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Modeling the Dynamic Linkage between Renewable Energy Consumption, Globalization, and Environmental Degradation in South Korea: Does Technological Innovation Matter?

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Abstract: The present research assesses the influence of globalization and technological innovation on CO₂ emissions in South Korea as well as taking into account the role of renewable energy consumption and energy consumption utilizing datasets between 1980 and 2018. The autoregressive distributed lag (ARDL) bounds testing method is utilized to assess long-run cointegration. The outcome of the ARDL bounds test confirmed cointegration among the series. Furthermore, the ARDL reveals that economic growth, energy consumption and globalization trigger environmental degradation while technological innovation improves the quality of the environment. In addition, the study employed the frequency domain causality test to capture causal linkage among the series. The major advantage of this approach is that causal linkage between series can be captured at the short, medium and long term, respectively. The outcomes of the causality test revealed that globalization, technological innovation, economic growth and energy use can predict CO₂ emissions in South Korea.

Keywords: CO₂ emissions; globalization; technological innovation; renewable energy consumption; South Korea

1. Introduction

Climate change is the most pressing challenge of the 21st century, and greenhouse gas (GHGs) emissions are the primary cause. According to British Petroleum (BP), total global CO₂ emissions from fossil energy were 33,890.8 million tons in 2018, up from 11,190 million tons in 1965. CO₂ emissions from utilization of energy increased by 0.5%, less than half the 10-year average annual growth rate of 1.1%. Nonetheless, this only partly reversed some of the year's abnormally high growth (2.1%). Extreme weather events contributed to the significant upsurge in CO₂ emissions in 2018 [1]. Global warming has never before posed such a significant threat to human lives and activity. The presence of air

contamination and severe weather conditions, as is regularly witnessed, pose substantial health risks to humans [2]. In this respect, it is critical to pay significant awareness to the topic of climate change; else, the dangers and concerns associated with climate change, which are predicted to rise in the future years, will have disastrous consequences for safety and human health [3,4].

Technological innovation (TI) performs an important role in reducing emissions while also assisting in energy saving. Furthermore, TI performs a vital role in the effective utilization of both traditional and renewable energy (RE) sources. Furthermore, TI can assist in the development of new RE sources. Technological advancements also enhance RE capability, hence improving the potential RE supply to satisfy the demand of energy in the future. Due to the ever-increasing need for energy, it is established that RE will be the most significant form of energy in the future, and it is also an environmentally benign source of power. We discovered a wealth of information on the influence of renewable energy on environmental pollution. To address CO₂ emissions, the majority of prior research recommends increasing the amount of renewable energy in the total energy mix.

The importance of TI in reducing CO₂ emissions is clearly established in the recent literature, although it is not given adequate attention. There are a few studies that have looked at the direct influence of TI on CO₂ emissions, but the results are varied. For example, studies of Ahmad et al. [5], Jin et al. [6], Ahmed et al. [7] and Adebayo and Kirikkaleli [7] found negative technological innovation and CO₂ emissions association while the studies of Su and Moaniba [8], Dinda [9] and Shahbaz et al. [10] established positive technological innovation and CO₂ emissions association. However, the studies of Ali et al. [11], Shaari et al. [12] and Garrone and Grilli [13] found an insignificant connection between technological innovation and CO₂ emissions. Even though the available research showed inconsistent proof of TI role in CO₂, its significance for CO₂ cannot be overlooked. We cannot rule out the potential that TI performs a key role in the global spread of renewable energy sources.

In recent years, scholars have focused disproportionately on the connections between energy resources, globalization, and their usage. The theoretical foundation for this connection is simple: as nations grow more globalized, their need for energy rises as well. It is a widely held belief that as globalization progresses, trade barriers fall, resulting in an increase in a country's output and revenue. A rise in energy consumption is linked with increases in income and production. As it is often assumed that growing globalization is related with greater levels of economic growth, it is commonly assumed that globalization is a source of rising energy consumption. Nevertheless, the extant research contains contradictory conclusions on this subject. For example, the studies of Shahbaz et al. [10], Kalayci [14] and Rahman [15] found positive association between globalization and CO₂ emissions. Globalization's gain in wealth and productivity is eventually augmented by technology spillovers in exporting countries; therefore it is likely that over a given length of time, globalization will reduce consumption of energy and CO₂ emissions. We can look at the service sectors of contemporary economies such as the United States and the European Union, where employment is being relocated to emerging economies, and given that consumption of energy in these sectors is less than in industrial production.

