-Z/METRICS

Kuznets, S. (1985). Economic Growth and Income Inequality. In M. A. Seligson (Ed.), *The Gap Between Rich and Poor* (pp. 25–37). Routledge. https://doi.org/https://doi.org/10.4324/9780429311208

Le, T. H., Chang, Y., and Park, D. (2017). Energy demand convergence in APEC: An empirical analysis. *Energy Economics*, *65*, 32–41. https://doi.org/10.1016/J.ENECO.2017.04.013

Leal, P. H., and Marques, A. C. (2022). The evolution of the environmental Kuznets curve hypothesis assessment: A literature review under a critical analysis perspective. *Heliyon*, *8*(11), e11521. https://doi.org/10.1016/J.HELIYON.2022.E11521

Liu, B., Mahmood, B. S., Mohammadian, E., Manshad, A. K., Rosli, N. R., and Ostadhassan, M. (2021). Measurement of solubility of CO2 in NaCl, CaCl2, MgCl2 and MgCl2 + CaCl2 brines at temperatures from 298 to 373 K and pressures up to 20 mpa using the potentiometric titration method. *Energies*, *14*(21), 7222. https://doi.org/10.3390/EN14217222/S1

Long, X., Chen, Y., Du, J., Oh, K., and Han, I. (2017). Environmental innovation and its impact on economic and environmental performance: Evidence from Korean-owned firms in China. *Energy Policy*, *107*, 131–137. https://doi.org/10.1016/J.ENPOL.2017.04.044

Maranville, S. (1992). Entrepreneurship in the Business Curriculum. *Journal of Education for Business*, *68*(1), 27–31. https://doi.org/10.1080/08832323.1992.10117582

Martínez-Navarro, D., Amate-Fortes, I., and Guarnido-Rueda, A. (2020). Inequality and development: is the Kuznets curve in effect today? *Economia Politica*, *37*(3), 703–735. https://doi.org/10.1007/S40888-020-00190-9

Mazlum, E. C. (2023). Ekonomik Büyüme Ve Ekolojik Ayak İzi İlişkisi: E7 Ülkeleri Örneği. *Uluslararası Anadolu Sosyal Bilimler Dergisi*, *7*(1), 123–135. https://doi.org/10.47525/ULASBID.1235614

Mor, S., Aneja, R., Madan, S., and Ghimire, M. (2024). Kyoto Protocol and Paris Agreement: Transition from Bindings to Pledges – A Review. *Millennial Asia*, *15*(4), 690–711. https://doi.org/10.1177/09763996221141546

National Centers for Environmental Information (NCEI). (2025). *Global Climate Report (Annual 2024)*. https://www.ncei.noaa.gov/access/monitoring/monthly-report/global/202413

Nielsen, F., and Alderson, A. S. (1997). The Kuznets curve and the great u-turn: Income inequality in U.S. counties, 1970 to 1990. *American Sociological Review*, *62*(1), 12–33. https://doi.org/10.2307/2657450

OECD. (2015). *Beyond the Millennium Development Goals: Towards an OECD contribution to the post-2015 agenda*. https://unstats.un.org/unsd/broaderprogress/pdf/POST-2015%20Overview%20Paper%20(OECD).pdf

OWID. (2024). OWID Homepage. *Our World in Data*. https://ourworldindata.org

Özbek, S. (2023). Enerji İthalatçısı Gelişmekte Olan Ülkelerde Enerji Yoğunluğunun Belirleyicileri. *Cumhuriyet Üniversitesi İktisadi ve İdari*

Bilimler Dergisi, *24*(1), 114–126. https://doi.org/10.37880/CUMUIIBF.1181547

Özekenci, E. K. (2023). Karbondioksit emisyonu (CO_2) ile ihracat, enerji, doğrudan yabancı yatırımlar ve ekonomik büyüme arasındaki ilişki: Türkiye örneği. *Uluslararası İktisadi ve İdari İncelemeler Dergisi*, *40*, 83–98. https://doi.org/10.18092/ULIKIDINCE.1251325

Pata, U. K. (2021). Renewable and non-renewable energy consumption, economic complexity, CO_2 emissions, and ecological footprint in the USA: testing the EKC hypothesis with a structural break. *Environmental Science and Pollution Research*, *28*(1), 846–861. https://doi.org/10.1007/S11356-020-10446-3

