How Economic Growth affected from Technological Innovation, CO2 Emissions, and Renewable Energy Consumption? Empirical Analysis in G7 Countries

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How Economic Growth affected from Technological Innovation, CO_2 Emissions, and Renewable Energy Consumption? Empirical Analysis in G7 Countries

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Abstract

Today's economically developed nations are also among the most advanced in terms of energy production and consumption. In particular, the widespread implementation of renewable energy sources and the plethora of technological advancements supporting long-term prosperity stand out. The research aims to examine how carbon dioxide (CO_2) emissions, technological advancements, and the use of renewable energy sources affect economic expansion. Research and development (R&D) expenses are regarded as a proxy for technological progress. Using annual data for the G7 countries from 1996 through 2020, the analysis quantified the interplay between the factors. We examine the association between our variables using panel unit root tests, Pedroni cointegration tests, ARDL coefficient estimations, and Granger (Dumitrescu Hurlin) causality tests. The Pedroni cointegration test indicated that the variables are cointegrated. According to the ARDL method of computation, increasing levels of CO_2 emissions are beneficial to long-term economic growth. However, improvements in renewable energy and technology dampen economic expansion. As a conclusion, the Dumitrescu-Hurlin causality test shows that there is a unidirectional chain of events from CO_2 emissions to technological improvements, from economic growth to use of renewable energy, and from consumption of renewable energy to technological advances. Expansion of the economy and increased emissions of carbon dioxide have a reciprocal relationship.

Keywords: Economic growth, ARDL, renewable energy consumption, technological innovations, CO_2 emissions, G7

Jel classification: O13, O32, O47, Q53

1. Introduction

Academic researchers and policymakers have long focused on economic growth, especially long-term sustainability. Economic growth is a subject related to research and development activities, energy consumption, and environmental pollution closely. Energy use, which is one of the foundations of economic growth, is of great importance in terms of the limited resources used. In addition, for the production factor, which is important factor for economic development, countries must constantly engage in innovative activities to ensure production techniques, product diversity, and product continuity. These creative activities are provided by technological innovations, patent studies, and research and development activities. As a result of all these activities, the concept of environmental pollution, which is one of the most critical issues of our century, appears before us. Here, the close relationship between innovation activities, economic growth, energy use, and air pollution emerges.

Energy is crucial for economic growth and activities, but environmental hazards arising from fossil fuels (oil, coal, gas) and the possibility of depletion of these resources have triggered the search for alternative energy sources (Bildirici and Gökmenoğlu, 2017). Researchers' attention to energy consumption, environmental safeguarding, and economic growth has increased remarkably to cope the common threat (Baz et al., 2019; Akadiri et al., 2019). At this point, renewable energy sources' importance comes forward. Renewable energy is an environment-friendly energy source known as harmless to public health. In addition, renewable energy resources are a continuous resource that can increase energy security by reducing a country's dependence on fossil fuels. (Al-Mulali et al., 2015). Considering specially developed countries' energy needs, economic growth and renewable energy consumption relationship gain tremendous importance. Increments in energy demand and climate problems resulting from the fossil fuel consumption intensively have forced most countries to move on renewable resources to improve air quality and reduce their

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ecological footprint (Nasrullah et al., 2021). In addition to renewable energy sources, technological progress and industrial innovation also play an essential role in ensuring long-term economic growth (Grossman and Helpman, 1994). Schumpeter (2010), one of the first thinkers of the relationship between industrial innovation and technological progress and economic growth, mentioned that these two factors have an essential role in economic development (Hasan and Tucci, 2010).

The study's goal is to analyze the connections between four variables that have been discussed individually in the literature: carbon dioxide emissions (CO_2), economic growth (GDP), R&D expenditures (RD), and renewable energy consumption (REN). One of the different values that the study will add to the literature is to expand the research line by assuming that innovation, which is thought to affect economic growth, makes a significant difference not only in the number of patents but also in R&D expenditures. Additionally, it is investigated whether there is a correlation between the economic might of nations with large R&D spending and the benefits of innovation on economic growth through previously developed economies.