Globalization has a favorable ecological impact on exporting nations in this way. Numerous research studies have identified a negative association between globalization and ecological deterioration. For instance, Shahbaz et al. [16], Haseeb et al. [17] and Zaidi et al. [18] established a negative globalization and CO₂ emissions association. The ecological effects of globalization differ from nation to nation and area to area, according to these considerations. Globalization does not have the same impact on all nations. In the process of globalization, several leaders and laggards can be discovered. As a result, the globe map depicts the nations that are most and least globalized. We may apply the same logic to globalization and energy linkages; however, the links are distinct in the long and short term.

Why South Korea? South Korea is the 8th biggest emitter in the world with GDP and GDP per capita amounting to USD 1.647 trillion and USD 31,846.22, respectively, in 2019 [19]. South Korea is the 3rd biggest LNG importer in the world in 2019. South Korea has established a goal of being carbon neutral by 2050 by expanding the percentage of renewable sources of energy, progressively phasing out coal, improving energy efficiency, and nurturing the nation's nascent hydrogen sector. In 2034, renewables should account for 40% of total capacity, whereas coal and nuclear should account for 10% and 15% of total capacity, respectively. To meet this goal, South Korea will need to considerably enhance its climate policies, especially if it wants to reach carbon neutrality by 2050, including modifying and improving its 2030 NDC to comply with the Paris Accord. South Korea total energy mix consists of renewable sources (3%), petroleum and other liquids (43%) natural gas (16%), coal (28%), and nuclear (10%) [20].

Thus, the present research tends to assess the influence of globalization and technological innovation on CO₂ emissions as well as take into account the role of renewable energy and energy consumption in South Korea between 1980 and 2018. The study contributes to the ongoing literature in the following ways; first, this is the first study investigating this association for the case of South Korea. Second, we applied ARDL approach to capture the short- and long-run interconnection between CO₂ emissions and the regressors. Third, we applied the frequency domain causality test to catch the causal association between CO₂ and REC, GDP, GLO, TI and EC. The major advantage of this technique is that it can catch causal linkage between series at different frequencies. Table 1 presents the synopsis of the related studies.

The next segment presents empirical methodology. Section 3 presents findings and discussion. Section 4 concludes the empirical analysis.

Table 1. Summary of studies.

Authors	Period	Country(s)	Technique(s) Used	Findings
Impact of Energy Use and Economic Growth on CO₂ Emissions				
Adebayo [21]	1970–2016	Mexico	ARDL, Granger Causality	GDP→CO ₂ (+) GDP→CO ₂ EC→CO ₂ (+) EC→CO ₂
Awosusi et al. [3]	1965–2019	South Korea	ARDL, Wavelet Tools, Granger Causality	GDP→CO ₂ (+) GDP→CO ₂
Olanrewaju et al. [22]	1970–2016	Thailand	ARDL, Granger Causality	GDP→CO ₂ (+) GDP→CO ₂ EC→CO ₂ (+) EC→CO ₂
Bekun et al. [23]	1965–2019	Indonesia	ARDL, Wavelet Tools	GDP→CO ₂ (+) GDP→CO ₂ GDP→CO ₂ (+)
He et al. [24]	1990–2018	Mexico	ARDL, Frequency Domain Causality	GDP→CO ₂ EC→CO ₂ (+) EC→CO ₂
Orhan et al. [25]	1970–2019	India	Wavelet Coherence	GDP→CO ₂
Soylu et al. [26]	1965–2019	China	PWC, MWC, WC	GDP→CO ₂ (+) EC→CO ₂ (+)
Impact of Globalization on CO₂ Emissions				
Zaidi et al. [18]	1960–2016	APEC Nations	CUP, Panel Causality	GLO→CO ₂ (−) GLO→CO ₂
Oluwajana et al. [27]	1980–2018	South Africa	ARDL, Frequency Domain Causality	GLO→CO ₂ (+) GLO→CO ₂

