Dynamic Effect of Disintegrated Energy Consumption and Economic Complexity on Environmental Degradation in Top Economic Complexity Economies

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Recommended Citation

Adebayo, T.S., Altuntaş, M. & Goyibnazarov, S. (2022). Dynamic effect of disintegrated energy consumption and economic complexity on environmental degradation in top economic complexity economies. *Energy Reports* vol. 8, pg. 12832–12842. doi:10.1016/j.egyr.2022.09.161

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Energy Reports 8 (2022) 12832–12842

Contents lists available at ScienceDirect

Energy Reports

journal homepage: www.elsevier.com/locate/egyr

Research paper

Dynamic effect of disintegrated energy consumption and economic complexity on environmental degradation in top economic complexity economies

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ARTICLE INFO

Article history:
Received 28 January 2022
Received in revised form 29 August 2022
Accepted 27 September 2022
Available online 12 October 2022

Keywords:
CO_2 emissions
Economic complexity
Technological innovation
Disintegrated energy consumption

ABSTRACT

The current paper explores the influence of disintegrated energy and economic complexity on CO_2 emissions (CO_2) in the top economic complexity economies. The model also incorporates other drivers of CO_2, such as technological innovation and economic growth. The current research utilizes data stretching from 1993 to 2018. The research employed Westerlund cointegration, fully modified OLS (FMOLS), dynamic OLS (DOLS), and method of moments quantile regression (MMQR) to evaluate these interconnections. The outcomes of the slope heterogeneity and cross-sectional dependence affirmed the use of second-generation techniques. The study confirmed the long-run association between CO_2 and the regressors. The results of the MMQR disclosed that in each quantile (0.1–0.90), renewable energy enhances the quality of the environment, while economic complexity and nonrenewable energy intensify CO_2. In addition, technological innovation enhances the quality of the environment from 0.1–0.70 quantiles, while from 0.80–90 quantiles, technological innovation intensifies CO_2. The EKC is also validated in each quantile (0.1–0.90). The DOLS, FE-OLS, and FMOLS outcomes also affirm the MMQR outcomes. These outcomes encourage policymakers to implement holistic economic and environmental policies that prioritize greener production processes for environmental reasons and meet the United Nations SDGs 7, 8, 13, and 17.

1. Introduction

Climate change and global warming have been ongoing problems facing governments, scholars, and policymakers since the early 21st century (Vo and Vo, 2022; Wang et al., 2022; Yuan et al., 2020). Environmental contamination remains an impediment to the sustainable economic growth since it presents a plethora of environmental challenges, including energy dependence, deforestation, freshwater scarcity, climate change, and air pollution, all of which have been viewed as significant threats since the 1960s. As a result, the connection between the factors that are directly related to climate change must be re-examined since they can cause global devastation, endanger human existence, and destroy the entire planet in various ways (Cao et al., 2019; Fan et al., 2020). Global warming is undoubtedly the most dangerous externality ever seen in the history of mankind. One of the main factors causing pollution is greenhouse gas (GHGs) emissions (Ozturk and Acaravci, 2016). In this sense, CO_2 emissions are regarded as the most significant source of GHGs, with CO_2 accounting for roughly 76% GHGs emissions. Due to the significant expansion of the industrial sector in developed nations, it is reasonable to assume that ecological deterioration significantly impacts their economies (Shahzad et al., 2021).

Increased worldwide awareness of ecological problems has aided the coordination of international initiatives such as the

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https://doi.org/10.1016/j.egyr.2022.09.161

Abbreviations

CD	Cross-sectional dependence
CO_2	CO_2 Emissions
DOLS	Dynamic Ordinary Least Squares
ECI	Economic Complexity
FMOLS	Fully Modified Ordinary Least Squares
GDP	Economic Growth
GHGs	Greenhouse Gas Emissions
MMQR	Method of Moments Quantile Regression
NREC	Nonrenewable Energy Consumption
REC	Renewable Energy Consumption
SDGs	Sustainable Development Goals
SH	Slope Heterogeneity
TEC	Technological Innovation

Stockholm Conference in 1972, the Kyoto Protocol in 1997, and the Paris Agreement in 2015. The main aims are to reduce global emissions and provide countries with sustainable economic prosperity. As a result, it is critical that immediate action is taken and effective remedies to minimize air pollution, avoid global warming, and combat climate variation are identified (Adebayo and Rjoub, 2021). Reducing the use of nonrenewable energy, which represents roughly 80% of global primary energy use and contributes 75% of all GHG emissions with renewable, modern, and greener energy sources, such as tidal, geothermal, nuclear, biomass, solar, and the wind are the major aim of all countries (Acheampong et al., 2019; Doğan et al., 2021; Fatima et al., 2021). There is a consensus among the majority of researchers that using renewable energy resources significantly helps to reduce CO_2 emissions and safeguard the environment (Abbasi et al., 2021a; Adebayo, 2022a,b; Usman et al., 2020).

The economic complexity index (ECI) measures how well a country's economy can export and create a diverse range of goods. It provides a structural assessment of interconnected network economies in relation to products, technology-intensive exports, and the degree of productive consciousness embedded in an economy (Abbasi et al., 2021b; Ahmed et al., 2021; Boleti et al., 2021). According to this viewpoint, contemporary economic complexity has increased the demand for energy sources, which has resulted in increased environmental pollution. On the one hand, increased ECI causes manufactured products to be more diversified and increases production levels, which contributes to global warming and climate change. On the other hand, ECI has the potential to maintain ecological quality since it includes research and development (R&D) operations, as well as the capacity to handle green technologies and environmentally-friendly products (Shahzad et al., 2021).

The EKC hypothesis serves as the theoretical framework for this study. Economic growth can have three different consequences on the environment (Grossman and Krueger, 1991). Growth in the economy has three distinct impacts on CO_2: the technique, composition, and scale effects. According to the scale effect, economic expansion causes ecological damage at first because it obliges more resources and energy, leading to greater pollution and waste. On the other hand, the amount of materials required and emissions generated in the production process are influenced by the nation's structure (Hashmi et al., 2020). Furthermore, the composition effect implies that structural shifts from the industrial to service sectors will curb the adverse ecological effects of growth. Finally, the technique effect suggests that when there is an increase in a nation's wealth, it clinches new and improved technology that increases output while curbing emissions.

