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RESEARCH ARTICLE

Can CO_2 emissions and energy consumption determine the economic performance of South Korea? A time series analysis

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Abstract

Following the United Nations Sustainable Development Goals (UN-SDGs), which place emphasis on relevant concerns that encompass access to energy (SDG-7) and sustainable development (SDG-8), this research intends to re-examine the relationship between urbanization, CO_2 emissions, gross capital formation, energy use, and economic growth in South Korea, which has not yet been assessed using recent econometric techniques, based on data covering the period between 1965 and 2019. The present study utilized the autoregressive distributed lag (ARDL), dynamic ordinary least square (DOLS), and fully modified ordinary least squares (FMOLS) methods, while the gradual shift and wavelet coherence techniques are utilized to determine the direction of the causality. The ARDL bounds test reveals a long-run linkage between the variables of interest. Empirical evidence shows that CO_2 emissions trigger economic growth. Thus, based on increasing environmental awareness across the globe, it is necessary to change the energy mix in South Korea to renewables to enable the use of sustainable energy sources and establish an environmentally sustainable ecosystem. Moreover, the energy-induced growth hypothesis is validated. This result is supported by the causality analysis, which shows a one-way causality running from energy consumption to GDP in South Korea. This suggests that South Korea cannot embark on conservative energy policies, as such actions will damage economic progress. Additionally, a unidirectional causality is seen from CO_2 emissions and energy consumption to economic growth. These findings have far-reaching consequences for GDP growth and macroeconomic indicators in South Korea.

Keywords CO_2 emissions · Economic growth · Urban population · Energy consumption · Gross capital formation · South Korea

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Introduction

The threat of global warming has raised the level of awareness throughout the world regarding the need to minimize the critical situation confronting all societies (Hasanov et al. 2021). Human activities on the planet's surface are the sole contributor to global warming, resulting in environmental destruction due to global warming (Kirikkaleli & Adebayo 2020). With the advent of global warming, countries have been charged with finding individual and collaborative ways of thinking and working towards mitigating global warming. Climate change is a global problem that has strengthened the international and domestic consciousness to identify ways of mitigating the growing trend (Olanrewaju et al. 2021; Adebayo 2021a). Emissions from diverse energy sources, particularly fossil fuels and other non-renewable sources of energy, are dispersed as pollutants into the air. These are responsible for adversely affecting both the climate and the welfare of the people. Not only are the pollutants released into the environment but they also have connections to bodies of water and wetlands, which can damage or poison marine life (Kirikkaleli & Adebayo2021). The pollution of both water bodies and air has a detrimental impact on society by impacting the populace's living conditions, health, and nutrition (Zhang et al. 2021; Udemba et al. 2021).

According to various measures, growth in the economy has been identified to have a disastrous impact as a result of pollution. Various economic practices, both directed at and based on economic growth, contribute to pollutants' emissions (Ayobamiji & Kalmaz 2020; Udemba 2020). Such practices from multiple sectors (petroleum sector, manufacturing, oil extraction, agriculture) of the economy that cause GDP growth also trigger pollution (Umar et al. 2020). This pollution from various sources and economic sectors negatively impacts human well-being through various types of diseases such as cancer and heart disease (Adedoyin et al. 2020; Oluwajana et al. 2021; He et al. 2021). Manufacturing practices such as the use of heavy duty equipment with the potential to burn huge amounts of fossil fuels, production processes, the delivery of products from the point of origin to the last or final customer with vehicles releasing CO_2 emissions via exhaust pipes, waste dumping in bodies of water, and electricity generation using other fossil fuels and coal all lead to environmental degradation.

Since 2016, South Korea's total energy use has remained stable after a period of constant growth (2.7%/year between 2000 and 2016). South Korea's economic performance's driving forces are oil and coal, which account for 37% and 26% of energy needs, respectively. This shows the reliance of the South Korean economy on oil and coal as an energy source. In 2019, South Korea consumed 2.5 million barrels per day of petroleum and other liquids, ranking it the 8th largest consumer globally (EIA, 2020). This implies that, as a consequence of the rising demand for oil and coal in South Korea, CO_2 emissions will certainly rise. Existing policies are projected to result in an emissions level of 665 to 743 $MtCO_2e$/year in 2030, subject to the ongoing impact of the COVID-19 crisis, without pollutions from LULUCF[1] (EIA, 2020). In its NDC, South Korea is officially committed to achieving 539 $MtCO_2e$/year except for LULUCF. To achieve this target, South Korea will have to improve its climate policies significantly, even more so if the government intends to achieve carbon neutrality by 2050, such as by amending and enhancing its 2030 NDC to be compliant with the Paris Accord. South Korea is ranked among the world's top five importers of coal, liquefied natural gas (LNG), and total petroleum liquids. According to the EIA (2020), in 2019, the total primary energy consumption of South Korea consisted of coal (28%), petroleum and other liquids (43%) natural gas (16%), renewable sources (3%), and nuclear (10%), as depicted in Fig. 1. Based on the fascinating energy mix of South Korea, the present research aims to examine the effects of the positive development and growth of South Korea, with an emphasis on the energy consequences of South Korea's economic performance via urbanization, gross capital formation, and use of energy. This research, therefore, explores the effects of CO_2 pollution, urbanization, gross capital development, and use of energy on South Korea's economic performance.

It is important to recognize that, as a foremost economy in terms of growth, it is necessary to explore the economy and render appropriate economic sustainability suggestions based on analytical results. Based on the results, a detailed analysis of the South Korean economy's sustainability will allow us to develop sustainable policies to answer questions including (a) Can South Korea diversify its policies regarding its energy mix by embracing renewable energy to boost its green economy? (b) Can South Korea introduce innovative pollution mitigating measures without weakening sustainable economic development? It is also essential to remember that, as the South Korean economy grows, the position of the nation in the international rankings of CO_2 is very vulnerable and the levels are rising at the same rate as those of other nations considered to be the major global emitters such as India, China, US, Japan, and Russia. In South Korea and Japan, which have the same economic characteristics and demographic composition, there is a disparity between the trend of output growth and the level of pollution. In both countries, this pattern has contributed to the emissions of CO_2. That being said, considering the rapid population growth rate, significant efforts have been made to mitigate the detrimental consequences of global warming without impacting GDP growth. This is the inspiration for the researchers to investigate the variables illustrated in this report, as we strive to utilize the implications of this research to make policy recommendations for government administrators and stakeholders.

[1] Land use, land use change, and forestry

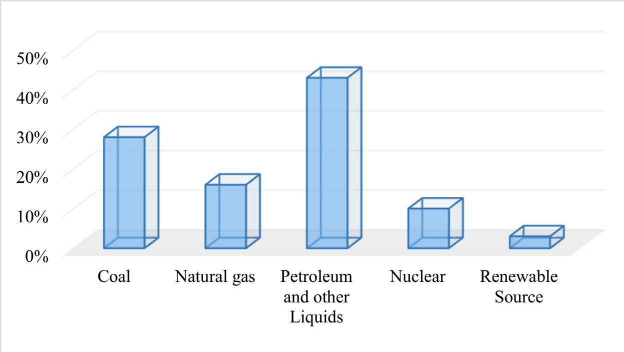

Fig. 1 South Korea total primary energy consumption by fuel 2019

Given this progress, despite the optimistic and substantial growth of the South Korean economy, there has been limited emphasis on examining this trend's significance. Nevertheless, this research intends to examine the economic performance in South Korea amidst CO_2 emissions. The current research is distinct from the existing studies because it accounts for other economic growth determinants, including energy usage, CO_2 emissions, gross capital formation, and urbanization. In addition to the autoregressive distributed lag (ARDL), fully modified ordinary least squares (FMOLS), dynamic ordinary least squares (DOLS), and Gradual shift tests, the study employs the wavelet coherence test. The advantage of the wavelet coherence test is that it can capture both correlation/causality between series at different frequencies and time periods. This report expands/complements the discussion on the South Korean economy on the growth-energy and pollution nexus and expands on India's research by Udemba et al. (2021). The research is inspired by the Sustainable Development Goals (SDGs-7, 8, 12, and 13) and discusses specific energy use concerns (SDG-7) with a particular emphasis on green and sustainable use of energy (SDGs 7 and 12) to meet the 2020 Agenda. This is to avoid problems associated with economic growth (SDGs-8) and climate change (SDGs-13). The present research is considered particularly timely and deserving of inquiry, especially in the current era in which responsible energy use and environmental protection are increasingly being targeted.