This research uses panel data analysis to examine the interplay between a wide range of factors, such as CO_2 emissions, technological advancement, and the adoption of renewable energy sources, and the long-term growth of economies. Using data on the G-7 nations from 1996 to 2020 and the Pedroni Cointegration test, we find that the variables have been persistently related. According to the ARDL model, increasing R&D investment and renewable energy use will have a negative impact on economic development, whereas increasing CO_2 emissions would have a favorable impact. According to the Dumitrescu and Hurlin causality test, there is only a one-way connection between renewable energy use and technical advancement, economic development and renewable energy, CO_2 emissions and technological advancement, and renewable energy use and CO_2 emissions. The correlation between CO_2 emissions and economic expansion is demonstrated.

Here's how the rest of the study is laid out. The theoretical underpinnings of the investigation were assessed in the review of relevant literature. Datasets, econometric models, methods, and findings are all described in detail in the methodology, data, and findings sections. The conclusion reveals the findings of the research.

2. Literature Review

The findings of a comprehensive investigation of the link between technological progress, economic expansion, and greenhouse gas emissions might have far-reaching policy ramifications and provide potential answers to a number of related issues. There is a wealth of research in the literature looking at how rising CO_2 levels are linked to thriving economies. Some academics argue that these two issues need to be addressed together for the purpose of the reliability of the study (Acheampong, 2018). Even while there is some published research on the issue of innovation and economic growth, the great bulk of this material focuses on the connection between carbon dioxide emissions and GDP growth.

Acheampong (2018) analyzed the GDP growth, carbon emissions, and energy usage of 116 countries from 1990 to 2014 using the PVAR and System-GMM. When economies expand, carbon emissions decrease globally, but there is no evidence that this is true for the Caribbean or Latin America. The research concluded that carbon emissions are helpful for economic expansion. Heidari et al. (2015) used a state-of-the-art PSTR model to test the environmental Kuznets curve (EKC) by analyzing the relationship between energy consumption, CO_2 emissions, and economic development in five ASEAN countries (Thailand, Indonesia, Singapore, Philippines, and Malaysia). The study validated the environmental kuznets curve for five ASEAN nations and revealed an inverse nonlinear relationship between CO_2 emissions and economic development. Saidi and Hammam (2015) used data from 58 states to analyze the connection between GDP growth, carbon dioxide emissions, and energy consumption. The panel data dynamics were calculated in this study using the Generalized Method of Moments (GMM) from 1990 to 2012. A rise in carbon dioxide emissions is shown to have a positive effect on energy efficiency, according to the reports of four international committees. Bouznit and Pablo-Romero (2016) analyzed Algeria's CO_2 emissions and economic development. By employing an autoregressive distributed lag model, we were able to verify the validity of the environmental kuznets curve (EKC) for Algeria between 1970 and 2010. Growth in the economy has been linked to lower carbon emissions, and this trend is likely to continue. Lotfalipour et al. (2010) used the Toda-Yamamoto technique, a novel time series methodology, to analyze the connection between GDP growth, fossil fuel use, and carbon dioxide emissions in Iran from 1967 to 2007. The correlation between economic growth and carbon emissions appears to be unidirectional, according to experimental evidence. A recent study found that emitting carbon dioxide had no positive effect on GDP growth. Using data from 1980 to 2009, Al-mulali (2011) examined how MENA oil consumption affected GDP growth. Using a panel model, the authors found that CO_2 emissions, oil consumption, and economic growth had a long-term relationship. A cointegration study was performed by Mikayilov et al. (2018) over the years 1992-2013 to look at how GDP growth and CO_2 emissions interacted in Azerbaijan. Long-term coefficients were predicted using a variety of techniques, including the cointegration test, CCR, ARDLBT, FMOLS, DOLS, and the Johansen approach. The studies showed that economic expansion had a statistically significant beneficial effect on carbon dioxide emissions. Oztürk and Acaravci (2010) used the autoregressive distributed lag limits test to look for cointegration between GDP per capita and carbon emissions per capita in Turkey between 1968 and 2005 and found none. Employment, GDP growth, carbon dioxide (CO_2) emissions, and energy use were all investigated to determine their respective causes and effects. However, linking per capita carbon emissions to GDP has not been verified. Changes in the driving forces of the economy were shown to have an impact on CO_2 emissions, which was investigated by Robalino-López et al. in 2015. The environmental Kuznets curve was used to verify the study's findings, and the results revealed that Venezuela did not satisfy the necessary parameters for the environmental Kuznets curve throughout the test period of 1980–2025. CO_2 emissions and economic development in EU member states were analyzed by Bengochea-Morancho et al. (2001). The correlation between GDP expansion and CO_2 emissions from 1981 to 1995 in 10 selected European countries was analyzed using a panel data technique. According to the data, there is a clear divide between the most and least industrialized nations. Those nations with incomes above the EU average were found to have higher carbon emissions than those with incomes below the average. According to the research of Bhattacharyya and Ghoshal (2010), who focused on the 25 nations responsible for the biggest proportion of global carbon emissions, the rate at which individual countries' economies expand is positively correlated with the rate at which their carbon emissions rise. Magazzino (2015) utilizes a VAR model, a unit root test, and a Granger causality test to investigate the correlation between CO2 emissions, GDP growth, and electricity consumption in Israel from 1971 to 2006. The findings demonstrated a cause-and-effect partnership between GDP and CO_2 output. Through the use of the cointegration test, Bozkurt and Akan examine the relationship between energy consumption, CO_2 emissions, and economic growth in Turkey (2014). Annual data on carbon dioxide emissions, GDP, and energy use were compiled from 1960 to 2010. The study found that carbon dioxide emissions slow economic expansion.

