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Does Globalization Moderate the Effect of Economic Complexity on CO_2 Emissions? Evidence From the Top 10 Energy Transition Economies

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The association between economic complexity (sophisticated economic structure) and carbon emissions has major implications for environmental sustainability. In addition, globalization can be an important tool for attaining environmental sustainability and it may also moderate the association between economic complexity and carbon emissions. Thus, this research examines the effects of economic complexity, economic growth, renewable energy, and globalization on CO_2 emissions in the top 10 energy transition economies where renewable energy and globalization have greatly increased over the last 3 decades. Furthermore, this study also evaluates the joint effect of globalization and economic complexity on carbon emissions. Keeping in view the presence of slope heterogeneity and cross-sectional dependence in the data, this research utilized second-generation unit root tests (CIPS and CADF), Westerlund cointegration approach, and CS-ARDL and CCEMG long-run estimators over the period of 1990–2018. The results affirmed the presence of cointegration among the considered variable. Long-run findings revealed that globalization, renewable energy, and economic complexity decrease carbon emissions. Conversely, economic growth increases carbon emissions. Moreover, the joint impact of economic complexity and globalization stimulates environmental sustainability. Based on these findings, the government of these groups of economies should continue to expand the usage of renewable energy. They should also promote interaction with the rest of the world by adopting the policy of opening up.

Keywords: economic complexity, globalization, energy transitions, environmental sustainability, carbon emission

1 INTRODUCTION

It is well known that the long-term objective of economic growth cannot be realized without an uninterrupted supply of inputs, such as energy. Consequently, the need for energy has increased sharply across nations (Adebayo & Kirikkaleli, 2021). Most countries around the globe rely significantly on non-renewable energy sources like coal, natural gases, and crude oil to satisfy the increasing energy need. The heavy dependence on fossil fuels has indeed intensified environmental problems (Adebayo et al., 2021a; Akinsola et al., 2021; Zhang et al., 2021). Anthropogenic greenhouse gas emissions (GHGs) have risen from the pre-industrial period and are presently at their highest level. In this context, carbon emissions in 2019 were about 34,169.0 million tonnes compared to 19,249.9 million tonnes in 1985 (BP, 2020), indicating a 43.66% increase over the last 35 years. In addition, carbon emissions are anticipated to peak by 2050, unless governments make substantial efforts to limit emissions in the future years. Between 1980 and 2012, the average temperature of the globe has increased by 0.85°C. Hence, environmental challenges, such as global warming and environmental deterioration, are among the most important concerns in the modern world.

One of the most controversial and widely debated issues of the 21st century is the connection between the environment and economic growth. However, one of the attributes of the 21st century is that nations are transitioning from agricultural and pollution-intensive manufacturing economies to more advanced knowledge-based economies (Acheampong & Adebayo, 2021). Consequently, this structural shift has been considered as a new environmental degradation determinant. The introduction of the economic complexity index by Hidalgo and Hausmann (2009) is regarded as a comprehensive measure of a country's economic development because it comprises of diversification of product, skill, knowledge, and ubiquity. Specifically, economic complexity accurately reflects the level of complexity, incorporates changes in production processes, and assesses its capacity. Furthermore, it can forecast and describe changes in economic development and carbon emissions on both regional and global levels (Neagu and Teodoru, 2019). The production of traditional energy-intensive products requires more energy consumption thereby increasing environmental deterioration. However, the complex and sophisticated products' manufacturing may lead to less energy usage, which may lead to environmental sustainability (Can and Gozgor 2017). Also, the Paris Climate Conference (COP21) stresses the need of mitigating environmental degradation by promoting green and sustainable growth. The objective of transiting to a low carbon economy and green growth requires structural reforms in the production process by utilizing cleaner energy sources (renewable energy).

Countries across the world are in dire need of significant changes in their energy production methods. This encourages the use of cleaner and renewable energy rather than using unsustainable fossil fuels. There are a broad variety of motivations for the rapid development and consumption of renewable energy, such as reducing emissions of GHGs, access to energy, improving economic growth, energy security, and mitigating changes in the environment. However, empirical studies report different outcomes regarding the impact of renewable energy on the environment. The study of Alola et al. (2021) established an insignificant association between renewable and environmental deterioration, although contrary opinion regarding the interaction between renewable and environment degradation was established by Soylu et al. (2021); Adebayo & Kirikkaleli, 2021; Chien et al. (2021); Doğan et al. (2021).

Globalization is considered as the transition from a self-contained and isolated economy with trade and investment obstacles, laws, and cultural distinctions to a more interconnected, interdependent global economy (Hill & Rapp, 2009; Acheampong & Adebayo, 2021). In recent decades, the tremendous economic, political and social interconnection of nations has had both adverse and beneficial environmental impacts. Openness to the rest of the globe attracts international investors that may employ advanced technology to establish or develop their business activities, therefore improving environmental quality by reducing the usage of energy. The adoption of new technology minimizes resource consumption and manufacturing costs, forcing domestic firms to embrace cleaner technology. In contrast, reliance on traditional or outdated technology by foreign businesses worsens the quality of the environment (Ahmed et al., 2019; Alola et al., 2021). Thus, the openness of these energy transition economies to the rest of the world may help them to develop sophisticated production structures through the inflow of capabilities i.e., knowledge and technologies. In addition, the expansion in the export market due to globalization may help them to focus on building sophisticated products with the intention of exporting them to other nations. Thus, we believe that globalization may interact with the economic complexity resulting in a cleaner environment.