Apart from assessing the EKC theory, the interrelationships between disintegrated energy, economic complexity, technological innovation, and CO_2 generated significant concern among policymakers and central authorities when the sustainable development goals were publicized (SDGs) (Doğan et al., 2021). In this context, research on the energy-environment relationship shows that energy use and economic expansion are two of the most important factors affecting CO_2 emissions (Güngör et al., 2021). The UN's position on energy management is stated in its Sustainable Development Goals; from its perspective, economies that are heavily dependent on nonrenewable energy sources are causing serious climate change. As a result, increased investments in renewable energy sources such as wind, thermal power, and solar are necessary to meet SDG 7 by 2030.

The use of nonrenewables to meet energy demand is causing substantial problems in terms of regulating this situation. As a consequence, the interrelationship between CO_2 and GDP has attracted significant attention in contemporary environmental and energy economics (Adedapo et al., 2021; Shahbaz et al., 2015). More significantly, as stated by IEA, the energy sector is anticipated to produce over 68 percent of global GHG emissions, with fossil fuels accounting for approximately 44 percent of GHG emissions (IEA, 2022). This confirms that nonrenewable energy supplies are more likely to emit toxins into the ecosystem. On the flip side, renewable sources of energy, such as wind, hydro, tidal, and solar energy, can maintain the sustainability of the environment.

Furthermore, some nations have undertaken well-known initiatives to fight climate change and meet abatement objectives. Promoting technological innovation (TEC) has evolved as a commonly acknowledged strategy for dealing with ecological challenges, including CO_2 in the chosen countries (Chen and Lee, 2020; Khan et al., 2020). In reality, the number of patents issued to the selected countries reflects an unprecedented increase in TEC. In light of the fast pace of technological advancement and its connected carbon reduction influence in the selected countries, scholars have assessed the TEC and CO_2 emissions nexus for the selected nations (Cheng et al., 2021; Rafique et al., 2021; Zhao et al., 2021b). With the help of TEC, renewable energy sources can also be generated. REC capability is also being boosted through TEC, growing the likelihood that renewable energy will be accessible to meet future energy demand. Due to the growing demand for energy, it is widely assumed that REC will become the most significant energy in the future and will also be the most eco-friendly. Based on the above discussion, the current paper assesses the effect of disintegrated energy (nonrenewable and renewable energy) and technological innovation (TEC) on CO_2 in the top economic complexity nations.[1]

The following are the study's primary contributions: (1) In this research, the association between TEC and CO_2 in selected top economic complexity nations is systematically examined; this not only presents a clear assessment of the effect of technological innovation on CO_2 in the selected top economic complexity nations, but it also provides additional facts for creating appropriate measures to reduce CO_2 and encourage TEC; (2) The present research examines whether EKC exists over the whole CO_2 distribution; and (3) since adopting the right econometric technique is critical for the outcomes' credibility, this research assesses not only conditional means, but also controls distributional heterogeneity and uncovers the exogenous variables' latent impacts across the conditional distribution of the endogenous variables. In doing so, we applied a novel method known as MMQR initiated by

[1] Japan, Switzerland, South Korea, Germany, Singapore, Austria and Czech.

Machado and Santos Silva (2019) to obtain more rigorous and relevant heterogeneous panel outcomes. Since the distributional effect of the independent variables on the dependent variable is divided into multiple quantiles, the quantile regression makes more sense. As a consequence, it is simpler to categorize the various effects of diverse cross-sectional groupings. The information provided by conditional quantile estimations thus differs from that of conditional mean estimation. The findings of this research will thus aid decision-makers in developing practical strategies to lessen the effects of economic complexity and disintegrated energy on environmental deterioration.

The subsequent sections are as follows: Sections 2 and 3 present a summary of past studies and the methodology, respectively. Section 4 depicts the findings, while Section 5 presents the conclusion and policy suggestions.

2. Literature review

Over the years, significant studies have examined the factors (economic growth, technological innovation, disintegrated energy) influencing carbon emissions (CO_2). Nevertheless, mixed findings have been reported based on the technique(s) used, period of study, and countries/country of investigation (Dong et al., 2021). For instance, Akadırı et al. (2021a), Akadiri et al. (2021b) explored the emissions-GDP interrelation using 28 European Union countries as a case study. The investigators utilized a dataset from 1995–2015 and the DH causality approach and the study's findings revealed that GDP triggers CO_2 in the selected nations. Furthermore, Bekun and Agboola (2019) on the association between GDP and CO_2 using a dataset between 1990 and 2014 uncovered that an expansion in GDP triggers CO_2. Similarly, using Indonesia and a dataset from 1965–2018, the study of Akinsola et al. (2021) on the emissions-growth association reported a positive coherence between CO_2 and real growth using the novel wavelet coherence. Similarly, He et al. (2021), in their research using Mexico and a dataset from 1990 to 2018, reported that an upsurge in GDP increased CO_2. Likewise, the studies of Khan et al. (2021), Zhao et al. (2021a,b), and Dong et al. (2020) also reported that an increase in GDP causes a surge in CO2. Furthermore, the research of Kihombo et al. (2021a,b) on the drivers of CO_2 in WEMA nations using a dataset between 1990 and 2018 disclosed that an expansion in GDP causes an increase in CO_2.

Recently, economic complexity (ECI) has been found to have a substantial effect on CO_2. ECI is a broad measure of a nation's size, structural changes, and technological advancement. The study of Can and Gozgor (2016) on the effect of ECI on CO_2 for the case of France using a dataset from 1964–2011 reported that an upsurge in ECI contributes to a decrease of CO_2 in France using ARDL. Similarly, Romero and Gramkow (2021) assessed the interconnectedness between GHGs emission and ECI and their research disclosed that an upsurge in ECI abate GHGs emissions. Similarly, Doğan et al. (2021), in their research on the drivers of CO_2 in 55 nations between 1971 and 2014, unveiled that ECI upsurges CO_2 using the quantile regression technique. Likewise, using a dataset from 1995–2017 in 25 selected European Union, Neagu (2020) studied the influence of ECI on CO_2 using CPR regression. The study finding disclosed that the decrease in CO_2 is caused by an upsurge in ECI in the nations selected. Moreover, Khezri et al. (2022) study on the ECI-emissions linkage in 29 Asia-Pacific nations using a dataset from 2000–2018 and their study finding disclosed that an upsurge in ECI causes increased CO_2 and economic expansion. Likewise, the research of Doğan et al. (2021) on the ECI-emissions nexus reported that lessening in CO_2 is caused by 1% intensification in ECI.