Maclaurin (1953) wrote about how technological innovation contributes to economic expansion. He defined innovation as the process of securing patents, and he talked about how this process correlates with a thriving economy. According to Timmons and Bygrave (1986), who analyzed the effects of investments in technological advances and the initiatives that resulted from these investments on economic growth from 1967 to 1982, the two factors interact positively. A dynamic stochastic general equilibrium (DSGE) model of economic expansion was developed by Segerstrom (1991). Some companies invest in research and development of high-quality items while others duplicate them, and this cycle repeats in the model's steady-state equilibrium. He claims that the discovery of new items through R&D procedures will boost national economies. Bilbao-Osorio and Rodríguez-Pose (2004) examined the effect of research and development (R&D) activities and investments on the economy and society at large. In recent years, rising rates of innovation have come to be viewed as one of the most important factors in fostering economic expansion. Using cross-sectional data for 37 countries that joined the GEM in 2002, Wong et al. (2005) employs a Cobb-Douglas production function to identify technological innovation and company creation as independent determinants of growth. Even if technical entrepreneurship were to increase or new businesses were to pop up more frequently as a result of the study, it would not necessarily lead to better economic performance or quicker economic growth rates, the authors state. Galindo and Méndez-Picazo (2013) examined the connection between economic growth and innovation using a Schumpeterian entrepreneurial framework. The three equations have been used to test hypotheses in this setting for industrialized nations. Estimating equations for the years 2001-2009 employs GLS and PLS techniques. The promotion of new technology in the pursuit of better profits through entrepreneurs is seen as crucial to economic progress, and innovation is seen as the vehicle to do just that. With their research, Galindo and Méndez (2014) hope to draw conclusions on the connection between economic development, technical innovation, and entrepreneurialism. The report offers a comparative analysis of entrepreneurial endeavors across advanced economies. For the years 2002–2007, the results reveal a positive association between entrepreneurial and innovative activity and economic growth, as well as a cyclical relationship between the three variables. Pece et al. (2015) investigated the potential impact of innovations on GDP growth over time. Central and Eastern European (CEE) nations are analyzed using multiple regression models. A favorable correlation between innovation and GDP growth was found when the variable was analyzed using a variety of tools (patents, number of brands, R&D expenditures, etc.). According to Adenle et al. (2017), novel company models and agricultural practices contribute to economic expansion. Thompson (2018) found that the rate of growth of internal innovations was crucial to the growth rates of the economy and all other macroeconomic variables. To contribute to the research on the link between institutions, innovation, and economic performance in developing nations, Bekana (2020) used an empirical panel dataset to assess 37 sub-Saharan African countries. According to the findings, a more stable democracy can boost economic growth and development by creating a more conducive environment for innovation.

Numerous studies have examined the relationship between the use of renewable energy and economic expansion. The brief literature on renewable energy and economic growth is included in Table 1.

Table 1 – A brief economic growth and renewable energy literature.