On this premise, this study focused on the top 10 energy transition economies, namely Iceland, France, New Zealand, United Kingdom, Finland, Austria, Switzerland, Denmark, Norway, and Sweden. There are three leading reasons for selecting these countries as the study's sample. Firstly, they are all advanced economies whose production processes are highly advanced and knowledge-based, therefore, these economies have a high economic complexity index. Secondly, these economies are responsible for about 3% of energy-related carbon emissions. Thirdly, the deficiency of literature regarding environmental degradation for energy transition economies and omission of significant factors necessitate more research to precisely establish the interaction of environmental degradation with economic complexity in energy transition economies. Consequently, understanding the impact of economic complexity and globalization on environmental quality in energy transition economies will have major consequences for achieving sustainable growth and minimizing climate change.

Given the purpose of the investigation, this research contributes to existing literature. First, this research provides more insight into the association between economic complexity and carbon emissions by incorporating the effect of economic growth, renewable energy, and globalization. Second, this research also includes the interactions between globalization and economic complexity to investigate whether the openness of their economies to the rest of the globe strengthens the role of economic complexity in environmental sustainability. The authors of this study are unaware of any prior research that investigates the combined impact of economic complexity and globalization on environmental deterioration from the standpoint of energy transition economies. Third, this research also contributes methodologically by utilizing the Cross-Sectionally Augmented Autoregressive Distributed Lag (CS-ARDL) model. The CS-ARDL is robust against heterogeneity, misspecification bias, endogeneity, non-stationarity, and cross-sectional dependence (Ahmad et al., 2021b). Four, this study utilizes the Common Correlated Effect Mean Group (CCEMG) to ensure the soundness of the estimation; thus, the study intends to report reliable outcomes and policy suggestions.

The following is the outline of the rest of the study: **Section 2** gives insights into the relevant literature for this study; **Section 3** describes the methods used for the empirical analysis. **Section 4** provides results, while **Section 5** presents the concluding remarks.

2 LITERATURE REVIEW

Previous studies suggest that not only economic growth but also other factors, such as economic complexity (Kirikkaleli & Adebayo, 2021a; Rjoub and Adebayo, 2021; Ahmad et al., 2021c; Adebayo et al., 2021; Doğan et al., 2021), renewable energy (Fareed et al., 2021; Adebayo & Kirikkaleli, 2021; Chien et al., 2021; Kirikkaleli and Adebayo, 2021b; 2021; Soylu et al., 2021) globalization (Aslam et al., 2021; Anser et al., 2021; Chien et al., 2021) and others (An et al., 2019; Miao et al., 2019; Zhang et al., 2019; Mohammad et al., 2020; Alola et al., 2021; Ahmed et al., 2021c; Ramzan et al., 2021; Shan et al., 2021; Chen et al., 2019) can impact environmental deterioration. Meanwhile, the main driver of CO_2 emissions is economic growth or per capita income, since all other variables are directly and indirectly related to CO_2 emissions. Prior studies have utilized economic growth as a major predictor of the quality of the environment. The subsequent part of this section evaluates the connection of economic complexity, economic growth, renewable energy, and globalization with CO_2 emissions.

Ayobamiji and Kalmaz (2020) explored the connection between economic growth and CO_2 emissions by utilizing the dataset of Nigeria spanning between 1971 and 2015 and the empirical findings revealed that economic growth contributes to environmental degradation in Nigeria. Also, Adebayo et al. (2021b) uncovered a positive connection between globalization and CO_2 emissions in South Korea by employing the dataset within the period from 1965 to 2019. The results of their research demonstrated that the economic growth tends to increase CO_2 emissions. The study of Alola et al. (2021) evaluated the CO_2 emissions, renewable energy, and economic growth association in China by employing data spanning from 1980 to 2017. The outcome revealed that the effect of economic growth on CO_2 emissions is positive, whereas, the influence of renewable energy on CO_2 emissions is revealed to be insignificant. The research of Aslam et al. (2021) uncovered the effect of economic growth and globalization on CO_2 emissions for Malaysia within the period from 1971 to 2016. The outcomes of this study revealed that there is a direct interaction between economic growth and CO_2 emissions, however, a similar connection was evident between globalization and CO_2 emissions. For Pakistan, Chien et al. (2021) evaluated the CO_2 emissions, renewable energy, economic growth, and globalization connection covering the period from 1980 to 2018. The study's findings indicated that economic growth and globalization impact CO_2 emissions positively, on the contrary, the findings uncovered a negative connection between renewable energy and CO_2 emissions. Anser et al. (2021) investigated the CO_2 emissions, economic growth, and globalization interconnection for five southern Asian nations (Sri Lank, Bangladesh, Maldives India, and Pakistan) covering between 1985 and 2019. The finding revealed that there is a positive linkage between economic growth and CO_2 emissions. Also, the association between CO_2 emissions and globalization is positive.