Energy is the heartbeat of economic activities; however, its effect may harm the environment if its consumption is not sustainable. Studies on the disintegration energy effect on CO_2 are vast; however, the study's outcomes are inconclusive. For instance, Oladipupo et al. (2021) assessed the effect of disintegration energy on CO_2 in Portugal using a quarterly dataset from 1980–2018. The novel wavelet was used and the study findings disclosed that nonrenewable energy (NREC) triggers CO_2 while renewable energy (REC) diminishes CO_2. In the same vein, the work of Cheng et al. (2021) on the disintegrated energy and CO_2 in China using a dataset from 1980–2014 disclosed that NREC triggers CO_2 while REC abates CO_2.

Similarly, Inglesi-Lotz and Dogan (2018) assessed the drivers of CO_2 using a dataset from 1980–2011. The investigators' utilized panel ARDL and the study findings unleashed that NREC caused an increase in CO_2 while REC caused a decrease in CO_2. Moreover, the research of Dogan and Ozturk (2017) reported that NREC and REC increase and decrease CO_2 emissions, respectively using a dataset from 1990 to 2014 and AMG estimator.

Since ecological issues are so important, significant scholars have assessed the consequences of technological innovation (TI) on CO_2. TI is identified to have a significant impact on CO_2 mitigation. In host nations, TI has decreased CO_2 and improved the quality of the environment by combining it with ecological protection measures. Numerous research has looked at the relationship between CO_2 and TI; nonetheless, mixed results surfaced. For instance, Adebayo and Kirikkaleli (2021) examined the CO_2-TI interconnectedness for the global economy case using a dataset between 1990 and 2018. The authors' used FMOLS and DOLS, and their findings disclosed that TI helps mitigate CO_2. Similarly, the research of Kihombo et al. (2021b) also reported that TI aid in diminishing the level of CO_2. Moreover, the research of Cheng et al. (2021) in China testified that TI plays a significant role in dwindling CO_2 levels in China. Similarly, the research of Lin and Zhu (2019) on the CO_2-TI nexus unveiled that TI curbs CO_2.

In light of the investigations summarized above, the following viewpoints came to light: The techniques commonly used in the reviewed literature regarding the connection between disintegrated energy consumption and economic complexity and environmental degradation are vector autoregressive (VAR), autoregressive distributed lag (ARDL), Toda-Yamamoto causality, ordinary least squares, panel ARDL and vector error correction model (Akadiri et al., 2022; Altarhouni et al., 2021; Kirikkaleli and Oyebanji, 2022; Olanrewaju et al., 2022; Samour et al., 2022; Shan et al., 2021; Xu et al., 2022). More specifically, Adebayo et al. (2022) used the NICs to evaluate the effect of fossil fuel and renewable energy on environmental degradation, while Awosusi et al. (2022) scrutinized the effect of energy (renewable and nonrenewable) on environmental sustainability. Moreover, Alola et al. (2021) used a quantile approach to evaluate the nexus between disintegrated energy and environmental deterioration. In summary, no empirical research has thus far been done utilizing the novel MMQR in top-economic complexity countries to investigate these relationships. As a result, this work is the first attempt to address research gaps using the MMQR technique to investigate the correlation between disintegrated energy, economic complexity, and environmental deterioration.

3. Theoretical underpinning, data, and methodology

3.1. Theoretical underpinning

The EKC theory serves as the theoretical framework for this study. Economic expansion can have three different consequences on the environment. Growth in the economy has three dissimilar impacts on CO_2: the technique, composition, and scale effects. According to the scale effect, Growth in the economy causes ecological damage at first since it obliges more resources and energy, culminating in larger pollution and waste. On the flip side, the amount of materials required and emissions generated in the production process are influenced by the structure of a country. Furthermore, the composition phase implies that shifts in the industry to service sectors will abate the destructive ecological effects of GDP growth. Finally, the technique suggests that an upsurge in a nation's wealth enables it to adopt new and improved technology that increases output while curbing emissions.

Another critical aspect that may influence environmental quality is economic complexity (ECI). ECI is a broad measurement of a nation's size, structural changes, and technological advancement. Nonetheless, an economy's complexity may aid governments in managing skills, technological innovation, and knowledge, encouraging greener goods and eco-friendly technology, resulting in less environmental harm. On the other hand, simple economies cannot manage efficient knowledge; as a result, commodities are created using nonrenewable energy sources and traditional technology. As a result, nonrenewable energy and outdated technologies have detrimental environmental effects.

Renewable energy (REC) is the purest form of energy accessible and produces no contamination or depletion of natural resources; therefore, its usage reduces the environmental impact. Wind, hydro and solar power are the most environmentally-friendly energy sources. REC, contrary to fossil fuels, has no limit. On the flip side, nonrenewable energy sources are finite and unmaintainable, and their extensive use exacerbates global warming and climate change by raising GHGs. This implies that utilizing NREC energy surges CO_2, but utilizing REC decreases emissions.

It is widely acknowledged that TEC has a significant influence on CO_2 mitigation. Due to the combination of TEC with environmental conservation measures, CO_2 levels have been reduced. TEC is crucial in lowering CO_2 while still helping to conserve energy. Furthermore, TEC is essential for the most efficient usage of conventional and renewable energy sources. With the help of TEC, renewable energy sources can also be generated. Renewable energy capacity is also being boosted through TEC, increasing the likelihood that renewable energy will be accessible to meet future energy demand. Due to the growing demand for energy, it is widely assumed that REC will become the most significant energy source in the future and that it will also be the most environmentally friendly. The current study is built on the study of Rafique et al. (2021) by incorporating technological innovation. The economic model is illustrated as follows:

$$C0_{2i,t} = \alpha_0 + \theta_1 GDP_{i,t} + \theta_2 GDPSQ_{i,t} + \theta_3 ECI_{i,t} + \theta_4 REC_{i,t} + \theta_5 NREC_{i,t} + \theta_6 TI_{i,t} + \varepsilon_{i,t} \quad (1)$$

where "i", and "t" signifies the cross-section and period of research (1993–2018). Also, $\theta's$ and ε denote parameters and error terms. CO_2, GDP, REC, ECI, NREC and TI stand for CO_2 emissions, economic growth, renewable energy, economic complexity, nonrenewable energy, and technological innovation.