Author(s)	Region	Methodology	Variables	Time	Results
Payne (2009)	USA	Toda-Yamamoto causality test	EC - real GDP	1949-2006	Neutrality hypothesis accepted.
Apergis et al. (2010)	19 Developed and Developing countries	Panel Granger causality test - Panel error correction model	real GDP - REC- NEC – CO2	1984-2007	NEC reduced carbon dioxide emissions, but REC did not in the short term.
Bowden and Payne (2010)	USA	Toda-Yamamoto long term causality test	EC- - real GDP - REC	1949-2006	One-way causality from REC to Reel GDP.
Menyah and Wolde-Rufael (2010)	USA	Granger causality test	real GDP – REC - NEC	1960-2007	NEC reduces CO2 contrary to REC.
Apergis and Payne (2010)	OECD countries	Granger causality test	REC - real GDP	1985-2005	Causality between REC and Y in the long and short term found.
Payne (2011)	USA	Toda-Yamamoto causality test	BEC –EC– real GDP	1949-2007	Uni-directional causality from BEC and EC to real GDP.
Ocal and Aslan (2013)	Turkey	ARDL - Toda-Yamamoto causality test	REC- real GDP –L- C	1990-2010	It shows that REC impacts Y negatively. Also, one-way causality from Y to REC is determined.
Omri (2014)		Literature Review	REC- Y–TEC–NEC–EC	---	---
Lin and Moubarak (2014)	China	Granger causality test - ARDL– Johansen Cointegration Tests	REC–Y–CO2–L	1977-2011	Bi-directional relationship between REC and Y determined in the long-term.
Chang et al. (2015)	G7 States	Granger causality test - Breusch & Pagan's Lagrange Factor (LM) Test	real GDP - REC	1990-2011	One-way causality from REC to Y.
Aslan and Ocal (2016)	8 New Member States of the European Union.	ARDL – Unit Root Test – Hatemi causality test	REC– GDP –C –L	1990-2009	The positive impact of REC on all countries.
Inglesi-Lotz (2016)	34 OECD country	Pedroni cointegration test	REC– GDP per capita –C–L–R&D	1990-2010	Real GDP shows long run balance relationship between total REC.
Bayar and Gavriletea (2019)	22 Economically Developing Countries	Dumitrescu and Hurlin causality test– Westerlund cointegration test	GDP per capita growth - REC	1992-2014	Y did not significantly affected from REC in the long term. Also, one-way causality from EE and REC to Y found in short-term.
Mahmood et al. (2019)	Pakistan	SEM – OLS – 2SLS – 3SLS	Real GDP per capita - NOREC- CO2- L- REC	1980-2014	CO_2 growth is significantly affected from REC and Y in a positive direction.

Abbreviations meanings => EC: Energy ConsumptionCO2: CO_2 Emissions, L: Workforce, R&D: R&D Expenditures, TEC: Total Energy Consumption, C: Capital, REC: Renewable Energy Consumption, NOREC: Non-renewable Energy Consumption, Y: Economic Growth, NEC: Nuclear Energy Consumption, BEC: Biomass Energy Consumption.

3. Data, Methodology and Results

The data sets, econometric models, and study procedures are all broken down here. The primary goal of this research is to analyze the effect of G7 countries' usage of renewable energy sources, technical advances, and CO_2 emissions on GDP growth from 1996 to 2020. To do this, the panel data method was employed.

Table 2 – List of variables and sources

Variables	Time	Abbreviation	Source
CO_2 Emission (metric tons per person)	1996-2020	lnCO_2	WDI
Renewable Energy Consumption	1996-2020	lnren	WDI
GDP (current US$)	1996-2020	lngdp	WDI
R&D Expenditures (percentage of GDP)	1996-2020	lnrd	WDI

One indication of technical progress included in the study is the amount spent on R&D. This is because these costs are factored into the budgets of wealthy nations. It has been possible to utilize the GDP variable as a proxy for economic growth, and then to use the CO_2 emission variables to analyze the effects of that increase on the natural world. All of the statistics are from the World Bank's World Development Indicators database. Table 2 displays every independent variable included in the analysis.

Similar to that of Aslan et al. (2021), the following function is created wherein economic growth (GDP) is the response variable, and renewable energy consumption (REN), CO_2 emissions (CO_2), and R&D expenditures (RD) are the dependent variables:

$$\mathbf{GDP} = \boldsymbol{f}\,(\mathbf{REN}, \mathbf{CO_2}, \mathbf{RD}) \tag{1}$$