For economic complexity, the initial debate concerning the association between economic complexity and CO_2 emissions started with the study of Can and Gozgor (2017) for France using the data spanning from 1964 to 2014, and the research outcome uncovered that CO_2 emissions can be mitigated by boosting the level of economic complexity. For 28 OECD nations, Doğan et al. (2020) discovered that economic complexity mitigates the challenges of environmental deterioration within the period from 1990 to 2014. On the contrary, the study of Neagu and Teodoru (2019) revealed that there is a positive effect of economic complexity on environmental degradation in 25 EU (European Union) countries for the period from 1995 to 2016. A similar outcome was evident in the research of Doğan et al. (2019) in 55 countries for the period between 1971 and 2014. Using the DOLS and FMOLS over the period from 1980 to 2016. Pata (2021) uncovered a positive association between economic complexity and CO_2 emissions. Chu (2021) also uncovered a positive association between economic complexity and CO_2 emissions in 118 countries covering the period between 2002 and 2014. The study of Ahmad et al. (2021) in emerging economies also revealed a positive connection between environmental degradation and economic complexity. Conversely, the study of Adedoyin et al. (2021) reported an insignificant connection between economic complexity and CO_2 emissions in 26 EU countries.

Considering these contradicting theoretical and empirical findings, additional investigations are required to resolve the discrepancy in the literature. Also, previous studies have assessed the direct influence of economic complexity on CO_2 emissions. In many studies, empirical estimates can be spurious because they ignored the issues of cross-sectional dependence and slope heterogeneity. Concerning this major gap in the prior literature, there is a necessity to address this issue by investigating the role of economic complexity, renewable energy, and globalization in CO_2 emissions in the top 10 energy transition economies using better methodologies. Also, it is important to evaluate the combined effect of globalization and economic complexity on the environment for suitable policies.

3 METHOD AND DATA

3.1 Theoretical Framework and Model Construction

Proceeding to the theoretical framework of this research, economic growth impacts carbon emission because economic activities require energy as an input resulting in greater waste and pollution. However, the degree of pollution and material utilized to produce depend on a nation's sectoral framework. Economic expansion has three distinct consequences on the environment, which are: scale, composition, and technique effects. Within the context of scale effect, economic expansion harms the environment at first because it necessitates additional energy and resources, resulting in greater wastage and pollution. The structural changes of economies from the industrial sector to the service sector are capable of decreasing the adverse impacts of economic development on climate, and these impacts are known as the composition effect (Ahmad et al., 2021). Lastly, the technique effect proposes that when the wealth of an economy increases, it embraces new and improved technology that increases productivity and mitigates emissions.

Economic complexity is another significant factor that may impact environmental degradation because it depicts the production structure of economies. Economic complexity offers an overview of the magnitude, technology, and structural transformations of a nation (Pata, 2021). Product complexity and structural modification might damage or improve the quality of the environment depending upon the nature of production (Doğan et al., 2020). Economic complexity can allow policy-makers to promote technological advancement, research, skills, and knowledge, which enhance environment-friendly technologies and greener goods, and reduce environmental deterioration (Doğan, et al., 2019). Conversely, a knowledgeable sophisticated economic structure is often lacking in many economies, thus, conventional technologies are utilized in the production process, which in turn, expand energy utilization and environmental deterioration (Shan et al., 2021).

Globalization is another significant factor that impacts environmental degradation. The trend of globalization has resulted in several environmental concerns, including the depletion of ozone, overutilization of resources, and deforestation (Kirikkaleli et al., 2021). Globalization encourages economic activity and energy consumption, resulting in an increase in carbon emissions. However, through eco-friendly technologies' inflow, globalization can enhance environmental quality (Adebayo et al., 2020; Ahmed et al., 2019).

Renewable energy is another significant factor that impacts environmental degradation. Generally, renewable energy sources are eco-friendly. The development and utilization of these resources could potentially assist in minimizing the dependency on fossil fuels and improving the quality of the environment. However, the excessive use of non-renewable energy exacerbates climate change and global warming by increasing GHG emissions (Panait et al., 2021), indicating that non-renewable energy emits more CO2 while renewable energy emits less emissions.

Following the latest studies of Ahmad et al. (2021) and Pata (2021), this model was built as follows:

$$CO_{2,it} = f\left(GDP_{it}, RE_{it}, ECI_{it}, GLO_{it}\right), \tag{1}$$

$$CO_{2,it} = \vartheta_0 + \vartheta_1 GDP_{it} + \vartheta_2 RE_{it} + \vartheta_3 ECI_{it} + \vartheta_4 GLO_{it} + \varepsilon_{it}, \tag{2}$$

Where t indicates the period of concern (1990–2018), i indicates the cross-section (top 10 energy transition economies), ϑ indicates parameters, ε indicates error term, CO_2 depicts carbon emissions, GDP depicts Gross Domestic Product per capita (constant 2010$), RE depicts renewable energy usage, ECI depicts economic complexity index, and GLO indicates globalization.

To probe the moderating effect of globalization on the connection between economic complexity and carbon emission, we incorporated the interaction term of economic complexity and globalization ($ECI * GLO$) into **Eq. 3**, and the modified model is presented as follows.

$$\begin{aligned} CO_{2,it} = \vartheta_0 + \vartheta_1 GDP_{it} + \vartheta_2 RE_{it} + \vartheta_3 ECI_{it} + \vartheta_4 GLO_{it} \\ + \vartheta_5 \left(ECI * GLO\right)_{it} + \varepsilon_{it}, \end{aligned} \tag{3}$$