3.2. Data

The current investigation used yearly data for the top economic complexity nation to evaluate the effect of disintegrated energy and economic complexity on environmental degradation. The data set for this empirical investigation covers between 1993 and 2018. The unavailability of data on economic complexity limit this study to 2018. The dependent variable is CO_2 emissions, while the exogenous variables are economic complexity, economic growth, technological innovation, renewable and nonrenewable energy consumption. The variables utilized in this analysis are converted into natural logarithms to lessen skewness and assure normal distribution. Table 1 presents information regarding the variables used. The flow of analysis is depicted in Fig. 1.

3.3. Techniques employed

The FE-OLS is a modification over Driscoll and Kraay standard errors initiated by Driscoll and Kraay (1998). Furthermore, heterogeneity, cross-sectional dependency, and autocorrelation are not a problem for this statistical procedure. To solve the heterogeneity dilemma, the mean difference within variations, cross-sections, and the panel structure of dynamic cointegration is changed to cointegrate equilibrium. According to Pedroni (2004), the FM-OLS is sufficient to resolve these issues. Compared to other estimation techniques, even with the sample population, it is evident that it is unbiased. Endogeneity may be managed using D-OLS by using lead and lagged differences. At first, Bassett and Koenker (1978) suggested a panel quantile regression model. The dependent conditional and variance mean are calculated using this regression with respect to the values of the explanatory components. Quantile regression offers more trustworthy results even when the data contains outliers. As a consequence, we applied the MMQR technique Machado and Santos Silva (2019). This statistical technique was created to evaluate several quantiles' heterogeneous and distributional effects. The scale-location variant conditional quantile estimates Qy(τ|X) are depicted in Eq. (2).

$$Y_{it} = \alpha_i + X'_{it}\beta + \left(\delta_i + Z'_{it}\Upsilon\right) U_{it} \quad (2)$$

where the probability and parameters P $\{\delta_I + Z'_{it}\Upsilon > 0 = 1\}$. *(*$\alpha$, β', δ, Υ') are to be estimated. Additionally, *i* illustrates fixed and discrete effects are shown by (αi, δi), i = 1, …, n, and k-vector of recognized portions of X is shown by Z which are differentiable changes with part l depicted in Eq. (3):

$$Z_l = Z_l\,(X)\,, l = 1, \ldots, k \quad (3)$$

where; X_{it} is proportionately and independently dispersed across time *t and* fixed *I*. Similarly, the distributed fixed cross-sections and across time is depicted by U_{it}, and it is orthogonal to X_{it} (Machado and Santos Silva, 2019). On the flip side, the remaining parts do not exhibit rigorous exogenous behavior as shown in Eq. (4):

$$Q_y(\tau|X_{it}) = (\alpha_i + \delta_i q(\tau)) + X'_{it}\beta + Z'_{it}\Upsilon q(\tau) \quad (4)$$

X_{it} denotes the vectors of the regressors. The dependent variable quantile distribution is shown by Y_{it} (For instance CO_2) is illustrated by $Q_y(\tau|X_{it})$, which is shown as conditional on the exogenous variable location and X'_{it}. -αi (τ) $\equiv$ αi + $\delta_i q(\tau)$ is the scaler coefficient which denotes the quantile fixed effect τ for an individual *i.* Unlike other least-square fixed effects, the individual effect does not have an intercept shift. Heterogeneous impacts are susceptible to change and conditional distribution in each quantile since the indicators are time invariant. $q(\tau)$ shows the $\tau -$ th sample quantiles that are examined by assessing the subsequent optimization issue as shown in Eq. (5).

$$min_q \Sigma_i \Sigma_t \rho_\tau \left(R_{it} - \left(\delta_i + Z'_{it}\Upsilon\right) q\right) \quad (5)$$

where $\rho_\tau(A) = (\tau - 1)$ AI{A $\leq$ 0} + TAI {A > 0} shows the check function.

4. Findings and discussion

In brief, this study's assessment strategies are divided into five parts: (1) This research first establishes the slope heterogeneity

Table 1
Data information.

Sign	Description	Measurement unit	Source
CO_2	Carbon emissions	Metric tonnes per capita	British petroleum database
ECI	Economic complexity	Economic complexity index	OEC database
TEC	Technological innovation	Addition of both patent resident and nonresident	World bank database
NREC	Nonrenewable energy	Exajoule	British petroleum database
GDP	Economic growth	GDP per capita (constant 2010 $)	World bank database
REC	Renewable energy	Exajoule	British petroleum database

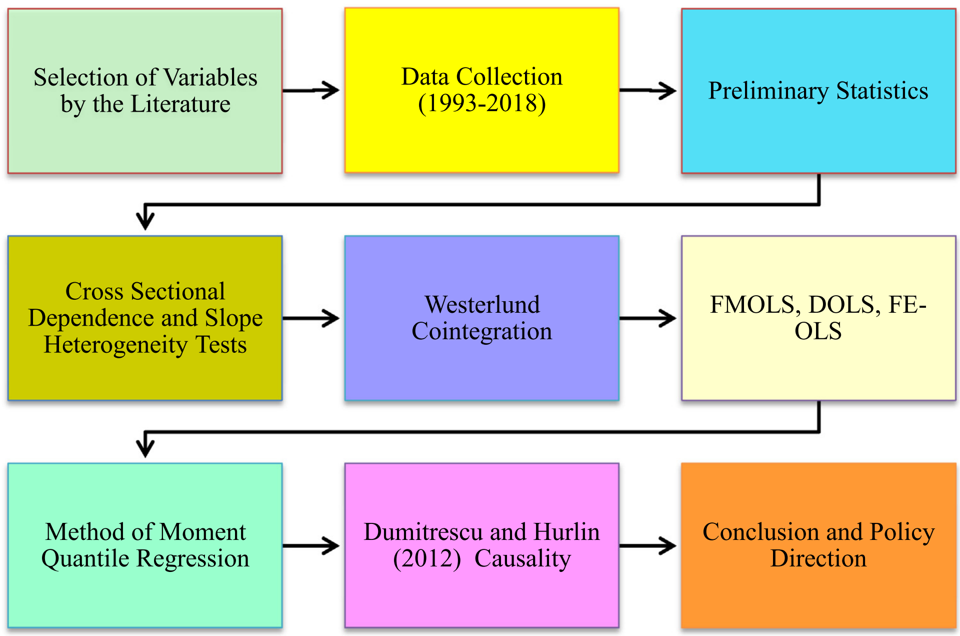

Fig. 1. Flow of the study.