The following econometric model Eq. (2) is constructed in line with the variables to be used in the study according to Eq. (1):

$$\mathbf{lnGDP_t} = \boldsymbol{\beta_0} + \boldsymbol{\beta_1}\mathbf{lnREN_t} + \boldsymbol{\beta_2}\mathbf{lnCO_{2t}} + \boldsymbol{\beta_3}\mathbf{lnRD_t} + \boldsymbol{\mu_t} \tag{2}$$

where t denotes times series (1996-2020), β_k (k=1,2,3) are the coefficients on REN, CO_2, and RD. Finally, μ_t represents the estimation residual. Table 2 displays the information that was analyzed throughout the investigation. In this study, we utilize logarithmic analysis on every variable. Using the aforementioned econometric model, we will do a panel series analysis (Eq. 2). Unit root tests will first be used to determine whether or not the variables are stationary. Finally, we'll use ARDL coefficient estimates and Granger causality tests to understand the nature of the long-term link between the variables we've identified.

Before proceeding to the analysis, variables' descriptive statistics will be presented in Table 3. The table figures the descriptive statistical information of its data.

Table 3 – Descriptive Statistics

	CO_2	GDP	R&D	REN
Mean	-0.042409	0.010071	-0.011187	-0.027507
Median	-0.003349	0.014239	0.002443	0.008672
Max	0.024265	0.092998	0.036528	0.180632
Min	-1.190248	-0.083327	-0.515227	-1.346018
Std. Deviation	0.186631	0.033496	0.075069	0.234089

We started by checking if the variables were stationary. To do so, scientists use panel unit root testing. High power makes panel unit root testing preferable to individual time series analysis. These tests are adapted versions of conventional multi-series unit root analyses for panels (al-Mulali et al., 2014). Two examples of panel unit root tests are Levin, Lin, and Chu (LLC) and Im, Pesaran, and Shin (IPS). Levin, Lin, and Chu (LCC) test suppose that there is a joint unit root process so that ρ_i is identical across cross-sections, whilst ρ_i might alter between the cross-sections in the Im, Pesaran, and Shin (IPS) unit root test because, it allows an individual unit root process (Im et al., 2003; Levin et al., 2002). By taking logarithms, panel unit root tests were performed to detect the stagnations of all variables. H_0 indicates that it contains unit root, whilst H_1 represents that it does not contain unit root. As can be seen in Eq. 3 below, the LLC and IPS tests both perform as expected when using the Augmented Dickey-Fuller (ADF) test:

$$\Delta y_{it} = \alpha y_{it-1} + \sum_{j=1}^{p_i} \beta_{ij} \Delta y_{it-j} X'_{it} \delta + \varepsilon_{it} \tag{3}$$

It is presumed that a standard $\alpha=\rho$-1 yet allow the lag order for different terms to diverge between cross-sections. The letter y presents the GDP on Eq. 3. The hypothesis used in the LLC test are as follows:

H_0: ρ_i: α=1 (where the null hypothesis contains unit root)

H_1: ρ_i: α<1 (where the alternative hypothesis contains no unit root).

Table 4 – LLC and IPS tests' results

	Levin, Lin and Chu (LLC)			
	Level		**First Difference**	
Variables	**With Intercept**	**With Intercept and Trend**	**With Intercept**	**With Intercept and Trend**
lnCO_2	2.31309	-1.69082	-9.94825***	-9.41496***
lngdp	-3.14592	1.66188	-6.86958***	-5.36172***
lnren	-0.65416	-1.61980	-9.18663***	-8.57883***
lnrd	0.18279	-1.81603	-8.23448***	-7.42474***
	Im, Pesaran and Shin (IPS)			
	Level		**First Difference**	
Variables	**With Intercept**	**With Intercept and Trend**	**With Intercept**	**With Intercept and Trend**
lnCO_2	2.95497	-1.31202	-10.0569***	-9.66838***
lngdp	-0.47175	2.14994	-5.87278***	-4.61182***
lnren	3.01220	-0.70959	-8.11348***	-7.09868***
lnrd	1.17358	-2.64283	-6.93121***	-5.80592***

***: Statistically significant at 1%

We first verified the stability of all of our observables before doing unit root testing through the LLC and IPS panel techniques. The results of the unit root testing are summarized in Table 4. None of the variables are statistically significant at the level of analysis, as shown by the panel unit root tests. The panel unit root condition holds for all variables, hence the null hypothesis cannot be rejected. As a result, it's likely that the variables aren't holding steady. Once past the initial level, all variables have stabilized, allowing the null hypothesis to be rejected.