Haseeb et al. [17]	1994–2014	BRICS nations	Panel DOLS, FMOLS	GLO→CO ₂ (–) GLO↔CO ₂ For Advanced nations
Muhammad and Khan [28]	1991–2018	155 emerging and advanced Nations	GMM	GLO→CO ₂ (–) For Developing Nations GLO→CO ₂ (+)
Pata [29]	1971–2016	Brazil and China	Fourier ADL cointegration, Granger Causality	GLO→CO ₂
Impact of Renewable Energy Consumption on CO₂ Emissions				
Kirikaleli and Adebayo [30]	1970–2018	Global Economy	FMOLS, DOLS, BC Causality	REC→CO ₂ (–) REC→CO ₂
Altinoz and Dogan [31]	1990–2014	82 countries	ARDL	REC→CO ₂ (–) REC→CO ₂
Pata [32]	1991–2018	BRICS and developing countries	GMM	REC→CO ₂ (–)
Mohsin et al. [33]	2000–2016	25 developing Asian countries	Panel FMOLS	REC→CO ₂ (–)
Impact of Technological Innovation on CO₂ Emissions				
Adebayo and Kirikkaleli [2]	1990Q1–2015Q4	Japan	Wavelet Tools	TI→CO ₂ (–) TI→CO ₂
Cheng et al. [34]	2005Q1–2018Q4	China	ARDL	TI→CO ₂ (–)
Ahmad et al. [35]	1990–2014	OECD economies	Panel FMOLS	TI→CO ₂ (–)
Dauda et al. [9]	1990 to 2016		Panel Techniques	TI≠CO ₂

2. Materials and Methods

In the empirical analysis, it is vital to ascertain the series order of integration by applying stationarity tests. Thus, the present research utilized ADF and PP unit root test to catch the order of integration of the series. Furthermore, it is known that if series exhibit break(s), utilizing the ADF and PP tests will yield incorrect outcomes. Therefore, the current research utilized Zivot and Andrews' unit root test to catch a series unit root and a single break. Following the studies of He et al. [4] for Mexico, Oluwajana et al. [27] for South Africa, and Chien et al. [36] for Pakistan, the current research assesses the influence of technological innovation and renewable energy use on CO₂ emissions. This study takes a step further by incorporating globalization into their model. In line with these prior studies, the present research formulated the model as follows:

$$CO_{2t} = \beta_1 + \beta_2 GDP + \beta_3 EC + \beta_4 REC + \beta_5 GLO + \beta_6 TI + \varepsilon_t \quad (1)$$

In Equation (1), CO₂ stands for emissions per capita, GDP denotes economic growth which is measured as GDP per capita (USD Constant 2020), EC stands for energy use which is measured as primary energy use per capita (KWh), REC means renewable energy use which is measured as renewable energy use per Capita (KWh), GLO stands for globalization which is measured as social, economic and political globalization, and TI represents technological innovation which is measured as the addition of both nonresident and resident patent application. The data utilized in this study stretched from the period 1980

to 2018 (39 observations). The CO₂, REC, and EC data are obtained from the British petroleum database while technological innovation and GDP data are gathered from the database of the World Bank.

In line with the studies of Awosusi et al. [3], Alola et al. [37] and Sarkodie et al. [38], we added GDP into the model. Furthermore, following the studies of Adebayo et al. [21], Rjoub et al. [39] and He et al. [24], we incorporate energy use into the model. REC was incorporated into the model in line with the studies of Kirikkaleli and Adebayo [40], Ahmed et al. [7] and Adebayo and Kirikkaleli [40]. Additionally, we incorporate GLO into the model following the studies of Kirikkaleli et al. [41], Adebayo and Kirikkaleli [2] and Oluwajana et al. [27]. Lastly, we introduced TI into the model following the studies of Kirikkaleli and Adebayo [30], Khan et al. [42] and Shahbaz et al. [10].