(SH) and presence of CD in the panel data; (2) the stationarity attributes of the study's indicators are checked by utilizing the CIPS and CADF unit root tests. (3) We assess the influence of disintegrated energy use (renewable and nonrenewable), technological innovation, economic complexity and economic growth on CO_2 emissions using long-run estimators (DOLS, FE-OLS and FMOLS); (4) We assess the effect of the aforementioned independent variables on CO_2 emissions using the novel MMQR; and (v) We assess the casual interconnection between CO2 and disintegrated energy use (renewable and nonrenewable), technological innovation, economic complexity and economic growth.

4.1. Cross-sectional dependence (CD) and slope heterogeneity outcomes

As globalization progresses, considerable interconnectedness between nations have emerged as a result of their economic cooperation (Shahbaz et al., 2015). It is crucial to mention that neglecting the CD might result in erratic and incorrect results. As a result, examining CD within the sample data is necessary before doing an econometric approximation. To measure CD, four-CD tests are performed. Table 2 summarizes the findings of the various CD tests. The tests' p-values are significant at the 1% level, indicating that the null hypothesis is firmly rejected (i.e., CD exists within the panel data). This necessitates considering CD while further empirical analyse are conducted. We also look at the slope coefficient heterogeneity. The Hashem Pesaran and Yamagata (2008) slope coefficient heterogeneity test was used in this case, with the estimated results shown in Table 3. The empirical findings show that the adjusted SH and SH are significant at the 1% level. As a result, the SH test estimates reject the null hypothesis that the slopes are homogeneous. As a result, the slope coefficients of the selected panel are found to be heterogeneous. As previously noted, various factors (such as globalization, trade, etc.) enhance the dependence of one nation on another. Globalization and Trade liberalization, on the other hand, is critical to achieving a variety of economic, environmental and financial goals.

4.2. Unit root outcomes

The stationarity of data is vital in empirical research since it refers to using an efficient estimator for short-run/long-run analysis. As a result, after examining the SH and CD, we sought the existence of a unit root in the data. The CIPS and CADF unit root tests were used in this case, and the results are disclosed in Table 4. The outcomes uncovered that all the investigation indicators are I(1).

4.3. Cointegration outcomes

After establishing the stationarity properties of the variables, we examine the long-run interrelationship between CO_2 and the exogenous variables (ECI, TEC, GDP, REC, and NREC). In doing so, it is necessary to use a cointegration test that considers SH and CD. Therefore, we used the Westerlund cointegration test. Table 5 reports the cointegration test outcomes. Based on these outcomes, the null hypothesis of "no cointegration" is refuted. Therefore, in the long run, there is an interrelationship between CO_2 and the exogenous variables.

Table 2
CSD test.

Tests	GDP	REC	NREC	ECI	TEC	CO_2
Breusch–Pagan LM	510.498*	247.966*	173.909*	276.489*	355.335*	206.693*
Pesaran scaled LM	75.5313*	35.0206*	23.5944*	39.4228*	51.5891*	28.6531*
Bias-corrected scaled LM	75.3913*	34.886*	23.4544*	39.2828*	51.4491*	28.5131*
Pesaran CD	22.5909*	8.06976*	1.46733*	10.2368*	17.7951*	4.60260*

Note: * denotes P < 1%.

Table 3
Slope heterogeneity test.

Test	Value	Pvalue
$\hat{\Delta}$	8.281	0.000
$\hat{\hat{\Delta}}_{adjusted}$	9.068	0.000

Note: * denotes P < 1%.

Table 4
Unit root outcomes.

CIPS			CADF	
Variables	Level	First difference	Level	First difference
CO_2	−2.041	−5.058*	−2.583	−5.301*
GDP	−1.947	−4.039*	−2.064	−3.988*
REC	−2.151	−5.318 *	−2.155	−5.464 *
NREC	−0.839	−5.265*	−2.077	−5.265*
ECI	−1.838	−3.880 *	−2.177	−4.685*
TEC	−1.391	−4.029*	−2.261	−4.029*

Note: * denotes P < 1%.

Table 5
Cointegration test.

	Value	Z-value	P-value	Robust P-value
Gt	−3.416**	−1.881	0.031	0.030
Ga	−8.406	3.636	0.964	0.640
Pt	−9.942***	−1.407	0.090*	0.068
Pa	−11.853***	1.573	0.980*	0.080

Note: P < 5% and P < 10% are represented by *, ** and *** respectively.

4.4. Long-run outcomes

The current paper proceeds by assessing the effect of GDP, ECI, TEC, REC and NREC on CO_2 utilizing long-run estimators (FMOLS, DOLS and FE-OLS). Table 6 reports the DOLS, FE-OLS and FMOLS outcomes. The influence of GDP on CO_2 is found to be positive. This demonstrates that holding other factors constant, a 1% upsurge in GDP increases CO_2 by 2.70% (FMOLS), 2.10% (DOLS) and 3.20% (FE-OLS),. Furthermore, we found a negative effect of GDPSQ on CO2. This demonstrates that a 1% upsurge in GDPSQ mitigates CO_2 by 0.55% (FMOLS), 0.38% (DOLS) and 0.78% (FE-OLS). Moreover, a negative association was observed regarding the connection between CO_2 and NREC. This illustrates that increases of 0.25% (FMOLS), 0.31% (DOLS) and 0.43% (FE-OLS) in CO_2 are caused by a 1% upsurge in NREC, keeping other factors constant. Furthermore, we established a positive ECI and CO_2 interconnection. This indicates that a 1% upsurge in ECI accelerates CO_2 by 0.10% (FMOLS), 0.20% (DOLS) and 0.14% (FE-OLS). Moreover, TEC impacts CO_2 negatively, as disclosed by the long-run estimators. This indicates that holding other indicators constant, a 1% upsurge in TEC mitigates CO_2 by 0.048% (FMOLS), 0.05% (DOLS) and 0.03% (FE-OLS), respectively. Lastly, we uncovered a negative REC-CO_2 interconnectedness. This implies that a 1% upsurge in REC decreases CO_2 by −0.04% (FMOLS), −0.05% (DOLS) and −0.03% (FE-OLS).