The results in Table 4 show that the variables are not steady since their levels have unit roots. Since they are not constant, the analysis moved on to the first differences of all variables. After calculating the initial difference, it was determined that all variables had attained stationarity. The initial difference of no variables contains a unit root. The next step was to examine the interdependencies between the variables. The cointegration test was run after the series was rendered stationary to look for evidence of a long-term correlation between the two variables.

According to the unit root test results, the cointegration test is applied. The concept of cointegration may be identified as the systematic long-term joint movement of more than one economic variable (Yoo, 2006). The Pedroni cointegration test (Pedroni, 1999) was applied to many studies such as Streimikiene and Kasperowicz (2016), Ozturk and Acaravcı (2010), and al-Mulali et al. (2014). Pedroni cointegration test is applied only when the stationary at first difference occurs in variables. The Pedroni cointegration test is essential in examining if the variables are cointegrated or not (al-Mulali, 2014). Also, it allows for heterogeneous intersections and trend coefficients between countries which is represented in Equation (4) below:

$$\boldsymbol{lnGDP_{it} = \alpha_{it} + \delta_{it} + \beta_{1i} lnREN_{it} + \beta_{2i} lnCO_{2it} + \beta_{3i} lnRD_{it} + \varepsilon_{it}} \qquad (4)$$

where i=1,…, N refers to members of the panel (7 countries), t=1,…, N represents the period (1996-2020), GDP represents economic growth, REN represents renewable energy consumption, CO_2 represents CO_2 emissions, RD represents technological innovation, and β refers to the slope of coefficients. The parameter δ_i symbolize the deterministic trend effects, and αi refers to individual effects. At last, the estimated residual deflections from the long-term relationship are represented with ε_i. To examine whether or not cointegration exists, Pedroni (1999, 2004) presented two tests: panel tests and group testing. The panel v-statistic, the panel rho-statistic, the panel PP-statistic, and the panel ADF-statistic are the four statistics used in panel tests based on the within dimension technique. But three statistics employ the between dimension method to generate group tests. It is recommended to use group statistics such as the rho-statistic, the PP-statistic, or the ADF-statistic. There is an asymptotic normality in these seven statistics. Pedroni's (1999) research provides comprehensive information on the statistics used to test for panel cointegration.

Table 5 – Pedroni Cointegration Test Results

Statistics	Stats.	p-value
Panel v-Stat.	-3.321879	0.9996
Panel rho-Stat.	0.108994	0.5472
Panel PP-Stat.	-3.976081***	0.0001
Panel ADF-Stat.	-4.615422***	0.0000
Group rho-Stat.	1.434235	0.9242
Group PP-Stat.	-3.286522***	0.0005
Group ADF-Stat.	-4.262312***	0.0000

*** indicates significance at the 1% level.

The Pedroni cointegration is employed, later recognizing that the study's variables show statioriness at the first difference. It is important to examine if the variables ($lnCO_2$, lnRD, lnREN) are cointegrated with lnGDP or not. Table 5 briefly reviews the result of the Pedroni cointegration test. According to the results, four statistics are significant, therefore, rejecting the null hypothesis. This shows relationship between lnGDP, $lnCO_2$, lnRD and lnREN, respectively in the long term.

Following the discovery of the cointegration between the series, ARDL (Autoregressive Distribution Delay) models were constructed to explicitly state the short- and long-run relationships. The ARDL framework has many benefits over alternative models (Adams et al., 2018). Data of types I(0) I(I) and short time series, or both, are suitable for usage inside the ARDL framework, as revealed by Abbasi et al. (2021). Also, the ARDL method gives coherent and vigorous results for the long-term and short-term relationships between variables. For dependent and independent variables, different lags might be used. As calculated, the Pedroni cointegration test (Table 5) reveals a cointegration between variables. Equation 5 represents the long-run ARDL model as follows:

$$\boldsymbol{\Delta lnGDP_t = \alpha_0 + \sum_{i=1}^{q} \alpha_1 \Delta lnGDP_{t-i} + \sum_{i=1}^{q} \alpha_2 \Delta lnREN_{t-i} + \sum_{i=1}^{q} \alpha_3 \Delta lnCO_{2t-i} + \sum_{i=1}^{q} \alpha_4 \Delta lnRD_{t-i} + \varepsilon_t} \qquad (5)$$

where Δ is the first difference operator and ε_t is the pure white noise term. ARDL (2, 3, 3, 3) model was estimated in the model where the maximum lag length was taken as 3. Table 6 shows the estimation results of the ARDL (2,3,3,3) model and the long-term and short-term coefficients calculated based on these results.