The study applied the ARDL bounds test to capture the long-run association between CO₂ emissions, technological innovation, economic growth, renewable energy consumption and energy consumption. The null and alternative hypotheses are no cointegration and there is cointegration among the variables [43]. Bounds tests based on the ARDL approach is represented by the following model:

$$\Delta CO_{2t} = \beta_1 + \sum_{i=1}^k \beta_2 \Delta CO_{2t-i} + \sum_{i=1}^k \beta_3 \Delta GDP_{t-i} + \sum_{i=1}^k \beta_4 \Delta EC_{t-i} + \sum_{i=1}^k \beta_5 \Delta REC_{t-i} + \sum_{i=1}^k \beta_6 \Delta GLO_{t-i} + \sum_{i=1}^k \beta_7 \Delta TI_{t-i} + \beta_8 CO_{2t-1} + \beta_9 GDP_{t-1} + \beta_{10} EC_{t-1} + \beta_{11} REC_{t-1} + \beta_{12} GLO_{t-1} + \beta_{13} TI_{t-1} + \varepsilon_t \quad (2)$$

In Equation (2), the difference operator is depicted by Δ and β 's represents the coefficients. In order to collect information regarding our model's short-run divergence from its long-run equilibrium, we used an error correction model (ECM), which states that short-term imbalances are corrected by an error. Equation (3) represents the ECM model as follows:

$$\Delta CO_{2t} = \beta_1 + \sum_{i=1}^k \beta_2 \Delta CO_{2t-i} + \sum_{i=1}^k \beta_3 \Delta GDP_{t-i} + \sum_{i=1}^k \beta_4 \Delta EC_{t-i} + \sum_{i=1}^k \beta_5 \Delta REC_{t-i} + \sum_{i=1}^k \beta_6 \Delta GLO_{t-i} + \sum_{i=1}^k \beta_7 \Delta TI_{t-i} + \beta_8 ECT_{t-1} + \varepsilon_t \quad (3)$$

The speed of adjustment coefficient is depicted by β_8 . ECT stands for error correction term. Δ stands for the changes of the variables which they are attached. Time is illustrated by t and ε represents error term. The ECT coefficient must be negative and significant.

Lastly, following the study of Breitung and Candelon [44], the present research applied the frequency domain causality test. In contrast to the time-domain technique, which displays the variability of the time series, the test indicates the degree of this precise fluctuation. This methodology is referred to as the spectral causality technique. In research with short series, a seasonal model can be vital, and the frequency domain can help to remove this variance. Furthermore, using a frequency-domain technique allows us to track nonlinearity and causal cycles at high and low frequencies. The major advantage of this approach is that causal linkage between series can be captured at short, medium and long term, respectively.

3. Findings and Discussion

Having a brief understanding of variables under investigation is essential in empirical analysis. Therefore, the current research utilized the RADAR chart to illustrate the variables' descriptive statistics. Figure 1 depicts the RADAR descriptive statistics of the variables. Technological innovation has the highest mean value which is followed by economic growth, energy use, globalization, CO₂, and renewable energy use. Regarding standard deviation, the globalization score is better which is followed by CO₂, REC, GDP, EC and TI. All the series of investigations are negatively skewed with the exemption of REC which is positively skewed. Furthermore, all the series of study are platykurtic in nature since their values are less than 3 with the exemption of REC which is leptokurtic in nature.