With regard to the anticipated signs of the regressors of carbon emission, it is generally considered that increased production contributes towards the deterioration of the environment as a result of the increasing energy demand. Therefore, we anticipate that there is a positive interaction between economic growth and CO_2 emissions i.e. ($\vartheta_1 = \frac{\partial CO_2}{\partial GDP} > 0$). Renewable energy is critical in mitigating environmental deterioration. It is regarded to be a clean and greener energy source that meets present and future requirements. Therefore, renewable energy is anticipated to reduce environmental deterioration and CO_2 emissions. i.e. ($\vartheta_2 = \frac{\partial CO_2}{\partial RE} < 0$). Also, there are different arguments about the connection between economic complexity and CO_2 emissions. Ahmad et al. (2021) revealed a positive connection between environmental degradation and economic complexity. Conversely, Doğan et al. (2020) discovered that the challenges of environmental deterioration can be mitigated by economic complexity. Therefore, we anticipate that economic complexity will have a positive or negative impact on CO_2 emissions i.e. ($\vartheta_3 = 0 < \frac{\partial CO_2}{\partial ECI} > 0$). Moreover, another major factor that influences environmental quality is globalization. By formulating and implementing rules and regulations on sustainable trade and FDI, globalization may benefit the environment. Also, these advanced nations have good environmental regulations. On this notion, globalization is expected to have a negative impact on CO_2 emissions i.e. ($\vartheta_4 = \frac{\partial CO_2}{\partial GLO} < 0$). Finally, the interaction term of economic complexity and globalization, which indicates their joint impact on CO_2 emissions, may decrease CO_2 emissions even more because globalization can bring knowledge and capabilities to the host nations, which in turn can boost their economic complexity level. As a result, producing complex products can decrease CO_2 emissions by decreasing energy utilization in the manufacturing process. Therefore, we expect that the joint impact of globalization and economic complexity on CO_2 emissions will be negative i.e. ($\vartheta_5 = \frac{\partial CO_2}{\partial (ECI * GLO)} < 0$).

3.2 Data

We utilized the panel data from 1990 to 2018 for the top 10 energy transition economies (Iceland, France, New Zealand, the United Kingdom, Finland, Austria, Switzerland, Denmark, Norway, and Sweden). Owing to the unavailability of data for globalization and economic complexity, the period for this study begin from 1990 and ends in 2018. The observed variables for this study include CO_2 emissions (CO_2), renewable energy (RE),

TABLE 1 | Variables, data source, and measurement.

Variable	Symbol	Measurement	Source
Carbon emissions	CO_2	Metric tons per capita	BP
Economic growth	GDP	GDP per capita (constant 2010$)	WDI
Renewable energy	RE	Renewable energy per capita consumption (KWH)	BP
Economic complexity	ECI	Economic complexity Index	AMD
Globalization	GLO	Globalization index based on economic, social, and political dimensions of a country	KOF

WDI, world development indicators; KOF-KOF, swiss economic institute; AMD, atlas media database; BP, british petroleum statistical review of world energy.

economic growth (GDP), economic complexity (ECI), and globalization (GLO). **Table 1** provides adequate information regarding the measurement and source of data for the observed variables.

3.3 Estimation Procedures

3.3.1 Cross-Sectional Dependence (CSD) and Slope Heterogeneity Tests

In this age of increasing globalization, with reduced trading restrictions, cross-sectional dependence in panel data analysis is increasingly likely to emerge. Failure to address the issue of cross-sectional dependence and claiming independence between cross-sections can result in incorrect, unreliable, and biased estimations (Adebayo and Rjoub, 2021). The Pesaran (2015) test for cross-sectional dependency is used in this investigation. Similarly, the assumption of a homogeneous slope coefficient would produce misleading estimating results without checking for heterogeneous slope coefficients (Adebayo and Rjoub, 2021). Based on this, the study employed the Pesaran and Yamagata (2008) test to evaluate the slope heterogeneity of the cross-section, however, this method is a modified version of the Swamy (1970) approach. It is crucial to evaluate the cross-sectional dependences and slope homogeneity before the stationarity properties of the cross-section are captured. The equation for the slope homogeneity test are shown as follows:

$$\tilde{\Delta}_{SH} = (N)^{\frac{1}{2}}(2k)^{-\frac{1}{2}}\left(\frac{1}{N}\tilde{S} - k\right), \tag{4}$$

$$\tilde{\Delta}_{ASH} = (N)^{\frac{1}{2}}\left(\frac{2k(T-k-1)}{T+1}\right)^{-\frac{1}{2}}\left(\frac{1}{N}\tilde{S} - 2k\right), \tag{5}$$

Where: $\tilde{\Delta}_{ASH}$ indicates adjusted delta tilde while $\tilde{\Delta}_{SH}$ indicates delta tilde.

3.3.2. Panel Unit Root Tests

The research employed the cross-sectional augmented Im, Pesaran and Shin (IPS) and cross-sectional augmented Dickey-Fuller tests (CADF) proposed by Pesaran (2007). The equation for CADF is as follows:

$$\Delta Y_{i,t} = \gamma_i + \gamma_i Y_{i,t-1} + \gamma_i \bar{X}_{t-1} + \sum_{l=0}^{P} \gamma_{il} \Delta\overline{Y_{t-l}} + \sum_{l=1}^{P} \gamma_{il} \Delta Y_{i,t-l} + \varepsilon_{it}, \tag{6}$$

Where: $\bar{Y}_{t-1}$ and $\Delta\overline{Y_{t-l}}$ denote the lagged and first differences averages, respectively. Also, the statistics for CIPS is derived by averaging each CADF, which is shown in **Eq. (6)**.

$$\widehat{\mathrm{CIPS}} = \frac{1}{\mathrm{N}}\sum_{\mathrm{i=1}}^{\mathrm{n}} \mathrm{CADF_i}, \tag{7}$$

Where: CIPS denotes cross-sectional augmented Im, Pesaran and Shin; CADF indicates cross-sectional augmented Dickey-Fuller tests. These unit root approaches are categorized as the second-generation unit root tests. These methods produce accurate estimates in the presence of cross-sectional dependence and heterogeneity, unlike first-generation unit root tests.