4.5. MMQR outcomes

We explored the influence of ECI, GDP, TEC, NREC and NREC on CO_2 in the top economic complex nations in each quantile. In doing so, the MMQR was applied to assess these interrelationships (See Table 7). In each quantile (0.1–0.90), we observed that GDP impact CO_2 emissions positively. This demonstrates that GDP accelerates CO_2 (0.1–0.90) across all quantiles. Primary output rises slowly in the early stages of economic expansion and accelerates in the later stages. As a result, an increase in these economic activities has a positive impact on CO_2. For all quantiles, however, GDPSQ has an adverse impact on CO_2. Likewise, even if the turning point varies between quantiles, the EKC hypothesis can be confirmed for all quantiles (0.1–0.90). In the top economic complexity economies, the legitimacy of the EKC indicates that these nations have reached a specific degree of economic expansion. Therefore, it is now necessary to shift to more environmentally-friendly economic expansion (Apinran et al., 2021). Economic growth appears to increase CO_2 at first, until it hits a peak, after which it begins to improve environmental quality. This is achievable thanks to strict environmental regulations and consumer pressure from high-income customers. Furthermore, increased economic expansion encourages technological advancements, supports alternative energy and renewable energy sources for manufacturing, and develops the service and tertiary sectors, all of which contribute to reducing CO_2. The studies of Kirikkaleli and Adebayo (2021), Shahzad et al. (2022), Akadırı et al. (2021a), Akadiri et al. (2021b) and Bekun et al. (2019) also reported similar findings.

Moreover, we found a positive NREC-CO_2 interconnectedness across all quantiles (0.1–0.90). This establishes that in each quantile (0.1–0.90), NREC contributes to the CO_2 upsurge in the selected nations. Furthermore, NREC increases as we move towards the higher quantiles. This means that the current energy policies in the selected countries must be closely monitored. These countries are significantly reliant on nonrenewable energy to attain faster economic expansion: to meet the increased energy demand, these countries use copious amounts of nonrenewable energy and fossil fuels. This could be because present renewable energy sources are not sufficiently strong to provide all of the energy demands for economic activities (Oladipupo et al., 2021; Rafique et al., 2021; Soylu et al., 2021). In such circumstances, the results of this study may be useful for policy initiatives, since they assist in achieving several of the SDGs. Importantly, the governments of these countries may aid organizations and businesses in their efforts to discover cleaner and renewable energy sources, as well as technological development, as an alternative to fossil fuel usage. Such initiatives may aid in the production of clean and affordable energy, thus contributing to the attainment of SDG 7.

We also found an adverse association between REC and CO_2 across all quantiles (0.1–0.90). This demonstrates that across all quantiles (0.1–0.90), REC abates CO_2. In addition, as we move towards the upper quantiles, the magnitude of reduction in CO_2 caused by REC increases. REC eliminates emissions and thus, has the power to benefit the environment by making it cleaner. As a result, climate change mitigation efforts should prioritize REC, which is environmentally favorable. The studies of Adebayo and Rjoub (2021) and Lin and Zhu (2019) on the renewable energy-emissions nexus in the global economy and Portugal reported similar findings. Nonetheless, the research of Alola et al. (2021) in China on the renewable energy-emissions association reported

Table 6
FMOLS, DOLS and FE-OLS Outcomes.

Variable	FMOLS		DOLS		FE-OLS	
	Coefficient	t-Statistic	Coefficient	t-Statistic	Coefficient	t-Statistic
GDP	2.7092*	3.1665	2.1004*	4.3579	3.2001**	−2.4547
GDPSQ	−0.5577*	−4.0703	−0.3859**	−2.2361	−0.7480*	2.8498
ECI	0.1071**	2.0239	0.2022*	−3.3656	0.1463*	2.6334
NREC	0.2584*	4.8083	0.3118***	1.9339	0.4342*	3.5375
REC	−0.0484*	−3.1298*	−0.0532**	−2.1406	−0.0393***	−1.8960
TEC	−0.0112*	−4.0232	−0.0140*	−4.2877	−0.0167***	−1.9177

Note: P < 1%, P < 5% and P < 10% are represented by *, ** and *** respectively.

Table 7
MMQR outcomes.

	Location	Scale	Lower quantiles			Middle quantiles			Higher quantiles		
			0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
GDP	5.6380*	1.2526*	5.4830*	4.9319*	4.4750*	3.8937*	3.4303*	3.0300*	2.5390*	2.2276*	1.8000*
GDPSQ	−0.4343*	−0.0589*	−0.5211*	−0.4952*	−0.4737*	−0.4463**	−0.4245**	−0.4057**	−0.3826***	−0.3678***	−0.3477***
ECI	0.1124*	0.1127*	0.1164*	0.1152*	0.1142*	0.1130*	0.1120*	0.1111*	0.1108*	0.1094*	0.1085*
NREC	0.5091***	0.2240*	0.4307*	0.4541*	0.4735*	0.4982*	0.5179*	0.5340*	0.5550*	0.5690*	0.5870*
REC	−0.0419*	−0.0147*	−0.0146*	−0.0228*	−0.0295**	−0.0381**	−0.0450**	−0.0508**	−0.0581***	−0.0627	−0.0678
TEC	−0.0143	−0.0130*	−0.0187*	−0.0174*	−0.0162*	−0.0149*	−0.0138*	−0.011**	−0.006**	0.0011***	0.0061***

Note: P < 1%, P < 5% and P < 10% are represented by *, ** and *** respectively.

that renewable energy accelerates CO_2. Though renewable energy is advantageous, its adverse effects must not be overlooked. For example, installing most renewable energy sources is expensive. The weather has a significant impact on sources like solar cells and wind turbines as well. Wind turbines will not turn if there is no wind and Solar cells will not generate much electricity if it is cloudy. Furthermore, wind farms change the direction of winds and cause birds' death. Moreover, hydro dams, if not properly maintained, can cause floods. Therefore, strong policies must be put on the ground to curb such occurrences.

Moreover, we established a positive ECI and CO_2 interrelationship for the selected nations. In addition, we noticed a decrease in the magnitude of the coefficient as we moved towards the upper quantiles. More precisely, the results indicate that there is a necessity to move ECI to a level of resource utilization effectiveness and efficiency, where sophisticated goods use advanced and highly efficient technologies. This outcome complies with prior studies (Abbasi et al., 2021b; Akadırı et al., 2021a; Akadiri et al., 2021b; Khezri et al., 2022; Neagu, 2020). This finding also lends credence to the notion that complex productive systems potentially damage the environment's quality. The outcomes of ECI for the selected countries are particularly interesting, suggesting that a productive structure influences energy use policies and increased consumption of nonrenewables lead to increased global emissions. Moreover, the positive ECI-CO_2 interconnection may be ascribed to the fact that outmoded technologies influence economic productivity, and thus, increase energy intensity and demand.