Patrick Arnold, O. K., Donald, D. S., Rovier, D., and Pauline, N. T. (2025). Perceptions of climate change and pro-environmental behavior: case study on the adoption of liquefied petroleum gas in Cameroon. *International Journal of Energy Sector Management*, *19*(4), 1061–1074. https://doi.org/10.1108/IJESM-05-2024-0008

Popp, D., Hascic, I., and Medhi, N. (2011). Technology and the diffusion of renewable energy. *Energy Economics*, *33*(4), 648–662. https://doi.org/10.1016/J.ENECO.2010.08.007

Porter, M. E. (1991). Towards a dynamic theory of strategy. *Strategic Management Journal*, *12*(2 S), 95–117. https://doi.org/10.1002/SMJ.4250121008

Raiser, K., Naims, H., and Bruhn, T. (2017). Corporatization of the climate? Innovation, intellectual property rights, and patents for climate change mitigation. *Energy Research and Social Science*, *27*, 1–8. https://doi.org/10.1016/J.ERSS.2017.01.020

Roy Chowdhury, R., and Moran, E. F. (2012). Turning the curve: A critical review of Kuznets approaches. *Applied Geography*, *32*(1), 3–11. https://doi.org/10.1016/J.APGEOG.2010.07.004

Sadorsky, P. (2009). Renewable energy consumption, CO_2 emissions and oil prices in the G7 countries. *Energy Economics*, *31*(3), 456–462. https://doi.org/10.1016/J.ENECO.2008.12.010

Tokal, P. (2022). Yükselen Ekonomilerde İnovasyon ve Büyüme İlişkisi: Panel Eşbütünleşme Analizi. *TESAM Akademi Dergisi*, *9*(2), 649–681. https://doi.org/10.30626/TESAMAKADEMI.1103653

Umair, M., Yousuf, M. U., Cheema, A. R., and Ul-Haq, J. (2025). Assessing the environmental consequences of fossil fuel consumption in newly industrialized countries. *International Journal of Energy Sector Management*, *19*(4), 1027–1044. https://doi.org/10.1108/IJESM-08-2024-0036

Uzunali, A., and Yazıcı, T. (2023). Carbon footprint changing with Covid-19 in Turkey. *Environment, Development and Sustainability*, *25*(10), 10685–10707. https://doi.org/10.1007/S10668-022-02500-6

Waggoner, P. E., and Ausubel, J. H. (2002). A framework for sustainability science: A renovated IPAT identity. *Proceedings of the National Academy of Sciences of the United States of America*, *99*(12), 7860–7865. https://doi.org/10.1073/PNAS.122235999

Wang, L., Chang, H. L., Rizvi, S. K. A., and Sari, A. (2020). Are eco-innovation and export diversification mutually exclusive to control carbon emissions in

G-7 countries? *Journal of Environmental Management*, *270*, 110829. https://doi.org/10.1016/J.JENVMAN.2020.110829

Wei, Y., Tao, X., Zhu, J., Ma, Y., Yang, S., and ayub, A. (2024). Examining the relationship between international digital trade, green technology innovation and environmental sustainability in top emerging economics. *Heliyon*, *10*(7), e28210. https://doi.org/10.1016/J.HELIYON.2024.E28210

World Bank. (2023). *World Development Indicators | DataBank*. https://databank.worldbank.org/source/world-development-indicators

World Intellectual Property Organization (WIPO). (2023). *WIPO IP Facts and Figures 2023*. https://www.wipo.int/publications/en/details.jsp?id=4686andplang=EN

Wu, S. (2010). Lag length selection in DF-GLS unit root tests. *Communications in Statistics: Simulation and Computation*, *39*(8), 1590–1604. https://doi.org/10.1080/03610918.2010.508143

Yilanci, V., Haouas, I., Ozgur, O., and Sarkodie, S. A. (2021). Energy Diversification and Economic Development in Emergent Countries: Evidence From Fourier Function-Driven Bootstrap Panel Causality Test. *Frontiers in Energy Research*, *9*, 632712. https://doi.org/10.3389/FENRG.2021.632712

Zheng, J. C., and Jiang, H. K. (2007). Correlation analysis and causality test between Ludong-Huanghai block and South Japan. *Acta Seismologica Sinica English Edition*, *20*(4), 381–391. https://doi.org/10.1007/S11589-007-0381-8