The concluding part of this report is planned in the following way: a short synopsis of the previous studies and theoretical framework is presented in the "Literature review" section. The "Data and methodology" section covers the data and the methodologies, whereas the "Findings and discussion" section presents the analytical results. The "Conclusion and policy directions" section presents the conclusion and policy directions.

Literature review

This part is divided into two, namely, (i) empirical review-which discussed the previous studies conducted regarding the relationship between economic growth, gross capital formation, CO_2 emissions, urbanization, and energy consumption, and (ii) the theoretical framework-which discuss the environmental Kuznets curve theory.

Empirical review

An overview of the relevant literature on this topic will be discussed by reviewing the connections observed between the dependent variable (GDP) and its regressors (CO_2 emissions, urbanization, gross capital formation, and energy use). There is no consensus in the literature on the relation between GDP and these regressors as a result of the mixed outcomes, which has led to an increase in interest in this subject matter. The study of Teng et al. (2020) found that GDP increased CO_2 emissions for ten different OECD economies during the period between 1985 and 2018. However, Ayobamiji and Kalmaz (2020) employed the wavelet technique to capture the time-frequency dependency between CO_2 and real output, which is consistent with the results of Teng et al. (2020). The study of Ahmed et al. (2020) revealed that GDP exerts a positive impact on CO_2 emissions in G7 economies. Aye and Edoja (2017) found a negative link between GDP and CO_2 emission in 31 developing countries. Salahuddin et al. (2018) showed no association between CO_2 and real output. In Kuwait, Wasti and Zaidi (2020) concluded that energy consumption and CO_2 emission accelerate GDP. Chontanawat (2020) and Gorus and Aydin (2019) suggested that there was no causal association between CO_2 and real GDP in ASEAN economies for the period from 1971 to 2015. Kirikkaleli and Adebayo (2020), Wang et al. (2019), Kirikkaleli et al. (2020), Aydoğan and Vardar (2020), and Jafari et al. (2015) revealed a one-way casual interaction from GDP to CO_2 emissions. However, while Gao and Zhang's (2021) study showed that there is a unidirectional causal link from CO_2 emission to GDP, a bidirectional causal link between CO_2 emission and GDP was revealed by Wu et al. (2018). The study of Ahmed et al. (2019) revealed a positive relationship between GDP and CO_2 emissions. Bouznit and Pablo-Romero (2016) examined the interconnection between CO_2 emissions and GDP in Algeria from 1970 to 2010 utilizing the ARDL approach. The results showed that there was a positive association between CO_2 emission and GDP. The study of Odugbesan and Adebayo (2020) in South Africa also revealed a positive interaction between CO_2 emissions and GDP. In Japan, the study of Ahmed et al. (2021) and Adebayo (2021b) established a positive association between GDP growth and environmental degradation. Al-Mulali (2011) established a positive connection between CO_2 emissions and GDP in the MENA region. Furthermore, they found evidence of a two-way causal link between CO_2 emissions and GDP. Awosusi et al. (2020) employed panel data from 1980 to 2018 for the MINT economies. The results showed that there is no significant link between CO_2 emission and GDP. However, economic growth Granger causes CO_2 emissions. Adebayo (2020) also employed the ARDL and wavelet coherence methods to examine the long-run and causal relationship between CO_2 emissions and GDP in Mexico. The results showed a positive link between these variables. In terms of causality, they identified a two-way interaction between CO_2 emissions and GDP. Zhang et al.'s (2021) study revealed a different causal interconnection between CO_2 emissions and GDP in Malaysia, namely a one-way link from GDP to CO_2 emissions.

The study of Khobai and Le Roux (2017) established a bidirectional link between GDP and energy usage. Muhammad (2019) examined the link between energy usage and GDP in the MENA economies from 2001 to 2017, suggesting a negative linkage between energy use and GDP. Shahbaz et al. (2018) established a positive interaction between energy consumption and GDP in the top ten energy-consuming economies utilizing the quantile-on-quantile (QQ) approach for the period 1960Q1 to 2015Q4. This is consistent with the study conducted by Magazzino (2018) in Italy. Mutascu (2016) explored the causal association between economic growth and energy use in the G7 nations. The author revealed a bidirectional link between economic growth and energy use in the USA, Canada, and Japan, but no causality was evident in the UK and Italy. Yang and Zhao (2014) examined the association between energy consumption and economic growth from 1970 to 2008 in India, utilizing the Granger causality test and DAG. The author revealed that there was a unidirectional linkage from energy consumption to GDP. Faisal et al. (2016) utilized the TY causality to examine the link between GDP and Russia's energy consumption. The authors revealed no causal link between these two variables. Ha and Ngoc (2020) also employed Toda-Yamamoto causality on data covering the period from 1971 to 2017 in Vietnam. The authors revealed a two-way causal link between GDP and energy use. Baz et al. (2019) confirmed a positive shock moving from energy consumption to GDP in Pakistan from 1971 to 2014. Rahman et al. (2020) revealed that energy consumption positively affected China's GDP, covering the period from 1981–2016.

The study of Nathaniel and Bekun (2020) examined the association between urbanization and GDP in Nigeria covering the period from 1971 to 2014 by employing the Bayer and Hanck cointegration test, ARDL, FMOLS, DOLS, CCR, and VECM Granger causality. They found that urbanization negatively inhibits GDP, and there is a bidirectional link between urbanization and GDP. Nguyen and Nguyen (2018) found that urbanization positively affects GDP in the ASEAN countries. Ali et al. (2020a) examined the association between urbanization and GDP using the Maki cointegration test, FMOLS, DOLS, CCR, and VECM Granger causality covering the period from 1971 to 2014. The authors found that urbanization hinders GDP in Nigeria, and there is unidirectional causality from urbanization to GDP. Zheng and Walsh (2019) concluded that urbanization is a major contributor to GDP in China. Yang et al. (2017) found a positive association between GDP and urbanization.

Numerous studies have been conducted in terms of the linkage between gross capital formation and GDP growth, although their findings are mixed. For instance, Topcu et al. (2020) explored the interaction between gross capital accumulation and GDP by using the panel vector (PVAR) for the period between 1980 and 2018 for 124 economies. The author concluded that the impact of gross capital formation differs based on the country's income level. Etokakpan et al. (2020) examined the association between gross capital accumulation and GDP in Malaysia covering the period 1980–2014, employing the Bayer and Hanck cointegration tests, ARDL, and Granger causality. The authors concluded that an increase in gross capital formation would increase GDP. Kong et al. (2020) employed recent panel techniques to examine the relationship between gross capital formation and GDP for 39 African economies. The authors established a positive link between gross capital formation and GDP. Furthermore, a bidirectional causal link was also evident between these two variables. Boamah et al. (2018) also found similar results for 18 Asian nations by employing panel data covering the period from 1990 to 2017. Table 1 presents a synopsis of related studies.