Also, we established a negative CO_2-TEC association in each quantile (0.1–0.90). This demonstrates that across quantile (0.1–0.90), TEC abate CO_2. In addition, as we move towards the higher tail, the TEC's coefficient's magnitude diminishes. This outcome aligns with the studies of Adebayo and Rjoub (2021) and Kihombo et al. (2021a,b), who reported a negative CO_2-TEC interconnection. In other words, encouraging TEC can help abate CO_2. Boosting a nation's level of TEC, in particular, will have considerable spillover and propelling impacts on its rapid development. On the other hand, TEC is probable to save a substantial amount of energy, minimize fossil energy use, and enhance the energy efficiency, therefore facilitating the goal of lowering CO_2. Furthermore, the comparison of the FE-OLS, FMOLS, DOLS and MMQR is presented in Fig. 2. Lastly, the summary of findings from FE-OLS, FMOLS, DOLS and MMQR is shown in Fig. 3.

Table 8
DH causality tests.

Causality path	W-Stat.	Zbar-Stat	Prob
REC → CO_2	3.9657	4.5123	0.0000
CO_2 → REC	1.9058	1.2688	0.2045
TEC → CO_2	3.6195	4.8180	0.0000
CO_2 → TEC	1.1102	0.0161	0.9871
GDP → CO_2	7.0046	9.2974	0.0000
CO_2 → GDP	2.5198	2.2357	0.0254
NREC → CO_2	3.4399	3.6845	0.0002
CO_2 → NREC	4.8812	5.9539	0.0000
ECI → CO_2	3.6104	3.9528	0.0000
CO_2 → ECI	1.9702	1.3702	0.1706

4.6. Panel causality outcomes

The present research also assessed the causal effect of ECI, NREC, REC, TEC and GDP on CO_2 in top economic complexity nations. Table 8 reports the causal associations' outcomes. Findings unveiled a one-way causal association from REC to CO_2 at a 1% level of significance. Moreover, a unidirectional causal association was establised, running from TEC to CO_2at a 1% significance level. Furthermore, a feedback causal association exists between GDP and CO_2, suggesting that both REC and GDP can significantly predict each other. In addition, feedback causality exists between NREC and CO_2, demonstrating that both CO_2 and NREC can significantly predict one another. Lastly, one-way causality exists from ECI to CO_2, demonstrating that ECI can significantly predict CO_2. The causality outcomes are of great importance to policymakers in the selected nations as all the exogenous variables can significantly predict CO_2 emissions.

5. Conclusion

5.1. Conclusion

The current paper assessed the effect of disintegrated energy and economic complexity on carbon emissions in the top economic complexity economies. Other drivers of CO_2, such as technological innovation (TEC) and economic expansion (GDP) were incorporated into the model. The current research utilized a dataset from 1993 to 2018. We utilized second-generation approaches such as MMQR, Westerlund cointegration, CADF and

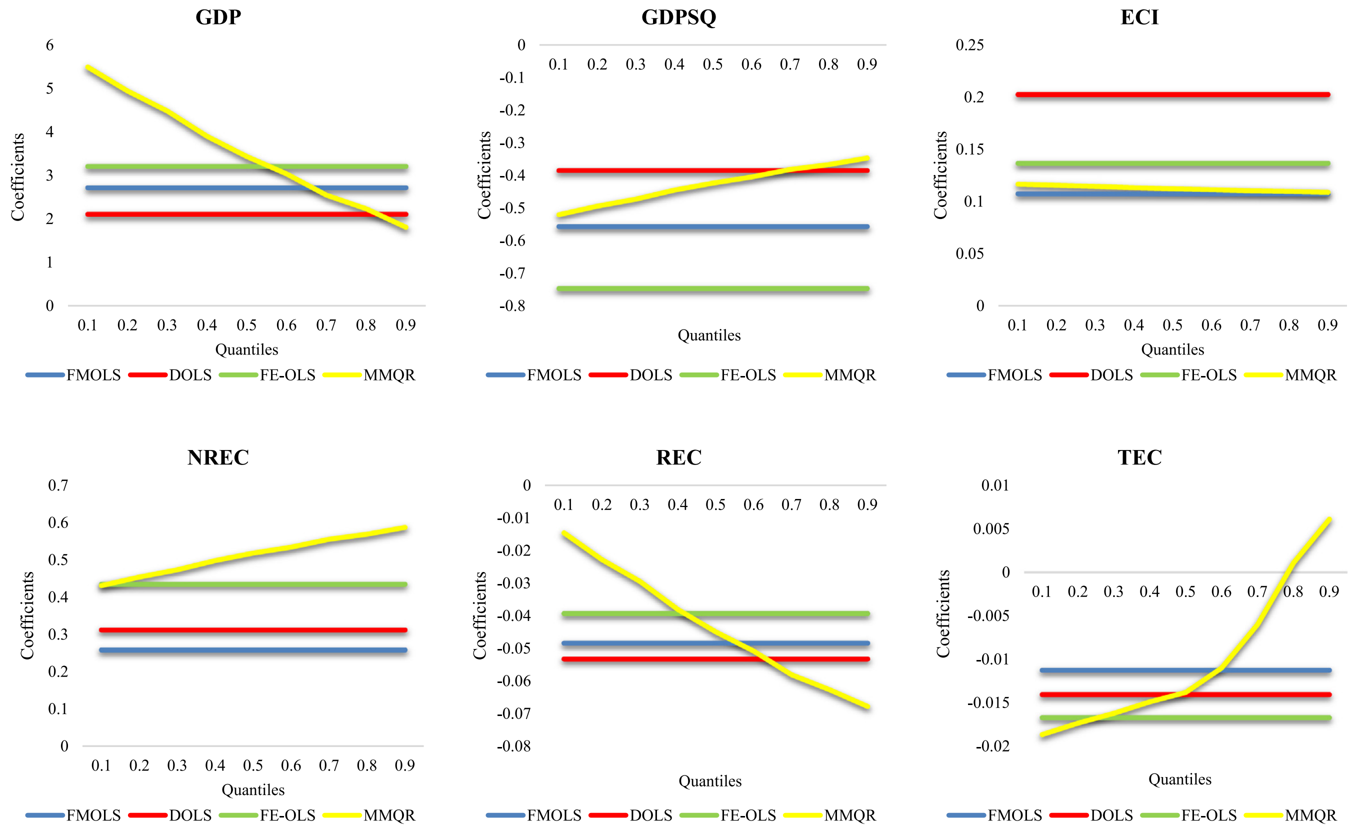

Fig. 2. Panel estimations (DOLS, FE-OLS, FMOLS and MMQR) comparison.