3.3.3 Panel Cointegration Test

Conventional panel cointegration test namely McCoskey and Kao (1998) cointegration test and Pedroni (2004) cointegration test produces incorrect estimates when cross-sectional dependence and heterogeneity exist in panel data. For this case, this research evaluates the linkage between carbon emissions, renewable energy, economic complexity, and globalization for energy transition economies using the Westerlund (2007) cointegration approach, which is defined as follows:

$$\alpha i(L)\Delta y_{it} = y2_{it} + \beta_i\left(y_{it} - 1 - \acute{\alpha}_i \mathrm{x_{it}}\right) + \lambda_\mathrm{i}(\mathrm{L})\mathrm{v_{it}} + \eta_\mathrm{i}, \tag{8}$$

Where $\delta_{1i} = \beta_i(1)\hat{\vartheta}_{21} - \beta_i\lambda_{1i} + \beta_i\hat{\vartheta}2_i \text{and} y2_i = -\beta_i\lambda 2_i$

The Westerlund cointegration test statistics are presented as follows.

$$G_t = \frac{1}{N}\sum_{i-1}^{N}\frac{\acute{\alpha}_i}{SE(\acute{\alpha}_i)}, \tag{9}$$

$$G_\alpha = \frac{1}{N}\sum_{i-1}^{N}\frac{\mathrm{T}\acute{\alpha}_i}{\acute{\alpha}_i(1)}, \tag{10}$$

$$P_T = \frac{\acute{\alpha}}{SE(\acute{\alpha})}, \tag{11}$$

$$P_\alpha = \mathrm{T}\acute{\alpha}, \tag{12}$$

Where: $\mathrm{G_a}$ and $\mathrm{G_t}$ are the group statistics whereas $\mathrm{P_a}$ and $\mathrm{P_t}$ are the panel statistics. The hypothesis for this approach is the null hypothesis of no cointegration against the alternative hypothesis of cointegration.

3.3.4 Cross-Section Augmented Auto-Regressive Distributed Lag (CS-ARDL) Test

Utilizing the approach developed by Chudik et al. (2016) known as the CS-ARDL test, this study evaluates the long and short-term association among carbon emission, renewable energy, globalization, and economic complexity. This approach solves the problem of endogeneity, unobserved common factors,

TABLE 2 | Pesaran (2015) Cross-sectional dependency test results.

Variables	Statistic	*p*-value	Abs (corr)
CO_2	19.656[a]	0.000	0.563
GDP	36.685[a]	0.000	0.979
RE	14.314[a]	0.000	0.568
ECI	20.119[a]	0.000	0.551
GLO	36.549[a]	0.000	0.975

[a]*depict significance level of 0.01.*

heterogeneous slope coefficients, non-stationarity, and cross-sectional dependence. Following is the CS-ARDL method:

$$Y_{it} = \sum_{i=1}^{py} \pi_{it} Y_{i,t} + \sum_{i=0}^{pz} \theta_{i1}^{\prime} Z_{i,t-1} + \sum_{i=0}^{pT} \phi_{i1}^{\prime} Z_{i,t-1} + e_{it}, \tag{13}$$

In the above equation, $X_{t-1}^{-} = (Y_{t-1}^{-}, Z_{t-1}^{-})\prime$, The average cross-sections are depicted by $\overline{Y_t}$ and $\overline{Z_t}$ respectively. In addition, X_{t-1}^{-} represents the averages of both independent and dependent variables. The CS-ARDL generates outcomes robust against heterogeneity, misspecification bias, endogeneity, mixed integration, and cross-sectional dependence (Ahmad et al., 2021).

For robustness, we used the Common correlated Effects Mean Group (CCEMG) estimator proposed by Chudik & Pesaran (2015), which permits for long-term heterogeneity of factors and tackles CSD. **Eq. 14** defines the CCEMG estimator as follows:

$$y_{it} = a_{1i} + b_i x_{it} + c_i f_t + \alpha_i \bar{y}_{it} + \beta_i \bar{y}_{it} + e_{it}, \tag{14}$$

In the above equation, x_{it} and y_{it} are the observed parameters, a_i depicts the intercept, and b_i depicts the coefficients of estimates for a specific country. In addition, the unobserved parameters with heterogeneous factors and the error term are indicated as e_{it}.

4 PRESENTATION OF FINDING AND DISCUSSION

Before undertaking the cointegration, the preliminary methodology undertaken by this study is the Cross-sectional dependence test. The outcomes (in **Table 2**) suggest that the observed variables have a CSD issue. The Cross-sectional dependence was further confirmed by the absolute mean value from 0.551 to 0.979. The results of the Pesaran (2015) cross-sectional dependence of all observed variables are statistically significant, indicating the rejection of the null hypothesis against the alternative hypothesis. The importance of cross-sectional dependence stems from the fact that these economies are interconnected.

The implication of this outcome suggests that any shock experienced in a country (e.g. Sweden) with respect to the observed variable might extend to other economies (Norway, Denmark, Switzerland, Austria, Finland, United Kingdom, New Zealand, France, and Iceland). The spillover effect is caused by interdependence amongst these economies. Thereafter, the slope homogeneity test was undertaken, and the outcomes of this test are summarized in **Table 3**. The countries selected for the study have varied rates of development as well as technological progress. As a result, the findings suggest that their slope coefficients are heterogeneous. Thus, this study proceeds with determining the stationarity tests and other methodologies that account for both these problems (cross-sectional dependence and heterogeneity).