Theoretical framework

This study's theoretical work is based on the EKC which was built on the Kuznets curve of Kuznets (1955), which was centered on income inequality. This theory explains the increasing trend of inequality and income per capita. There is a turning point along the curve that shows where the farmers' per capita income, who exit the farming practices to take up white collar jobs in urban regions is increasing, which closes the large gap between rich and poor. Environmental economists such as (Panayotou 1997; Grossman and Krueger 1991) improved this theory by examining the association between economic growth and environmental quality. The effect of GDP growth on the quality of any economy's environment arises in 3 phases—scale effect, structural effect, and composite effects. In the first phase, environmental degradation is experienced but reaching a point (turning point), the environmental quality begins to improve due to development in innovations and increasing environmental consciousness. This first phase is termed the scale effects. This phase is related to developing nations because non-renewable energy sources promote their economic and production activities. The structural and composite effects are regarding as the turning point. This is associated with developed countries, where most of their economic activities are service and technology driven.

Table 1 Synopsis of studies

Investigator (s)	Timeframe	Nation (s)	Technique(s)	Findings
CO_2 emissions and economic growth				
Teng et al. (2020)	1985–2018	10 OECD economies	PMG-ARDL	$CO_2 \rightarrow$ GDP (+)
Rjoub et al. (2021)	1960–2018	Turkey	FMOLS, DOLS	$CO_2 \rightarrow$ GDP (+)
Zhang et al. (2021)	1960–2018	Malaysia	Maki cointegration, wavelet, and gradual shift	GDP $\rightarrow CO_2$ (+) GDP $\rightarrow CO_2$
Odugbesan and Adebayo (2020a)	1971–2016	South Africa	ARDL & wavelet coherence	$CO_2 \rightarrow$ GDP (+)
Al-Mulali (2011)	1980–2009	MENA	Panel Granger causality	$CO_2 \leftrightarrow$ GDP (+)
Odugbesan and Adebayo (2020b)	1980–2016	Nigeria	ARDL, NARDL	$CO_2 \rightarrow$ GDP (+)
Ayobamiji and Kalmaz (2020)	1971–2015	Nigeria	ARDL, FMOLS, DOLS, wavelet coherence	$CO_2 \rightarrow$ GDP (+)
Wasti and Zaidi (2020)	1990–2014	Kuwait	ARDL	$CO_2 \rightarrow$ GDP (+)
Aye and Edoja (2017)	1971–2013	31 emerging nations	Panel techniques	$CO_2 \rightarrow$ GDP (−)
Kalmaz and Kirikkaleli (2019)	1960–2016	Turkey	ARDL, FMOLS, DOLS, wavelet coherence	$CO_2 \rightarrow$ GDP (+)
Kirikkaleli et al. (2020)	1950–2016.	China	Maki cointegration, wavelet, and gradual shift	$CO_2 \rightarrow$ GDP
Bouznit & Pablo-Romero (2016)	1970–2010	Algeria	ARDL	$CO_2 \rightarrow$ GDP (+)
Aydoğan and Vardar (2020)	1990–2014	E-7	Panel VECM	$CO_2 \rightarrow$ GDP
Wu et al. (2018).	1995–2017	World	PRISMA	$CO_2 \leftrightarrow$ GDP
Khan et al. (2020)	1987–2017	China	GMM	$CO_2 \rightarrow$ GDP (+)
Adebayo (2020)	1971–2016	Mexico	ARDL & wavelet coherence	$CO_2 \leftrightarrow$ GDP (+)
Jafari et al. (2015)	1980–2007	Bahrain	TY causality	$CO_2 \rightarrow$ GDP
Li et al. (2021)	1995–2017	20 provinces in China	Panel CSARDL, AMG	$CO_2 \rightarrow$ GDP (+)
Salahuddin et al. (2018)	1980–2017	South Africa	ARDL	$CO_2 \neq$ GDP
Awosusi et al. (2020)	1980–2018	MINT economies	ARDL and Panel Granger causality	$CO_2 \neq$ GDP
Akinsola and Adebayo (2021)	1971–2016	Thailand	ARDL & wavelet coherence, Granger and Toda-Yamamoto causality	$CO_2 \rightarrow$ GDP (+) $CO_2 \rightarrow$ GDP
Ali et al. (2020b)	1990–2017	Top 10 emitter countries	Panel CSARDL	$CO_2 \rightarrow$ GDP (+)
Gao and Zhang (2021)	1980–2010	13 Asian developing countries	FMOLS and panel Granger causality tests	$CO_2 \rightarrow$ GDP
Energy consumption and economic growth				
Shahbaz et al. (2018)	1960Q1–2015Q4	Top 10 energy-consuming countries	Quantile-on-quantile (QQ) approach	EC $\rightarrow$ GDP (+)
Khobai and Le Roux (2017)	1971–2013	South Africa	Johansen cointegration and VECM Granger causality tests	EC $\leftrightarrow$ GDP
Ha and Ngoc (2020)	1971–2017	Vietnam	ARDL and Toda-Yamamoto causality	EC $\leftrightarrow$ GDP
Rahman et al. (2020)	1981–2016	China	Hatemi-J and FMOLS	EC $\rightarrow$ GDP (+)
Baz et al. (2019)	1971–2014	Pakistan	NARDL	EC $\rightarrow$ GDP (+)
Faisal et al. (2016)	1990–2011	Russia	Toda-Yamamoto causality	No causal link
Yang and Zhao (2014)	1970–2008	India	Granger causality and DAG	EC $\rightarrow$ GDP
Mutascu (2016)	1970–2012	G7 economies	Granger causality tests	EC $\leftrightarrow$ GDP
Muhammad (2019)	2001–2017	MENA	MENA	EC $\rightarrow$ GDP (−)
Urbanization and economic growth				
Nathaniel and Bekun (2020)	1971–2014	Nigeria	Bayer and Hanck cointegration tests, ARDL, FMOLS, DOLS, CCR, and VECM Granger causality	URB $\leftrightarrow$ GDP (−)
Nguyen and Nguyen (2018)	1971–2014	ASEAN	D-GMM and PMG	URB $\rightarrow$ GDP (+)
Ali et al. (2020a)	1971–2014	Nigeria	Maki cointegration, FMOLS, DOLS, CCR, and VECM Granger causality	URB $\rightarrow$ GDP (-)
Adebayo (2021b)	1971–2015	Japan	Wavelet coherence, ARDL, FMOLS, DOLS	URB $\rightarrow$ GDP (+)
Yang et al. (2017)	2000–2010	China	Pooled ordinary least squares (POLS), fixed effects (FE), and random effect (RE	URB $\rightarrow$ GDP (+)
Zheng and Walsh (2019)	2001–2012	29 provinces in China	FE and sys-GMM estimated methods	URB $\rightarrow$ GDP (+)
Gross capital formation and economic growth				
Topcu et al. (2020)	1980–2018	124 countries	PVAR	GCF $\rightarrow$ GDP (+)
Etokakpan et al. (2020)	1980–2014	Malaysia	Bayer and Hanck cointegration tests, ARDL and Granger causality	GCF $\rightarrow$ GDP (+)

Table 1 (continued)

Investigator (s)	Timeframe	Nation (s)	Technique(s)	Findings
Zhang et al. (2021)	1971–2016	Malaysia	ARDL, wavelet coherence, gradual Shift	GCF → GDP (+)
Kong et al. (2020)	1997–2017	39 African countries	AMG and CCEMG	Urban → GDP(+) Urban ↔ GDP (+)
Boamah et al. (2018)	1990–2017	18 Asian nations	POLS	GCF → GDP (+)

Note: *EC*, energy consumption; *GDP*, economic growth; *CO_2*, carbon emission; → (+), positive relationship; → (−), negative relationship; →, one-way causality; ↔, bidirectional causality; urban, urbanization; *GCF*, gross capital formation