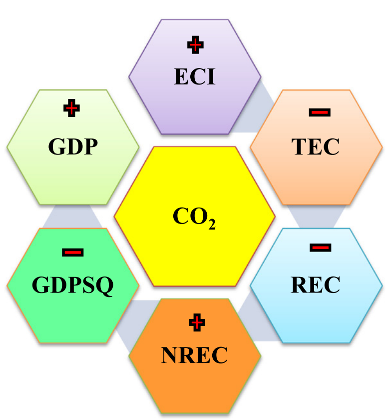

Fig. 3. Summary of findings from FE-OLS, FMOLS, DOLS and MMQR.

CIPS unit root, FMOLS, DOLS, FE-OLS, and DH causality to evaluate these interconnections. The outcomes of the CD and SH affirm the use of second-generation techniques. Furthermore, the CADF and CIPS unit root tests outcomes revealed that all the study's variables are integrated of order I(1). In addition, the Westerlund cointegration confirmed the long-run association between CO_2 and the exogenous variables. The influence of GDP on CO_2 is found to be positive. This demonstrates that a 1% upsurge in GDP increases CO_2 by 2.70% (FMOLS), 2.10% (DOLS) and 3.20% (FE-OLS). Furthermore, we found a negative effect of GDPSQ on CO2. This demonstrates that a 1% upsurge in GDPSQ mitigates CO_2 by 0.55% (FMOLS), 0.38% (DOLS) and 0.78% (FE-OLS). Moreover, a negative association was observed regarding the connection between CO_2 and NREC. This illustrates that increases of 0.25% (FMOLS), 0.31% (DOLS) and 0.43% (FE-OLS) in CO_2 are caused by a 1% upsurge in NREC. Furthermore, we established a positive ECI and CO_2 interconnection. This indicates that a 1% upsurge in ECI accelerates CO_2 by 0.10% (FMOLS), 0.20% (DOLS) and 0.14% (FE-OLS). Moreover, TEC impacts CO_2 negatively, as disclosed by the long-run estimators. This indicates a 1% upsurge in TEC mitigates CO_2 by 0.048% (FMOLS), 0.05% (DOLS) and 0.03% (FE-OLS), respectively. Lastly, we uncovered a negative REC-CO_2 interconnectedness. This implies that a 1% upsurge in REC decreases CO_2 by 0.04% (FMOLS), 0.05% (DOLS) and 0.03% (FE-OLS). We also utilized the novel MMQR, and the outcomes disclosed that in each quantile (0.1–0.90), REC enhances the quality of the environment. At the same time, NREC and ECI deteriorate the quality of the environment. In addition, TEC curbs CO_2 from 0.1–0.70 quantiles, while between 0.80–90 quantiles, TEC harms the quality of the environment. The EKC is also validated across all quantiles (0.1–0.90). Lastly, the outcomes of causality disclosed that all the investigation variables could strongly predict CO_2 emissions.

5.2. Policy direction

Economic complexity is linked to the host nation's R&D and innovative operations, which aid in producing advanced and sophisticated products. Regarding policy consequences for a cleaner climate and environment, the outcomes for economic complexity are highly novel and hopeful. This is explained by the fact that increasing economic complexity aids in the structural reorganization of the economy: shifting away from resource extraction and agriculture towards more sophisticated products. Therefore, while formulating economic and energy strategies, policymakers in the top ECI nations must consider the product production complexity and structure. Such creative techniques may aid in meeting their policy commitments in terms of achieving a cleaner and greener environment as well as their climate change objectives.

Likewise, energy use in the form of NREC sources impacts CO_2 emissions positively. This suggests that the existing energy policies in the selected countries must be re-evaluated. These nations primarily depend on fossil fuel-based energy to achieve economic growth. This might be because current renewable energy sources are insufficient to meet all the energy demands for economic operations. In this case, the findings of this research might be valuable for policy measures since they help achieve SDGs 7. The authorities of these nations may assist organizations and enterprises in their attempts to find renewable and cleaner energy sources, as well as technology development, as a substitute for the use of NREC. Such endeavors may contribute to generating clean and inexpensive energy, hence assisting in achieving SDG 7. Regulations at the national level may assist countries with achieving a range of goals, including cleaner and greener growth and job creation.

Furthermore, since TEC can only reduce CO_2 emissions in 0.1–0.70 quantiles, governments should adopt suitable effective policies to limit the impact of GHG emissions. Increased TEC, in particular, can aid in the reduction of CO_2 in nations with low carbon emissions. As a result, authorities should develop appropriate policies and allocate adequate resources to encourage the advancement of TEC. On the flip side, the positive TEC-CO_2 connection in the 0.80–0.90 quantiles reveals that the reduction of CO_2 emissions caused by TEC cannot be realized in high-carbon-emission nations. As a result, high-carbon countries should concentrate their research and development efforts on green technologies and low-carbon initiatives.

Selected Nations

Number	Countries
1	Japan
2	Switzerland
3	South Korea
4	Germany
5	Singapore
6	Austria
7	Czech

CRediT authorship contribution statement

Tomiwa Sunday Adebayo: Conceptualization, Writing, Review, Editing. **Mehmet Altuntaş:** Writing, Review, Editing, Supervision. **Sanjar Goyibnazarov:** Investigation, Formal Analysis, Writing, Review, Editing. **Ephraim Bonah Agyekum:** Conceptualization, Writing, Review, Editing. **Hossam M. Zawbaa:** Funding, Writing, Review, Editing. **Salah Kamel:** Supervision, Writing, Review, Editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

The work of Hossam M. Zawbaa was supported by the European Union's Horizon 2020 Research and Enterprise Ireland under the Marie Skłodowska-Curie Grant 847402.

The author (Ephraim Bonah Agyekum) acknowledges the research funding from the Ministry of Science and Higher Education of the Russian Federation (Ural Federal University Program of Development within the Priority-2030 Program), the youth laboratory with Grant number FEUZ-2022-0031.

The authors thank the support of the National Research and Development Agency of Chile (ANID), ANID/Fondap/15110019.

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