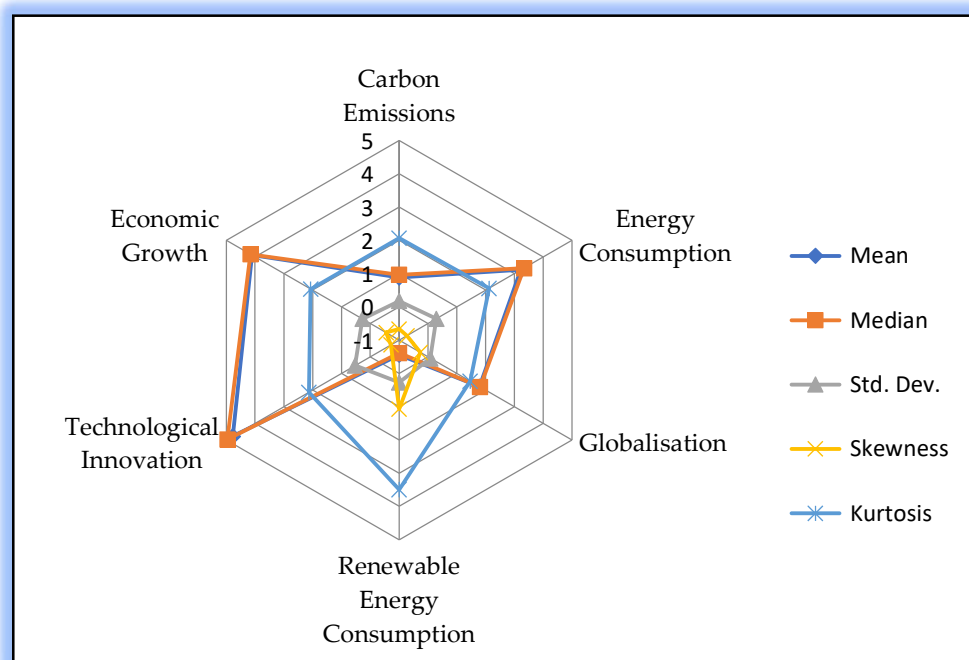


Figure 1. Descriptive statistics.

Furthermore, it is crucial to catch the series other of integration before commencing on additional analysis. Based on this, the present study utilized both traditional unit root tests and Zivot and Andrews' (ZA) stationarity tests. The outcomes of the ADF and PP stationarity tests are presented in Table 2. The outcome disclosed that at level, all the series are non-stationary. Nonetheless, after the first difference is taken, all the series are found stationary which suggest that all series are $I(1)$ variables. It is generally established that the conventional stationarity tests will yield inaccurate outcome if there is a break in series. Thus, the ZA unit test is utilized to solve this issue. The outcomes of the ZA are depicted in Table 3 and their outcomes disclosed that all the series are non-stationary at level. Nonetheless, after the series' first difference is taken, all the series are stationary at first difference. We progressed to the cointegration test after confirming that the series are of order (1). The Bounds test outcome is disclosed in Table 4. The F-statistic (6.76) is greater than the lower and upper critical value at 1%, 5% and 10% significance level. This implies that the null hypothesis of no cointegration is rejected suggesting proof of long-run association between CO_2 emissions and economic growth, technological innovation, renewable energy consumption and energy consumption.

Table 2. ADF and PP tests.

Variables	ADF		PP	
	Level	First Difference	Level	First Difference
CO2	-1.0957	-6.2803 *	-0.9183	-6.7159 *
GDP	-0.6664	-6.4591 *	-0.3546	-10.160 *
REC	-2.0133	-6.0307 *	-2.0133	-20.106 *
GLO	-1.0407	-4.3327 *	-1.4199	-4.2704 *
EC	0.0489	-5.0848 *	-0.1406	-5.0391 *
TI	-1.1665	-5.4308 *	0.2867	-8.0468 *

Note: * represent 1%, level of significance.

Table 3. ZA tests.

Variables	Level		First Difference	
	T-Statistics	BD	T-Statistics	BD
CO ₂	−5.1778 **	1998	−7.388 *	1998
GDP	−4.879	2006	−7.046 *	1998
REC	−5.6645	2006	−6.054 *	1994
GLO	−3.0211	1993	−6.125 *	1988
EC	−4.9090	1996	−7.165 *	1998
TI	−4.3905	1995	−5.901 *	1997

Note: *, and ** represent 1%, and 5% level of significance.

Table 4. Bound test.

	F-Statistics		15.42411 *			
	Cointegration		Yes			
	10%		5%		1%	
F-statistics CV	2.26	3.35	2.62	3.79	3.41	4.68

Note: * represent a 1% level of significance.