Data and methodology

Data

The present research explores the impact of CO_2 emissions (CO_2) on economic growth (GDP) and also the role of gross capital formation (GCF), energy use (EC), and urbanization (URB) in South Korea using data spanning between 1965 and 2018. In the case of South Korea, the current research was conceived with the perspective of examining the connections between GDP growth, CO_2 pollution, urbanization, and energy use. The empirical modeling is based on the ARDL technique. This analysis is based on the study by Udemba (2020) and Nathaniel et al. (2020) by adjusting for further catalysts of growth that have been overlooked in the literature, including growth theory caused by the urban population. As shown in the model of Solow growth regarding capital and labor contribution. For South Korean cases that have the same economic characteristics, urban populations are included in our sample scenario. The parameters utilized are transmuted into a logarithm. This was conducted to ensure data is normally distributed (Rjoub et al. 2021; Kirikkaleli et al. 2020). Table 2 illustrates the data source, measurement, and unit of measurement. Also, the flow of analysis is depicted in Fig. 2. The study economic function and econometric model are depicted in Eqs. (1) and (2):

$$\mathrm{GDP}_t = f(\mathrm{CO}_{2t}, \mathrm{URB}_t, \mathrm{EC}_t\ \mathrm{GCF}_t) \quad (1)$$

$$\mathrm{GDP}_t = \vartheta_0 + \vartheta_1\mathrm{CO}_{2t} + \vartheta_2\mathrm{URB}_t + \vartheta_3\mathrm{EC}_t + \vartheta_3\mathrm{GCF}_t + \varepsilon_t \quad (2)$$

In Eq. (1), GDP, CO_2, GCF, EC, and URB represent economic growth, CO_2 emissions, gross capital formation, energy consumption, and urbanization.

Methodology

Analysis of correlation is used to verify the association of two time series data. The correlation can be defined as follows:

$$\mathrm{Corr}\ (\mathrm{X}, \mathrm{Y}) = \frac{\mathrm{Cov}\ (X, Y)}{\sqrt{\mathrm{Var}(X)\mathrm{Var}(Y)}} \quad (3)$$

where the covariance between the two time series (X,Y) is denoted as Cov(X,Y) while Var (X) and Var(Y) denote the value of the two time series of X and Y, respectively.

To achieve this purpose, ADF, PP, and Zivot and Andrews (ZA) unit root tests were employed to establish the order of integration. However, the ZA can capture both the stationarity property and structural break. This study employed the ARDL approach because this technique accommodates a limited number of observations (Ayobamiji and Kalmaz 2020; Kirikkaleli et al. 2018; Adebayo and Kirikkaleli 2021). Its

Table 2 Variable units and sources

Variable	Description	Units	Sources
GDP	Economic growth	GDP per capita constant $US, 2010	WDI (2021)
CO_2	Environmental degradation	Metric Tonnes Per Capita	WDI (2021)
GCF	Gross capital formation	% of GDP	WDI (2021)
URB	Urbanization	Urban population	WDI (2021)
EC	Energy use	Primary energy consumption is measured in terawatt-hours (TWh)	BP (2021)

model is suitable for a model with different lags and mixed order of integration. It is also beneficial because of the attributes of revealing coefficients in the short and long run simultaneously and solves the problem of autocorrelation. This makes the credibility of the formulated policy of this study to be effective. ARDL modeling is defined in the equation below:

$$\Delta \mathrm{InGDP}_t = \alpha_0 + \sum_{i=1}^{t} \alpha_1 \Delta \mathrm{InGDP}_{t-i} + \sum_{i=1}^{t} \alpha_2 \Delta \mathrm{InC0}_{2t-i} + \sum_{i=1}^{t} \alpha_3 \Delta \mathrm{InEN}_{t-i} + \sum_{i=1}^{t} \alpha_4 \Delta \mathrm{InGCF}_{t-i} + \sum_{i=1}^{t} \alpha_5 \Delta \mathrm{InURB}_{t-i} + \beta_1 \mathrm{InGDP}_{t-1} + \beta_2 \mathrm{InCO}_{2t-1} + \beta_3 \mathrm{InEN}_{t-1} + \beta_4 \mathrm{InGCF}_{t-1} + \beta_5 \mathrm{InURB}_{t-1} + \rho \mathrm{ECT}_{t-i} + \varepsilon_t \quad (4)$$

where $\alpha_{i=5}$ and $\beta_{i=5}$ are the long- and short-run parameters respectively, ρ denotes parameter for ECT_{t-i}, ε_t and Δ denote the error term and first difference respectively, and ECT_{t-i} represents the error correction term, which is the adjusted speed to long-run balance from short-run shock. The ARDL hypotheses are written below. The null hypothesis reiterates that there is no cointegration presence in the model, while the alternate hypothesis affirms a contradictory view, which is the presence of cointegration.

$$H_o : \alpha_0 = \alpha_1 = \alpha_2 = \alpha_3 = \alpha_4 = \alpha_5 \quad (5)$$

$$H_1 : \alpha_0 \neq \alpha_1 \neq \alpha_2 \neq \alpha_3 \neq \alpha_4 \neq \alpha_5 \quad (6)$$

The testing procedure in the ARDL model is by comparing the *F* or *T* statistics calculated with the critical bound (lower and upper bound). Normality test, heteroscedasticity test, Ramsey RESET, and serial correlation are the diagnostic tests undertaken to examine for BLUE. Model stability was checked employing the cumulative sum of recursive residuals (CUSUM) and cumulative sum of squares of recursive residuals (CUSUM of squares). Furthermore, the long-run coefficients of the ARDL model were verified using the FMOLS and DOLS tests.

Wavelets coherence is employed to detect the time-frequency dependence of energy consumption, CO_2 emissions, urbanization, and gross capital formation on economic growth. Time-frequency dependence puts into account the changes over time and how the relationship varies from one frequency to another becomes essential and strategic in the formulation of policies (Beton Kalmaz and Adebayo 2020; Mutascu 2018; Alola and Kirikkaleli 2019; Umar et al. 2020; Alola and Kirikkaleli 2020). The Morlet wavelet function was employed since it brings balance between phase and amplitude. Morlet wavelet function is defined as follows:

$$\sqsupset(\backslash) = \pi^{-\frac{1}{4}} e^{-i\sqsupset\backslash} e^{-\frac{1}{2}\backslash^2} \quad (7)$$

Note: non-dimensional frequency was used by $\sqsupset$; i denotes $\sqrt{-1}$ p(\ ). Using the time and space, with \ = 0,1, 2, 3……N-1, the time series continuous wavelet transformation (CWT) is defined as:

$$\sqsupset_{k,f}(\backslash) = \frac{1}{\sqrt{h}} \sqsupset\left(\frac{n-k}{f}\right), \quad k, f \in \mathbb{R}, f \neq 0 \quad (8)$$

where *k* and *f* symbolize time and frequency, respectively. CWT helps the cross-wavelet analysis to interrelate between two variables (Kirikkaleli 2019). The CWT equation is written below as follows:

$$\mathscr{W}_p(k,f) = \int_{-\infty}^{\infty} p(n) \frac{1}{\sqrt{f}} \sqsupset\left(\overline{\frac{n-k}{f}}\right) dn \quad (9)$$

The local variance was revealed using the wavelet power spectrum (WPS). The equation defining the WPS is as follows:

$$\mathrm{WPS}_p(k,f) = \left|W_p(k,f)\right|^2 \quad (10)$$

To examine the co-movement between two time series, the wavelet coherence approach (WTC) was used, which is defined in the equation below:

$$R^2(k,f) = \frac{\left|S\left(f^{-1} W_{pj}(k,f)\right)\right|^2}{S\left(f^{-1}\left|W_p(k,f)\right|^2\right) S\left(f^{-1}\left|W_j(k,f)\right|^2\right)} \quad (11)$$