TABLE 3 | Slope homogeneity test results.

Test	Model-1		Model-2	
	Value	*p*-value	Value	*p*-value
$\tilde{\Delta}$	20.840[a]	0.000	18.507[a]	0.000
$\tilde{\Delta}_{adjusted}$	22.703[a]	0.000	20.483[a]	0.000

[a]*depict significance level of 0.01.*

TABLE 4 | Unit root test results.

Variable	CIPS		CADF	
	Level	First-difference	Level	First-difference
lnCO_2	−1.965	−5.967[a]	−1.522	−3.603[a]
*ln*GDP	−1.338	−3.697[a]	−1.810	−3.531[a]
*ln*RE	−2.637[a]	−5.767[a]	−2.896[a]	−3.635[a]
*ln*ECI	−1.422	−4.893[a]	−1.623	−3.264[a]
*ln*GLO	−3.103[a]	−6.007[a]	−1.972	−3.764a

[a]*depict significance level of 0.01.*

TABLE 5 | Westerlund cointegration test results.

Statistic	Model–1		Model–2	
	Value	Z–Value	Value	Z–Value
G_t	−2.685**	−2.059	−2.773**	−1.693
G_a	−11.179	−0.548	−11.601	0.048
P_t	−8.660*	−3.007	−8.694*	−2.496
P_a	−12.313*	−2.544	−11.466***	−1.296

, ** and * depict significance level of 0.01, 0.05 and 0.1 respectively.*

For the stationarity test, this study utilized the CIPS and CADF unit root and their results are summarized in **Table 4**. We can judge that all observed variables are stationary at a mixed level. Since the stationary outcome for CIPS indicates that all observed variables are stationary at first difference with the exception of renewable energy and globalization, whereas similar outcomes were established by CADF, in which all variables are stationary at first difference with the exception of only renewable energy. The cointegration test can be initiated, after confirming the stationarity nature of the observed variable.

In order to determine a long-run connection, this research utilized the Westerlund (2007) cointegration test, whereas, the summary of the outcomes is illustrated in **Table 5**. The results of **Table 5** indicate that the observed parameters are related since the null hypothesis of no cointegration is rejected in the two models. The indication of this outcome uncovers the presence of a long-run cointegration amongst the concerned variable for the two models. The error correction term (ECT) is calculated as $\frac{P_a}{T}$. The ECT for

TABLE 6 | CS–ARDL test results.

Dependent variable = *ln*CO_2	Model–1		Model–2	
	Coefficient	Z–Value	Coefficient	Z–Value
Short–run results	—	—	—	—
*ln*GDP	0.263*	3.340	0.258*	2.650
*ln*RE	−0.061**	−2.300	−0.073*	−2.770
*ln*ECI	−0.064**	−1.980	−0.054**	−2.000
*ln*GLO	−0.337***	−1.760	−0.368***	−1.660
ln*(GLO*ECI)*	—	—	−0.095**	−2.010
ECM (−1)	−0.802*	−11.990	−0.804*	−12.640
Long–run results	—	—	—	—
*ln*GDP	0.150*	3.390	0.151*	2.730
*ln*RE	−0.034**	−2.300	−0.040*	−2.740
*ln*ECI	−0.036**	−2.030	−0.029**	−1.970
*ln*GLO	−0.219***	−1.880	−0.235***	−1.790
ln (GLO*ECI)	—	—	−0.053**	−2.080

, ** and * depict significance level of 0.01, 0.05 and 0.1 respectively.*

model one is $\frac{-12.313}{29} = -0.4245$ and for model two is $\frac{-11.296}{29} = -0.3895$, indicating that in case of imbalance in the short-term, the rate of convergence is 43.67% for model 1 and 38.95% for model two for 1 year. Moreover, it is imperative to evaluate the impact of the independent variables on carbon emissions in the short and long-run. For this purpose, the CS-ARDL has been employed in this research.

The outcomes of the CS-ARDL estimators for the two models in the short and long-run are presented in **Table 6**. The association of CO_2 emissions with GDP is affirmed to be positive across all models in both periods (long and short-run). For model 1, on average, an upsurge of 0.263% in CO_2 emissions in the short-term, is attributed to an increase in percentage change of GDP; however, in the long-term, the increase of GDP by 1% will increase carbon emissions by 0.150%. Also, for model 2, a 1% rise in GDP will result in an increase in CO_2 emissions by 0.258% in the short-run; whereas, an increase of GDP by 1% will cause an upsurge in CO_2 emissions by 0.151% in the long-run. This outcome discloses that the economic expansion in these economies contributes to environmental degradation. Thus, these outcomes are in line with our theoretical anticipation that economic growth positively impacts environmental degradation. A major contribution of economic expansion can be attributed to energy utilization during production processes. As mentioned earlier, such energy usage contributes to the increasing level of environmental pollution in these countries. This perspective is supported when the energy mix of these nations is observed because some of these economies still rely largely on fossil fuels for their energy needs. For instance, just to mention a few, according to the BP (2020), the United Kingdom energy mix constitutes 79.16% of fossil fuel (39.61% oil; 36.20% gas, and 3.35% coal), 66.27% of Austria's energy mix are fossil fuels, and Denmark's energy mix constitutes 68.37% of fossil fuel energy. To offset this adverse effect of economic growth, there is a need for the industrial or production sector to undergo a structural change for implementing lower carbon-intensive manufacturing methods. This outcome substantiates the study of Ramzan et al. (2021) for Latin American economies that used the FMOLS and DOLS approaches for the period from 1980-2017, Awosusi et al. (2021) for Japan that used the FMOLS and DOLS approaches for the period from 1965-2019, Odugbesan et al. (2021) for Brazil that relied on FMOLS and DOLS approaches for the period from 1965-2019, and Adebayo et al. (2020) for MINT economies that employed panel ARDL approach for the period from 1980-2018.