After the cointegration among the series of interest is established, we move forward by examining the influence of GDP, REC, EC and GLO on CO₂ emissions in South Korea. This is done by applying the ARDL approach to capture concurrently both short- and long-run association between CO₂ emissions and the regressors. The outcomes of the ARDL short and Long-run estimate is depicted in Table 5. The outcomes of the ARDL estimation disclosed the following: GDP and CO₂ are positively connected which infers that when holding other indicators constant, 1% upsurge in GDP will trigger CO₂ emissions in South Korea by 0.38%. This is unsurprising considering that the economy of South Korea is predominantly an investment-oriented and manufacturing economy that strongly depends on the use of energy; nevertheless, altering the energy mix to include more renewable choices including wind and solar energy has the capability to minimize CO₂ emissions. This outcome complies with the studies of Kirikkaleli and Adebayo [40] for India, Soylu et al. [26] for India, Orhan et al. [25] for China, Tufail et al. [45] for highly decentralized economies and Bekun et al. [23] for Indonesia who established that GDP triggers CO₂ emissions positively.

Energy use impacted CO₂ emissions positively in South Korea which implies that a 1.09% upsurge in CO₂ emissions is due to a 1% increase in the utilization of energy when other indicators are kept constant. The key reason for the positive energy use and CO₂ emissions association in South Korea is due to the country's substantial nonrenewable energy usage. Furthermore, this result is unsurprising, given that coal and petroleum, and other liquids account for 71% of total primary energy use. It requires time, technology, and a large fixed cost to shift from nonrenewable to renewable energy sources. This is why nuclear and natural gas power plants are viewed as low-carbon alternatives to coal and oil power plants. This outcome agrees with past studies [22–25] which established positive energy use and CO₂ emissions association.

REC exerts a negative and insignificant impact on CO₂ which implies that REC does not aid in mitigating CO₂ emissions in South Korea. This is not surprising given the fact that REC accounts for a small fraction (3%) of the South Korea energy mix.

Globalization impacts CO₂ positively which infers that when keeping other indicators constant, 1% upsurge in globalization will cause CO₂ emissions to rise by 1.60% keeping other indicators constant. The probable reason for this association is that globalization process enables developed nations to transmit superior technology to developing countries, which helps these countries expand the division of labor and boost their comparative

advantage. Globalization also boosts total factor productivity through increasing commerce. It enhances the activity of the economy by FDI and the transfer of sophisticated technology between advanced and emerging nations. This procedure, in fact, benefits commerce, economic growth and financial markets, as well as energy consumption and the environment. As stated by Adebayo and Kirikkakeli (2021), the process of globalization triggers CO₂ emissions due to the wide use of energy in the consumption and production of activities in both advanced and emerging economies. This outcome complies with the studies of Kirikkaleli et al. [41] for Turkey, and Oluwajana et al. [27] for South Africa.

Technological innovation exerts a negative impact on CO₂ which implies that when keeping other indicators constant, a 0.08% decrease in CO₂ emissions is due to a 1% increase in technological innovation. This outcome demonstrates that innovation has a significant and positive impact on environmental sustainability. The probable reason for this association is that states and industries will focus more on R and D that develops environmentally friendly capital goods and improves the efficiency of production technology that uses less energy. This outcome corroborates prior studies [30,42] that established negative technological innovation and CO₂ emissions association.

The outcome of the ECT is negative and significant which demonstrates that corrections made in previous periods can be rectified in succeeding periods. Moreover, the present study conducts several diagnostic tests which are depicted in Table 6. The outcomes disclosed that there is no heteroscedasticity and serial correlation in the model. Additionally, there is no misspecification as revealed by the RESET test. The outcomes of the CUSUM and CUSUM of Sq in Figure 2a,b uncovered that the model is stable at a 5% level of significance.

Table 5. ARDL long- and short -outcomes.

Variable	Long-Run Outcomes				Short-Run Outcomes			
	Coefficient	Std. Error	t-Statistic	Prob	Coefficient	Std. Error	t-Statistic	Prob
EC	1.098 *	0.156	6.998	0.000	1.098 *	0.120	9.132	0.000
GDP	0.385 ***	0.222	1.732	0.094	0.385 **	0.148	2.588	0.015
GLO	1.606 *	0.206	7.788	0.000	1.606 *	0.147	10.90	0.000
REC	−0.007	0.010	−0.724	0.475	−1.008	0.173	−1.000	0.325
TI	−0.081 **	0.033	−2.414	0.022	−0.036	0.027	−1.323	0.196
ECT(−1)					−0.110 *	0.010	−10.47	0.000
R ²	0.98							
Adj-R ²	0.97							
F-stat	1161.5							
Prob(F-stat)	0.000							

Note: *, ** and *** represent 1%, 5% and 10% level of significance.