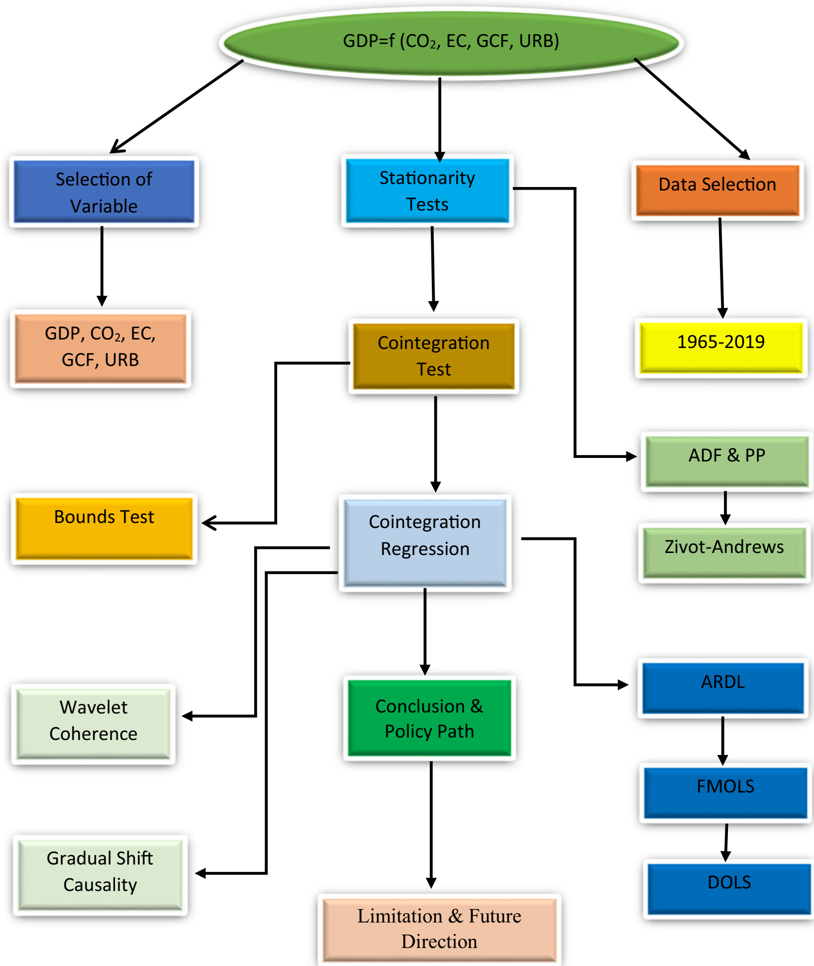

Fig. 2 Analysis flowchart

where the smoothing operator to both time and scale with $0 \leq R^2(k,f) \leq 1$ is denoted as S. WTC can also detect the phase difference ϕ_{pq} of the two time series; it is defined in this form:

$$\phi_{pq}(k,f) = \tan^{-1}\left(\frac{L\{S(f^{-1}W_{pj}(k,f))\}}{O\{S(f^{-1}W_{pj}(k,f))\}}\right) \quad (12)$$

where L denotes an imaginary operator while O stands for a real part operator.

Apart from the wavelet coherence approach, the gradual shift causality test developed by Nazlioglu et al. (2016) was utilized to establish the direction of causation between two variables. Nazlioglu et al. (2016) employed the Toda and Yamamoto (1995) and Fourier approximation, which captures the structural changes during the period of coverage (Kirikkaleli and Gokmenoglu 2020; Gokmenoglu et al. 2019). This technique helps to overcome the inaccuracies and inconsistencies associated with the VAR model. Using the modified VAR model stated in the equation below:

$$y_t = \sigma(t) + \beta_1 y_{t-1} + \ldots + \beta_{p+d\max} y_{t-(p+d\max)} + \varepsilon_t \quad (13)$$

where y_t symbolizes variable used; σ symbolizes intercept; β symbolizes coefficient matrices; ε symbolizes the error term; and t symbolizes time function. The Fourier approximation with cumulative frequencies is defined as:

$$\sigma(t) = \sigma_0 + \sum_{k=1}^{n} \gamma_{1k}\sin\left(\frac{2\pi kt}{T}\right) + \sum_{k=1}^{n} \gamma_{2k}\cos\left(\frac{2\pi kt}{T}\right) \quad (14)$$

where γ_{2k} and γ_{1k} measures the displacement and frequency amplitude respectively and the number of frequencies is denoted as n. Fourier Toda-Yamamoto causality with cumulative frequencies (CF) is defined as follows in:

$$y_t = \sigma_0 + \sum_{k=1}^{n} \gamma_{1k}\sin\left(\frac{2\pi kt}{T}\right) + \sum_{k=1}^{n} \gamma_{2k}\cos\left(\frac{2\pi kt}{T}\right) + \beta_1 y_{t-1} + \ldots + \beta_{p+d\max} y_{t-(p+d\max)} + \varepsilon_t \quad (15)$$

where approximation frequency is symbolized as k. For the Fourier Toda-Yamamoto causality with single frequencies, single-frequency components are defined in Eq. (11) as follows:

$$\sigma(t) = \sigma_0 + \gamma_1 \sin\left(\frac{2\pi kt}{T}\right) + \gamma_2 \cos\left(\frac{2\pi kt}{T}\right) \quad (16)$$

The Fourier Toda-Yamamoto causality with single frequencies (SF) is defined as follows:

$$y_t = \sigma_0 + \gamma_1 \sin\left(\frac{2\pi kt}{T}\right) + \gamma_2 \cos\left(\frac{2\pi kt}{T}\right) + \beta_1 y_{t-1} + \ldots + \beta_{p+d} y_{t-(p+d)} + \varepsilon_t \quad (17)$$

Findings and discussion

The present paper aims to examine the connection between CO_2 emissions (CO_2) and economic growth (GDP) as well as the role of urbanization (URB), gross capital formation (GCF), and energy usage (EC) in South Korea between 1965 and 2018. Figure 3 (correlation box) depicts the correlation among the parameters. In Fig. 3, the blue color illustrates a positive correlation, while the red color illustrates a negative correlation between variables. The correlation outcomes show that all the variables have a strong correlation with each other with the exemption of GCF with a weak correlation with other indicators. Consequently, the elementary summary statistical characteristics that report the measure of central tendencies and dispersion outlined in Table 3 show that urbanization reveals the highest average followed by economic growth, energy use, and the least gross capital formation. All series shows negative skewness with light tail, and the kurtosis revealed that data are normally distributed with the exemption of GCF. Furthermore, the study utilized the aforementioned methods to test the stationarity features of the data. The outcomes show that the parameters are integrated in mixed order, i.e., I(I) and I(0), as depicted in Tables 4 and 5.

After the stationarity characteristics of the series are affirmed, we proceed to estimate the ARDL framework, which is reported in Table 6. The outcomes are presented in such a manner that the existence of a long-run association between the parameters is verified if the estimated value of the *F*-test is greater than the values of both limits (lower and upper bound). In this scenario, we fail to accept the null hypothesis of no cointegration. Nonetheless, if the *F*-statistics is less than the lower bound critical value, the alternative explanation of the presence of cointegration is dismissed, although, if the *F*-stats breakdown between the two thresholds critical values, the finding is called inconclusive.