The figures in Table 6 show that all of the variables are significantly different from chance at the 1%, 5%, and 10% levels. The long-term estimating model found a statistically significant positive connection between CO2 emissions and economic growth of 0.675221%. Investment in innovative technologies and the use of renewable energy sources both dampen GDP growth by 2.542573 percent and 0.161304 percent, respectively. When considering the bigger picture, this CO2 emission finding agrees with what has been found by Say and Yucel (2006), Ahmad and Du (2017), Chen (2001), and Muhammad (2019). Our finding is consistent with those of Khan et al. (2020), Mohiuddin et al. (2016), and Abbasi et al. (2021), who all found that rising carbon emissions had a negative impact on short-term economic growth. There is a statistically significant negative link between technical innovation and economic growth, suggesting that rising levels of technological innovation dampen economic growth by 2.542573% over the long run. Kahouli (2018), who discusses a similar pattern in Mediterranean nations, lends credence to this conclusion. It was also shown that technical innovation significantly predicted future GDP growth. Contrary to what Shahbaz et al. (2020) assert, renewable energy slows down economic growth. Adopting renewable energy sources may potentially contribute to economic growth in the not-too-distant future. Our results have been confirmed by studies conducted in Turkey and 15 nations in West Africa (Ocal and Aslan, 2013; Maji et al., 2019).

Table 6 – ARDL Long-term and short-term estimation results

Variables	Coefficients	Std. Error	t-statistics
Long-run results			
$lnCO_2$	0.675221**	0.268030	2.519195
lnrd	-2.542573***	0.565760	-4.494085
lnren	-0.161304*	0.092980	-1.734823
Short-run results			
D(lnGDP(-1))	0.151338	0.114600	1.320575
D($lnCO_2$)	-0.297594	0.220568	-1.349218
D($lnCO_2$(-1))	-0.049839	0.110735	-0.450074
D($lnCO_2$(-2))	-0.302360*	0.171116	-1.766991
D(lnRD)	1.057705**	0.518333	2.040590
D(lnRD(-1))	0.631374	0.412125	1.531996
D(lnRD(-2))	0.664245	0.433745	1.531419
D(lnREN)	0.132986	0.157287	0.845498
D(lnREN(-1))	0.203705**	0.084750	2.403594
D(lnREN(-2))	0.109930***	0.035778	3.072566

The symbols ***, **, and * denote 1%, 5%, and 10% level of significance, respectively.

Causality analysis, first developed by Granger (1969), helps to understand whether a variable can obtain helpful information from other variables. The main reason for making Granger causality in panel data analysis is that it can produce more effective results. Finally, using the Dumitrescu Hurlin causality approach, the causal association between the variables was established after the estimate of the ARDL coefficients. The Granger causality test was performed and summarized in Table 7.

Table 7 provides the probabilities for six distinct chains of causation. To begin, research and development (R&D) and the use of renewable energy sources are inextricably linked. This result is in agreement with the causal link between R&D and renewable energy consumption expressed by Zafar et al. (2019) and Adedoyin et al. (2019). (2020). While Adedoyin et al. (2020) show a bidirectional causation correlation between renewable energy consumption and R&D, Zafar et al. (2019) only find a unidirectional relationship. In addition, there is a direct correlation between a growing economy and the use of renewable energy. Consistent with the findings of Liu et al. (2021) and Jebli and Youssef (2015), but not with the findings of Chang et al. (2015), Saidi and Mbarek (2016), Khobai and LeRoux (2017), Troster et al. (2018), and Sebri and Ben-Salha (2014), who discovered a bi-directional causal relationship between economic growth and renewable energy. Our findings challenge the claims of Tugcu et al. (2012), Chiou-Wei et al. (2008), and

Narayan and Doytch (2017), who argued that economic growth and the use of renewable energy sources are unrelated. Our findings that using renewable energy sources is linked to decreased carbon dioxide emissions are in line with those of Jebli and Youssef (2015) and Liu et al. (2015). (2021). Alam et al. (2021) and Kahouli (2017) both agree that there is a direct link between rising CO2 levels and reduced funding for R&D. (2018). In contrast to this conclusion, however, Lin (2021) claims that no causal association exists between CO2 emissions and R&D investment. Finally, we find that an expanding economy is directly linked to higher CO2 emissions. Evidence from other studies, including those by Peng et al. (2018), Shahbaz et al. (2016), Saidi and Mbarek (2016), Appiah (2018), and Shahbaz et al. (2016), corroborate this result (2016).