With regards to the influence of renewable energy on carbon emissions, a negative and significant influence was established. Precisely, for model 1, on average, a decrease of 0.061% in carbon emissions in the short-term is attributed to a 1% increase of renewable energy consumed. Also, in the long-run, the increase of renewable energy consumption by 1% will decrease CO_2 emissions by 0.034%. For model 2, the reduction in CO_2 emissions by 0.034% is associated with the increase in the usage of renewable energy in the short-run. Likewise, in the long-run, a similar effect is evident, indicating a 0.040% decrease in CO_2 emissions. This specifies that the increasing usage of renewable energy continues to reduce environmental degradation. The outcomes reveal that the usage of renewable energy is beneficial in reducing the detrimental consequences of human actions and is a useful tool for achieving sustainable growth and the environment. This outcome complies with the studies of Adebayo & Kirikkaleli (2021) that relied on wavelets tools for the period from 1990Q1 to 2015Q4, Chien et al. (2021) for Pakistan that employed QARDL for the period from 1980 to 2018, Soylu et al. (2021) for China that utilized wavelets tools for the period from 1965 to 2019, and Ahmed et al. (2021c) for G7 countries that used the CUP-FM method for the period from 1987 to 2017.

Moreover, the findings reveal that economic complexity is negatively related to CO_2 emissions and the values of the coefficient are 0.036 and 0.029 in the long-run, indicating that a percentage change in economic complexity will result in the reduction of 0.036 (model 1) and 0.029 (model 2) in CO_2 emissions. Also, in the short-run, a negative influence of economic complexity on CO_2 emissions is evident. The negative influence of economic complexity on CO_2 emissions suggests that structural shift (production processes) and complexity of products in these economies are eco-friendly. Precisely, the results indicate that diversifying products into more knowledgeable and sophisticated ones improves the quality of the environment with respect to CO_2 emissions. This is because the complex and sophisticated products often require less energy consumption during their production (Can and Gozgor, 2017), and in these advanced nations with sophisticated production structures, production of less energy-intensive products is reasonable. This validates the theoretical basis of economic complexity and environmental degradation nexus suggested by Can and Gozgor (2017) in a developed nation France. Since the outcome of the economic complexity is encouraging for environmental sustainability and also relates to the host economy's production process, therefore, policymakers should take into account the roles of economic complexity when formulating economic growth strategies and environmental regulations. This outcome substantiates the estimates of Doğan et al. (2020) for 28 OECD nations. They used similar econometric approaches using the dataset for the period from 1990 to 2014. However, this estimate contradicts the outcome of Pata (2021) for the USA, Adedoyin et al. (2021) for 26 EU nations, and Chu (2021) for 118 countries. The differences in results can arise due to the different periods under investigation, different sample countries, and different econometric approaches applied. Nevertheless, as discussed above, our results follow the theoretical foundations of economic complexity in the context of developed countries, as economic complexity is expected to decrease environmental deterioration in developed nations (Can and Gozgor, 2017).

Similarly, globalization negatively impacts CO_2 emissions across all models in both periods (long and short-term). Findings in **Table 6** reveal that in model 1, 0.337% decrease in CO_2 emissions is associated with a 1% upsurge in globalization in the short-run while in the long-run, such an increase in globalization will cause a reduction in CO_2 emissions by 0.219%. For model 2, 0.235% reductions in CO_2 emissions can be attributed to an increase of 1% in globalization in the long-run while in the short run, the reduction in emissions is 0.368%. This outcome reveals that the pattern of globalization exerts a negative impact on environmental deterioration in these economies. The possible explanation is that as globalization evolves, green technology is increasingly transferred across nations, and polluting resources decrease (Ahmed et al., 2021). Another possible reason is that there is a shift in comparative advantage to economies especially the developing ones that do not have a climate policy in place. This conclusion aligns with prior studies, such as Yuping et al. (2021), Balsalobre-Lorente et al. (2021), but, the studies of Chien et al. (2021) and Adebayo et al. (2021) contradict this finding because their studies cover a different period and different sample countries.

Finally, the impact of the interaction between globalization and economic complexity on CO_2 emissions is negatively significant, suggesting that the joint influence of economic complexity and globalization improves the quality of the environment. The empirical investigation on the role of globalization and economic complexity is novel, and it is considered a new contribution to the environmental literature. This offers new possibilities for the use of globalization as a tool for achieving long-term structural transformation in these economies. Concluded that globalization fosters technological innovation, improves environmental standards when effectively managed, promotes overall productivity by boosting trade activity, and increases economic activities through foreign direct investment and technologically advanced transactions. These nations can develop their economies into more sophisticated knowledgeable manufacturing-based economies, and produce less energy-intensive goods. This will improve environmental quality through the openness of their economy to the rest of the globe and achieving the desired benefits of structural change.