We proceed to estimate the long-run and short-run association between variables of concern, and findings are depicted in Table 7. Appropriate lag selection is essential when applying the ARDL. Thus, we utilized the AIC criteria proposed by Akaike (1987). As stated by Udemba et al. (2021) and Zhang e al. (2021), the AIC is preferred for selection lag due to its superior characteristics. The model goodness of fit is depicted by the R^2 (0.99) and Adj R^2 (0.98), respectively. The outcomes of the R^2 and Adj R^2 illustrate that 99% and 98% variation in GDP can be explained by urbanization, gross capital formation, CO_2 emissions, and energy consumption, and the remaining percentage can be attributed to error. The speed of adjustment is seen to facilitate long-term convergence between the parameters with a significant and negative error correction model coefficient (ECM). The outcome of the ECT is 0.22, which illustrates evidence of cointegration among the parameters, and this signifies the capability of the model to witness 22% speed of adjustment to verify the alignment to equilibrium in the long run on GDP due to the effect of the regressors (URB, EC, CO_2, and GCF). The outcomes of the ARDL illustrate the different linkage between GDP and the regressors (URB, EC, CO_2, and GCF). For instance, there is proof of a negative linkage between GDP and CO_2 emissions in the short run. This illustrates that an increase in CO_2

Table 3 Descriptive statistics

	GDP	CO_2	EC	GCF	URB
Mean	3.899157	0.722277	1.905183	1.494485	7.435024
Median	3.990954	0.812789	2.046541	1.508928	7.520742
Maximum	4.457504	1.141450	2.389607	1.615256	7.624351
Minimum	3.062850	− 0.059921	0.968732	1.169181	6.967840
Std. Dev.	0.433817	0.337479	0.434017	0.075982	0.196133
Skewness	− 0.388375	− 0.696901	− 0.558883	− 1.695635	− 0.921605
Kurtosis	1.819464	2.317733	1.986679	7.925874	2.583351
Jarque-Bera	4.576475	5.518732	5.216344	81.96133	8.183577
Probability	0.101445	0.063332	0.073669	0.000000	0.016709
Observations	55	55	55	55	55

Table 4 Traditional unit root tests

	At level I(0) Intercept & trend	First difference I(1) Intercept & trend	Decision
ADF unit root test			
GDP	0.3979	− 0.9324*	I(1)
CO_2	− 0.9710	− 8.0537*	I(1)
EC	− 0.5678	− 7.0742*	I(1)
GCF	− 4.7370*	− 6.3073*	I(0), I(1)
Urban	− 4.9187*	− 2.1810	I(0)
PP unit root test			
GDP	0.6869	− 6.9458*	I(1)
CO_2	− 0.9463	− 8.0591*	I(1)
EC	− 0.5908	− 7.0742	I(1)
GCF	− 4.7149*	− 15.3632	I(0), I(1)
URB	− 4.0221**	− 2.6810	I(0)

Note: 1% and 5% level of significance is illustrated by * and ** respectively

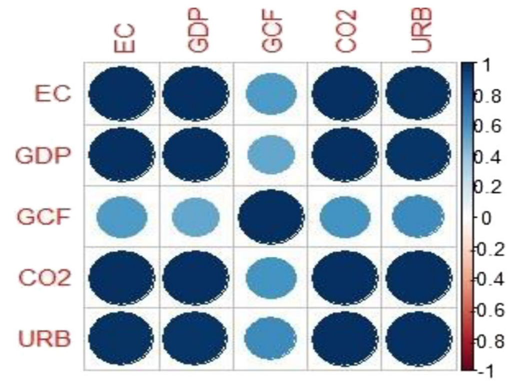

Fig. 3 Correlation between GDP, URB, EC, GCF, and CO_2

emissions will mitigate GDP, which infers that an increase in CO_2 by 1% in the short run is accompanied by a 0.28% decrease in GDP when other indicators are held constant. This result concurs with the findings of Lee (2013) for G-20 nations and Udemba et al. (2021) for India. Furthermore, urbanization and energy consumption exert a positive impact on economic growth in the short run, which illustrates that 1% in urbanization and energy consumption will increase economic growth by 1.92% and 0.23%, respectively. This is a strong indicator that the intensity of energy and the populace are critical indicators in the growth of the South Korean economy. The industrial sector uses a momentous quantity of energy as one of the main contributors and generators of the South Korean economy, which in turn affects income positively. This outcome aligns with the results of Zhang et al. (2021) for Malaysia and Kirikkaleli and Demet (2020) for Turkey. Moreover, there is no evidence of interconnection between gross capital formation and GDP in the short run, which aligns with the study of Olanrewaju et al. (2021) for Thailand and Zhang et al. (2021) for Malaysia.

In the long run, there is evidence of a long-run association between GDP and CO_2 emissions, which illustrates that a 0.15% increase in GDP is linked with a 1% upsurge in CO_2 emissions. This is not unexpected given that the South Korean economy is primarily an investment-oriented and manufacturing economy that relies heavily on the utilization of energy; nonetheless, a positive side of this is the potential to minimize CO_2 by shifting the energy mix to include more renewable options such as wind and solar energy (renewables). Furthermore, urbanization influences economic growth positively in South Korea, which is in harmony with a positive linkage with GDP growth and urbanization. We see that a 1.92% increase in GDP growth is due to a 1% increase in the urban population. We make the claim based on the empirical revelation that the growing population in South Korea is productive to her economic trajectory. Nevertheless, there is a necessity for cautiousness on the part of policymakers to match urban infrastructure and amenities in the rural area. This is to avoid the rush to urban cities, given that most government officials develop urban areas more than rural areas. Otherwise, the urban infrastructure might be overwhelmed and might impede economic growth in the long run. We noticed that energy use improves economic growth as we noticed that a 0.23% increase in economic growth is due to an increase in energy use by a magnitude of 1%. This outcome gives credence to the energy-induce growth hypothesis, which complies with the study of Nathaniel et al. (2020) for Nigeria

Table 5 ZA unit root test

	At level I(0)		First difference I(1)		Decision
	Intercept & trend	Break-date	Intercept & trend	Break-date	
GDP	− 2.8836	1994	− 7.8407*	1983	I(1)
CO_2	− 3.8751	1993	− 8.6482*	1998	I(1)
EC	− 4.2704	1991	− 7.9482*	1984	I(1)
GCF	− 6.4665*	1998	− 7.0113*	1997	I(0), I(1)
URB	− 5.2474**	1986	− 5.7052*	1996	I(0), I(1)

Note: 1% and 5% level of significance is illustrated by * and ** respectively and also in Pakistan by Shahbaz et al. (2012). This outcome implies that the South Korean economy is energy driven and cannot embark on conservative energy strategies as such action will compromise economic growth.

Furthermore, various post-estimation tests are conducted. The outcomes of the normality, serial correlation, heteroscedasticity, and Ramsey tests show that the model is well specified, and there is no serial correlation. Moreover, the outcomes of the CUSUM and CUSUMSQ depict in Figure 4a, and 4b, respectively, which exemplifies that the model is stable.

To confirm the ARDL long-run estimations' outcomes, the current study utilized the FMOLS and DOLS, which are portrayed in Table 8. The outcomes show that CO_2 emissions. Energy consumption and urbanization enhance economic growth in the long run, while there is no significant interconnection between gross capital formation and economic growth.