Table 6. Diagnostic Tests.

Tests	Value	Probability
χ ² ARCH	0.7060	0.4065
χ ² RESET	0.3518	0.7278
χ ² Normality	1.1290	0.5686
χ ² LM	1.2328	0.3086

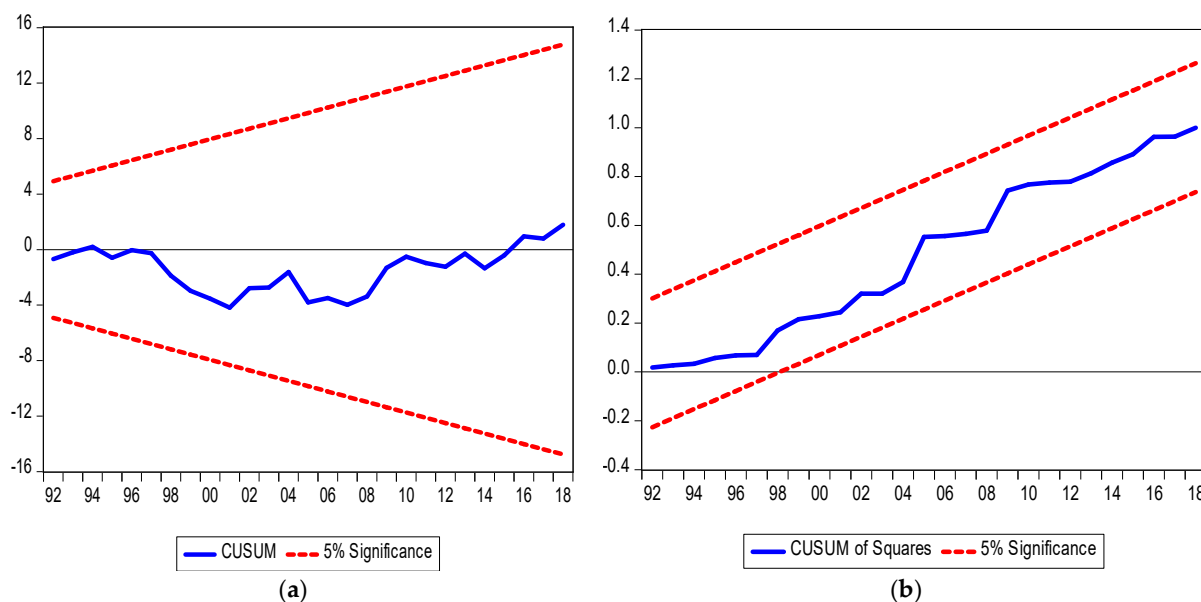


Figure 2. (a) CUSUM; (b) CUSUM of squares.

The present research takes a step further by examining the causal effects of REC, TI, GDP, EC, GLO and TI on CO₂ emissions in South Korea by utilizing the BC causality test. The major advantage of this test is that it can capture causal linkage between series at different frequencies. Table 7 depicts the outcomes of the frequency domain causality test. At a significance level of 0.10, the null hypothesis of no causality from EC to CO₂ is rejected. This demonstrates that EC can predict CO₂ emissions in the long term. This result complies with the study of Soylu et al. [26] for China, Oluwajana et al. [27] for South Africa, and Zhang et al. [46] for Malaysia. In the medium and short term, the null hypothesis of no causal linkage from GDP to CO₂ is rejected at a 5% and 10% level of significance. This demonstrates that in the medium and short term, GDP can predict CO₂. This outcome corroborates the findings of Shan et al. [47], Awosusi et al. [3] for South Korea, and Bekun et al. [23] for Indonesia. Furthermore, in the short term, the null hypothesis of no causality from GLO to CO₂ is rejected at a significance level of 5% and 1%, respectively. In the medium term, there is evidence of causality from TI to CO₂ at a significance level of 10% in the short and medium term. This outcome demonstrates that TI can predict CO₂ in both the short and medium term. This outcome complies with the studies of Kirikkaleli and Adebayo [40], Khan et al. [42] and Shahbaz et al. [10].