Table 7 – Granger Causality (Dumitrescu and Hurlin) Results

	Z-bar Statistics	P- value	Causality
lnrd ≠> lnren	-1.28869	0.1975	Uni-directional
lnren≠>lnrd	13.6880***	0.0000	
lngdp≠>lnren	-1.99125**	0.0465	Uni-directional
lnren≠>lngdp	0.60468	0.5454	
lnco2≠>lnren	-1.64849*	0.0993	Uni-directional
lnren≠>lnco2	-1.35249	0.1762	
lngdp≠>nrd	-1.52918	0.1262	No causality
lnrd≠>lngdp	1.55809	0.1192	
lnco2≠>lnrd	20.1668***	0.0000	Uni-directional
lnrd≠>lnco2	-0.94662	0.3438	
lnco2≠>lngdp	2.06406**	0.0390	Bidirectional
lngdp≠>co2	-1.91665*	0.0553	

The symbols ***, **, and * denote 1%, 5%, and 10% level of significance, respectively.

4. Conclusion and Policy Implications

Since the beginning of industrialization, energy use has significantly grown. Countries have started looking for alternate energy sources due to the progressive depletion of energy resource stocks caused by rising demand and environmental harm. Countries have shifted to using renewable energy because energy resources must be used effectively, efficiently, and sustainably to ensure sustainable development. This way, the balance between the economy and the environment will be established. With this innovative approach, technological investments in countries have increased.

The link between technological innovation, the use of renewable energy sources, and CO_2 emissions for the G7 countries is investigated in this paper, as well as how these factors affect economic growth. The panel data analysis approach was used to examine the long-term relationships between the variables between the 1996 and 2020 time periods. As an indicator of technological innovation, the variable of R&D expenditures was preferred. This is because developed countries allocate much of their budgets to R&D expenditures. In the following parts of the study, the Pedroni cointegration test, ARDL coefficient estimation and Dumitrescu Hurlin panel causality tests were performed, and the relationship between variables was examined.

There is a link between G7 countries' CO_2 emissions, consumption of renewable energy, and technological innovations from 1996 to 2020, according to the study's authors. Based on Pedroni's cointegration results, we know that the variables are fully cointegrated. The long-term coefficients were calculated using the ARDL estimation method after the Pedroni cointegration test established the existence of a long-term relationship between the variables. It turns out that the coefficients we estimated using the ARDL method are statistically significant. According to the estimated coefficients, a one percentage point rise in the variables (RD and REN) would have a negative impact on economic growth. But it's obvious that a growing economy is linked to higher levels of carbon dioxide emissions. It was determined by a Granger causality test that there was a unidirectional relationship between REN and RD, CO_2 and RD, GDP and REN, and CO_2 and GDP.

The analysis suggests that the following describes the negative impact of the variables on economic growth. Renewable energy may have a dampening effect on economic growth because it is more expensive than traditional energy sources and necessitates more costly investments. Taking into account the utilization rate of renewable energy resources in the energy share of industrialized nations, the substantial expenditures made in renewable energy to minimize environmental pollution have a negative influence on economic growth. In addition, it is thought that investments in innovative technologies and R&D expenditures may be more public benefit investments that do not positively affect economic growth, or those technological innovations have superabundant costs to cause a long payback period. These results do not show us that investments in renewable energy sources should be reduced. On the contrary, economic growth can be significantly contributed via renewable energy investments and those investments can reduce environmental pollution in the future for a sustainable environment. On the other hand, shifting the technological innovations to other areas with much higher return areas will help turn the negative effect on economic growth into a positive direction.

Author Contribution

E.E. Ayvaz is responsible for organizing the progress of paper, part of the manuscript writing, analysis and software, finalization, and submission. D. Over is responsible for guiding the topic selection, data collection and part of the manuscript writing.

Declarations

Ethical approval The authors affirm that they are free of any known financial conflicts of interest or close personal ties that could have an impact on the work described in this publication.

Consent to participate We confirm that we do not have any human participants, data, or tissues.

Consent to publish The authors grant permission for publication, and this paper has not been submitted to or published in any other journals.

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