The current research further utilizes the wavelet coherence (WTC) test to catch the causality and correlation between economic growth and the regressors (CO_2, EC, URB, and GCF). This method is crafted from physics to obtain formerly undetected information. Therefore, the research investigates the connection in the short, medium, and long run between GDP and its regressors. The cone of influence (COI) is the white cone where discussion is carried out in the WTC. The thick black contour illustrates a level of significance based on simulations of Monte Carlo. Figure 5a–5d 0–4, 4–8, and 8–16 illustrate short, medium, and long term, respectively. Moreover, the vertical and horizontal axis in the figure depicts frequency and time, respectively. The blue and yellow colors depict low and high dependence between the series. In-phase and out-of-phase connections are depicted by rightward and leftward arrows, respectively. Moreover, the rightward-down (leftward-up) illustrates that the first variable lead (cause) the second parameter while the rightward-up (leftward-down) depicts that second parameter lead (cause) the first parameter. Figure 5a illustrates the WTC between GCF and GDP between 1965 and 2019. At different frequencies between 1970 and 2016, the arrows are rightward-up, showing the positive interconnection between the series with GCF leading. Figure 5 b depicts the WTC between EN and GDP between 1965 and 2018 in South Korea. The majority of the arrows are rightward-up, which illustrates a strong connection (dependency) at different frequencies with energy use leading. Figure 5c illustrates the WTC between URB and GDP in South Korea between 1965 and 2019. At different scales, from 1970 to 2016, the bulk of arrows are facing rightward-up, which show positive association (dependency) at different frequencies. Furthermore, the rightward-up arrows show that URB lead (cause) GDP. Figure 5 d illustrates the WTC between URB and GDP in South Korea between 1965 and 2019. From 1995 to 2003, the bulk of arrows are facing rightward-up at high and medium frequencies, which shows a positive association (dependency) between GDP and GCF. Furthermore, the rightward-up arrows show that GCF lead (cause) GDP. The outcomes from the wavelet coherence test comply with the results of DOLS, FMOLS, and ARDL.

To capture the causal association among the indicators, the gradual shift test is applied, and the results of this technique are presented in Table 9. The outcomes of the gradual shift causality revealed: (i) a one-way causality from energy consumption to GDP at a significance level of 1%. This suggests that South Korea's economic growth is not immune from development caused by fossil fuels. This is because South Korea's economy is heavily reliant on production and manufacturing operations. This outcome corresponds to the findings of Ramakrishna and Rena (2013) and Udemba et al. (2021); (ii) a unidirectional causality from CO_2 emissions to

Table 7 ARDL long-run and short-run results

Variables	Long-run results			Short-run results		
	Coefficient	*t*-statistic	Prob	Coefficient	*t*-statistic	Prob
CO_2	0.1552**	2.0736	0.045	− 0.2804*	− 2.999	0.006
EC	0.2370**	2.1121	0.041	0.4142*	3.993	0.000
GCF	0.0486	1.1719	0.248	0.0695	1.691	0.103
URB	1.9218**	2.1331	0.039	4.0658*	2.789	0.010
ECT(− 1)	-	-	-	− 0.2273*	− 4.030	0.000
R^2	0.99					
Adj R^2	0.98					

Note: 1% and 5% level of significance is illustrated by * and ** respectively

Table 6 Bound test

Model	*F*-statistics	Cointegration	χ^2 ARCH	χ^2 RESET	χ^2 normality	χ^2 LM
GDP=*f*(CO_2, EC, GCF, URB)	5.61*	Yes	0.57 (0.56)	0.72 (0.47)	0.91 (0.63)	0.58 (0.44)
	10%		5%		1%	
	LB	UB	LB	UB	LB	UB
	2.26	3.35	2.62	3.79	3.41	4.68

*Represents a 1% level of significance and LB and UB denote lower bound and upper bound critical value

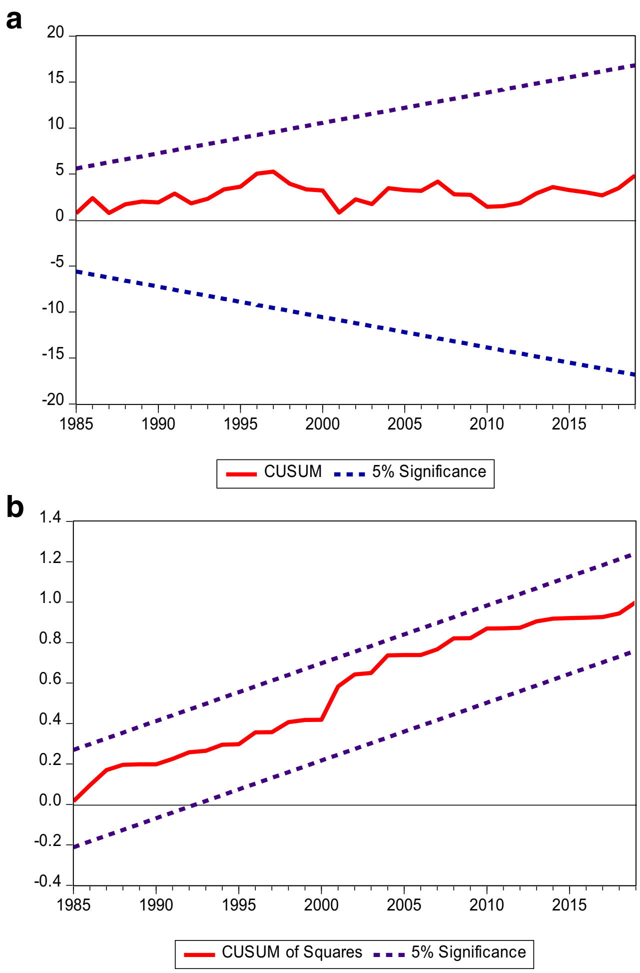

Fig. 4 **a** CUSUM. **b** CUSUM of squares

GDP growth at a 1% level of significance, which implies that CO_2 emissions are a strong predictor of GDP growth in South Korea. In this regard, South Korean policymakers should develop policies in line with the nation's energy portfolio diversification. This finding is consistent with the results of Zhang et al. (2021) for Malaysia, Adebayo (2020) for Indonesia, and

Table 8 FMOLS and DOLS outcomes

Variable	FMOLS			DOLS		
	Coefficient	*t*-statistic	Prob.	Coefficient	*t*-statistic	Prob.
CO_2	0.1443**	2.5057	0.017	0.2370**	2.4821	0.017
EC	0.2437*	2.8833	0.006	0.2332**	2.3277	0.025
GCF	0.0574	1.3338	0.185	0.0486	1.3770	0.177
URB	2.0115**	2.5782	0.014	1.9218**	2.5067	0.016
R^2	0.98			0.98		
Adj R^2	0.97			0.97		

Note: * and ** represents 1% and 5% level of significance respectively

Table 9 Gradual shift causality test

Causality path	Wald stat	No of Fourier	*P*-value	Decision
GDP ➔ EC	10.940	3	0.1412	Do not reject Ho
EC ➔ GDP	18.828*	3	0.0087	Reject Ho
GDP ➔ URB	21.986*	1	0.0025	Reject Ho
URB ➔ GDP	5.868	1	0.5551	Do not reject Ho
GDP ➔ CO_2	10.721	2	0.1512	Do not reject Ho
CO_2 ➔ GDP	23.974*	2	0.0011	Reject Ho
GDP ➔ GCF	10.721	2	0.1512	Do not reject Ho
GCF ➔ GDP	5.1177	2	0.6455	Do not reject Ho

Note: 1%, 5%, and 10% level of significance is illustrated by *, **, and *** respectively

Awosusi et al. (2020) for the MINT economies; (iii) a one-way causality from GDP to urbanization at the significance level of 1%, which suggests that GDP can predict URB. This finding has consequences for South Korea's economic growth in terms of rapid urbanization, where investment will be attached mainly to the vulnerable population with the promise of improvement in welfare. This outcome concurs with the findings of Awosusi et al. (2020), Udemba et al. (2021), and Zhang et al. (2021).