Table 7. Frequency domain causality test.

	Long-Term		Medium-Term		Short-Term	
Causality Path	$w_i=0.01$	$w_i=0.05$	$w_i=1.00$	$w_i=1.50$	$w_i=2.00$	$w_i=2.50$
EC→CO ₂	5.369 ***	5.374 ***	1.4954	0.552	1.144	2.110
GDP→CO ₂	0.857	0.951	8.162 *	5.442 ***	6.981 **	9.895 *
GLO→CO ₂	0.349	0.390	3.882	1.8755	4.576 ***	6.964 **
TI→CO ₂	1.377	1.386	4.629 ***	4.683 ***	5.643 ***	3.385
REC→CO ₂	0.757	0.557	0.386	0.177	0.133	0.135

Note: → stands for the direction of causality. *, ** and *** stands for 1%, 5% and 10% level of significance.

4. Conclusions

The present research assesses the influence of energy use and renewable energy use on CO₂ emissions in South Korea as well as taking into account the role of globalization and technological innovation. The study utilized yearly data stretching between 1980 and 2018 as well as recent econometric techniques to capture this interconnection. The outcomes of the ADF, PP and ZA disclosed that all the series are I(1) variables which give room for the utilization of the ARDL bounds test. The outcomes of the ARDL bounds test disclosed a long-run association between CO₂ emissions and regressors. Furthermore, we applied the ARDL approach to catch the long- and short-run linkages between CO₂ emissions and the regressors. The outcomes of the ARDL long- and short-run estimate disclosed that GDP, globalization, and energy use triggers CO₂ emissions while technological innovation improves it. Moreover, the present research assesses the causal linkage between the series at different frequencies by applying the frequency domain causality test. The major advantage of this test is that it can capture causal linkage between series at different frequencies (small-, medium- and long-term). The outcomes of the causality test disclosed that technological innovation, globalization, economic growth and energy use can predict CO₂ emissions.

Our research findings have just a few policy ramifications. The findings imply that economic expansion in South Korea has negative environmental consequences. The worldwide level, which demonstrates that South Korea's economic growth is strongly reliant on the utilization of energy, is a major impediment to reducing CO₂ emissions. Environmental costs may rise as a result of increased energy usage, which leads to environmental resource catastrophes and global warming. As a result, one effective strategy to cut CO₂ is to minimize the nation's reliance on nonrenewable sources of energy (e.g., natural gas, petroleum and coal) and invest more in the nation's renewable energy sources (e.g., wind, nuclear power and solar). Additionally, globalization impacts CO₂ emissions positively in South Korea as disclosed by the empirical finding. Globalization has been identified as a significant contributor to the rise in CO₂ emissions. Thus, the government should consider the social, economic and environmental aspects of globalization. Furthermore, according to the empirical findings, it is critical to invest in technological innovation in order to reduce CO₂ emissions since technological innovation not only helps to minimize CO₂ emissions but also discovers new and inventive methods to use conventional sources of energy efficiently. Technological innovation also aids in the production of new renewable energy sources at a cheaper cost. As a result, technological innovation not only effectively uses both traditional and renewable energy sources but also offers a cost-effective alternative in today's world, where energy consumption has become an integral component of the economic growth process. Renewable energy consumption has a negative and insignificant influence on CO₂ emissions, according to the findings. As a result, South Korea must increase its investment in renewable energy. It is a well-known fact that green energy emits less carbon than conventional sources of energy such as fossil fuels. Furthermore, green sources of energy are both cost-effective and efficient. To fulfill South Korea's high energy demand, the government must take a significant step by increasing the total percentage of renewable energy in the total energy mix.

Additionally, while CO₂ emissions are used as a proxy for environmental deterioration, they are not the only indicator of environmental deterioration. More research should be done in South Korea to investigate this relation by including additional environmental degradation variables.

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