For the robustness analysis, the CCEMG method is employed in this study. **Table 7** presents the findings. The findings demonstrate the validity of the results generated by the CS-ARDL, as this approach also provided outcomes in line with the results of the CS-ARDL.

TABLE 7 | Robustness test (CCEMG).

Dependent variable = *ln*CO_2	Model–1		Model–2	
	Coefficient	Z–Value	Coefficient	Z–Value
*ln*GDP	0.281*	2.840	0.216*	2.710
*ln*RE	−0.054**	−2.010	−0.137*	−2.920
*ln*ECI	−0.178*	0.061	−0.146***	−1.710
*ln*GLO	−0.435*	−4.240	−0.546**	−2.290
ln (GLO*ECI)	—	—	−0.341*	−2.600
Constant	−1.042**	−2.470	−0.865**	2.560

, ** and * depict level of significance of 0.01, 0.05 and 0.1 respectively.*

5 CONCLUSION AND POLICY RECOMMENDATIONS

This research evaluates the association between CO_2 emissions, GDP, renewable energy, economic complexity, and globalization for the top 10 energy transition economies covering the period from 1990 to 2018. This study also takes into account the joint impact of economic complexity and globalization on carbon emissions. The study used Pesaran (2015) CD test for checking cross-sectional dependency, whereas, Pesaran and Yamagata (2008) test is applied to evaluate the slope homogeneity. The study detected the problem of CSD in the dataset. Likewise, the model was also plagued with slope heterogeneity. Thus, the study used a methodology that could account for CSD and heterogeneity issues. For instance, the research utilized the cross-sectionally augmented IPS and ADF tests of Pesaran (2007) to assess the stationarity nature of the concerned variables. In order to assess the long-term interconnection amongst the variables of concern, the Westerlund (2007) cointegration technique is employed. The estimates for the long and short were uncovered by applying the CS-ARDL test. Furthermore, for the robustness analysis of the CS-ARDL estimates, the CCEMG method was employed. For the cointegration approach, the outcome affirmed the presence of cointegration amongst the considered variable. The CS-ARDL findings indicate that GDP increases environmental degradation; however, renewable energy and globalization reduce carbon emissions. Also, economic complexity mitigates carbon emissions. Moreover, the joint impact of economic complexity and globalization decreases carbon emissions with more intensity. From this outcome, policies channeled toward improving renewable energy, globalization, and economic complexity will substantially boost environmental sustainability. The formulation of a suitable policy for economic growth will also influence carbon emissions.

Policy Recommendation

Based on the study's finding of a tradeoff between income and environmental quality, it becomes critical to seek cost-effective ways to conduct economic (income) activities that could reduce emissions and, thereby, enhance the environmental quality. Also, economic commitments to create a low-carbon ecosystem should stimulate long-term investment towards the development of clean technology for decreasing emissions of the top ten energy transition economies. The economic system will eventually decarbonize if the appropriate steps are taken.

Based on the contribution of renewable energy towards environmental sustainability, the research suggests that these groups of economies should continue to expand the usage of renewable energy. This may be accomplished by increasing investments in the production of various types of renewable energy in the energy mix of the economies and making renewable energy affordable and economically accessible. The policymakers can promote the usage of renewable energy by offering incentives for its usage, like providing price subsidies for different forms of renewable energy. It will also encourage more renewable energy usage in these economies. In addition, the negative effect of renewable energy consumption on environmental degradation suggests that all these economies appear to be on the appropriate route regarding the objective of achieving decarbonization and sustainable growth. Furthermore, governments need to put aggressive efforts towards diversifying energy sources, minimizing the reliance on fossil fuels, and increasing the use of renewable energy.

Also, it is evident that these economies can achieve environmental sustainability through globalization. Hence, it is important to ensure that the upsurge in energy can be reduced by increasing globalization. Thus, these economies should promote interaction with the rest of the world by adopting the policy of opening up. The rules and regulations for trade and FDI should be designed keeping in view environmental sustainability targets. This will help to improve the existing knowledge of manufacturing sophisticated products. Technological inflows from globalization and enhancement of capabilities will help to develop complex and knowledgeable production structures. These strategies can promote environmental sustainability in the host economies without decreasing economic growth.

Economic complexity reduces emissions which provides a vital option to continue developing more complex products and reduce the production of dirty energy-intensive products. In this way, diversifying the production basket by relying on the production of sophisticated products will eventually decrease environmental deterioration. Policymakers should encourage knowledge and skill-intensive products exports for a sustainable environment. Companies that are exporting sophisticated products should be offered lucrative tax exemptions and subsidies. This will encourage them to utilize greener energy sources. Hence, the government of these economies can boost the exports of high-value-added commodities and sophisticated items to decrease carbon emissions.

The focus of this current research is restricted to the top ten countries in terms of energy transition and just a few parameters have been taken into consideration when assessing the influence of globalization and economic complexity on carbon emissions. Future research might expand the model by incorporating other macroeconomic variables like financial development and economic policy uncertainty. City and state-level assessments will also be beneficial for more accurate policy consequences.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Materials, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

WP: project administration. RM: writing – review and editing, supervision, project administration, methodology, formal analysis and funding acquisition. AA: conceptualization, data curation, writing original draft. MA: writing – review and editing, and visualization. ZA: methodology, investigation. TSA: project administration, formal analysis, and software validation. All authors: contributed to the article and approved the submitted version.

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Conflict of Interest: Author KH was employed by company Taian DaoXiangYuan Food Company.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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