Conclusion and policy directions

The current study adds to the previously existing literature by assessing the linkage between economic growth, CO_2 emissions, energy usage, urbanization, and gross capital formation in South Korea using yearly data stretching between 1965 and 2019. To accomplish the stated objectives, the ARDL bounds test, the gradual shift causality test, and the novel wavelet coherence test are utilized. The outcomes show a mix (significant and insignificant) of associations between economic growth and the regressors. The outcome of the bounds test reveals that all the indicators have a long-run interconnection. Furthermore, the outcomes of the ARDL long-run and short-run estimations show that energy usage, urbanization, and CO_2 emissions enhance the economic performance of South Korea, while gross capital formation exerts an insignificant impact on the economic performance of South Korea. Furthermore, we applied the novel wavelet test to capture the correlation and causal association between economic growth and the regressors. The wavelet analysis findings revealed a positive connection between economic growth and the regressors with the exemption of gross capital formation, which has a weak interconnection with economic performance. Furthermore, the wavelet coherence test outcomes provide further support for the ARDL, FMOSL, and DOLS tests. The gradual shift causality test outcomes provide

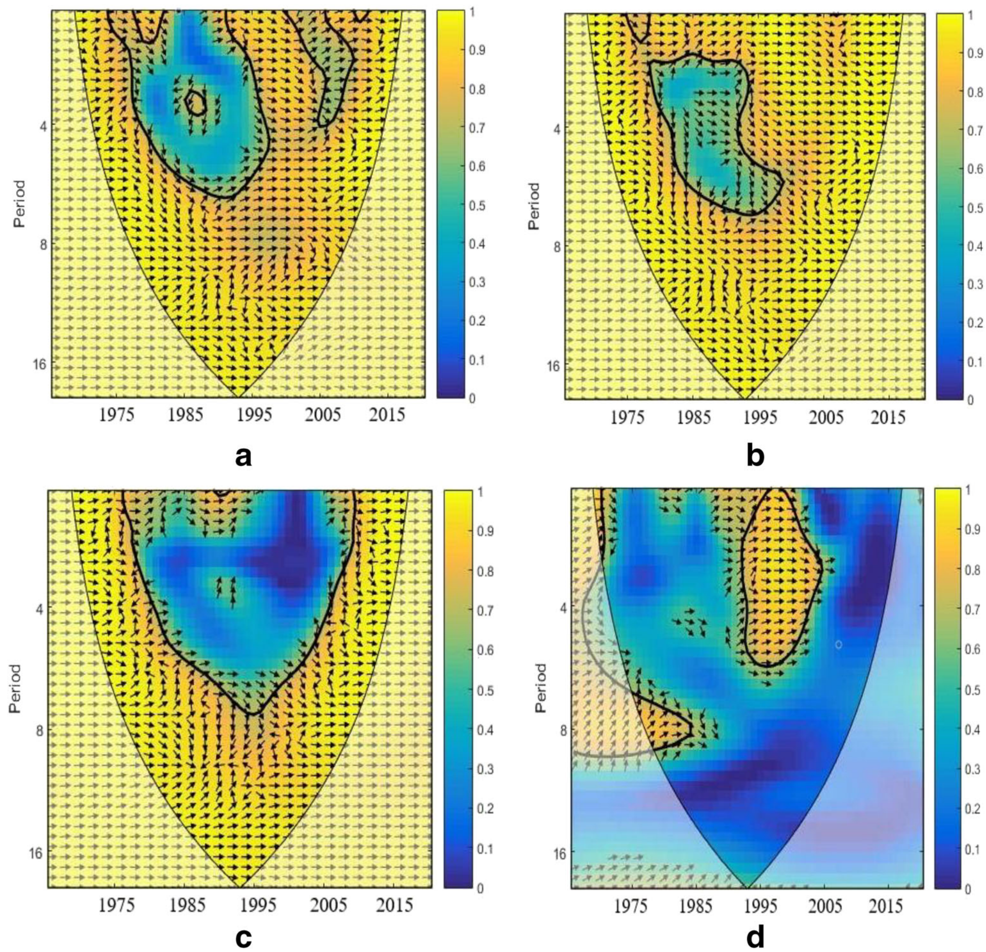

Fig. 5 **a** WTC between GDP and CO_2 emissions. **b** WTC between GDP and energy consumption. **c** WTC between GDP and urbanization. **d** WTC between GDP and gross capital formation

intuition and credibility to the linkage among economic growth and urbanization, energy usage, gross capital formation, and CO_2 emissions.

This research's outcomes have aided us in embracing the promotion of energy intensity diversification of South Korea. This could be achieved by implementing a more ambitious green energy initiative that will maintain the nation's economic momentum. The design and execution of successful policies to regulate South Korean energy and manufacturing sector practices will improve its sustainable growth. This will continue to regulate the CO_2 pollution levels in the nation if the government sets emission restrictions on firms and factories who are emitting CO_2 emissions. The threat of punitive action or high taxes on infringers of this policy will deter environmental pollution. Also, energy usage should be embraced by incorporating sustainable (renewable) energy sources, including hydropower, oceanic, and wind energy sources. Furthermore, South Korea should be careful when formulating policies that will stimulate economic growth at the expense of environmental degradation. Implementing the aforementioned policies will help to maintain sustainable economic development and South Korea's proven environmental performance. This study's outcome could also have a positive impact on neighboring nations who are willing to take the steps suggested in this paper to strengthen their sustainable growth. In conclusion, this study has examined the nexus between energy use, urbanization, energy consumption, gross capital formation, and economic growth in South Korea using recent time series data. Further studies can be conducted for other emerging nations while considering asymmetric in the econometrics modeling or the use of micro-disaggregated data. Furthermore, other studies can account for other drivers of growth that have not been explored in this study.

Acronyms *ADF,* Augmented Dickey-Fuller; *ARDL,* Autoregressive distributed lag; *BRICS,* Brazil, Russia, India, China, and South Africa; *CCO_2,* Consumption-based carbon emissions; *CO_2,* Carbon dioxide; *COP21,* UN Climate Change Conference in Paris; *DOLS,* Dynamic ordinary least square; *ECM,* Error correction model; *ECT,* Error correction term; *EKC,* Environmental Kuznets curve; *EC,* Energy consumption; *FMOLS,* Fully modified ordinary least square; *GCF,* Gross capital formation; *GMM,* General method of moment; *GDP,* Economic growth; *GHGs,* Greenhouse gas emissions; *GMM,* Generalized method of moments; *IEA,* International Energy Agency; *OECD,* The Organization for Economic Co-operation and Development; *PMG-ARDL,* Pooled mean group autoregressive distributed lag; *PP,* Phillips-Perron; *TY,* Toda and Yamamoto; *URB,* Urbanization; *VAR,* Vector autoregression; *ZA,* Zivot & Andrews

Symbols *β*, Coefficient of the regressors; *ρ*, Speed of adjustment; e_t, Error term; ECT_{t-1}, Error correction term; H_0, Null hypothesis; H_a, Alternative hypothesis

Author contribution Madhy Nyota Mwamba and Tomiwa Sunday Adebayo designed the experiment and collect the dataset. The introduction and literature review sections are written by Tomiwa Sunday Adebayo, Gbenga Daniel Akinsola, and Abraham Ayobamiji Awosusi. Dervis Kirikkaleli and Abraham Ayobamiji Awosusi constructed the methodology section and empirical outcomes in the study. Tomiwa Sunday Adebayo and Gbenga Daniel Akinsola contributed to the interpretation of the outcomes. All the authors read and approved the final manuscript.

Availability of data Data is readily available at https://data.worldbank.org/country/SouthKorea.

Declarations

Ethical approval This study follows all ethical practices during writing.

Consent to participate Not applicable.

Consent to publish Not applicable.

Competing interests The authors declare no competing interests.

Transparency The authors confirm that the manuscript is an honest, accurate, and transparent account of the study was reported; that no vital features of the study have been omitted; and that any discrepancies from the study as planned have been explained.

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