Heliyon 9 (2023) e22705

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Striving towards 2050 net zero CO_2 emissions: How critical are clean energy and financial sectors?

Haibo Chen [a], Jiawei Lu [a], Emma Serwaa Obobisa [b,c,*]

[a] School of Finance and Economics, Jiangsu University, Zhenjiang 212013, PR China
[b] Global Commons and Climate Policy, Kiel Institute for the World Economy, Kiel, Germany
[c] ZF-Centre for Sustainability Research, Zeppelin University, Friedrichshafen, Germany

A R T I C L E I N F O

Keywords:
Clean energy use
Financial development
net zero emissions
Sustainble development and Top emitters

A B S T R A C T

The development of clean energy and financial sectors have been highlighted as critical factors in tackling climate change and achieving net zero emissions goals. Hence, using a dataset for the top 20 emitter countries from 1990 to 2019, this study examines whether clean energy consumption, financial development, human capital, population, and economic growth are connected with environmental quality through a reduction in carbon emissions. The long-run estimates show that renewable energy utilization, financial development, and human capital are significant in reducing CO_2 emissions in the quest for net zero emissions. Contrarily, economic growth and population have a increases CO_2 emissions. The results of the causality test show a two-way causality between renewable energy use, financial development, economic growth, population, and CO_2 emissions. Moreover, one incidence of unidirectional causality is observed from CO_2 emissions to human capital. Based on the findings, policy implications are suggested.

1. Introduction

The last few decades have witnessed unparalleled climate change and global warming. This has raised concerns over its causes and effects on humanity. Researchers believe that the increasing CO_2 emissions make up the vast majority of greenhouse gases, which has resulted in the recent high temperatures. International climate change discussions have been ongoing to reach a consensus in reducing the rapid increase of anthropological CO_2 emissions globally. Many international organizations are therefore calling for the stringent adoption of a net zero CO_2 emissions target by 2050 in order to spearhead a new and decisive effort to prevent widespread climate damage. In a landmark agreement signed in Paris in 2015, many countries pledged to reach net zero emissions, including the top emitters, China, the United States, and the European Union. Failing to reduce anthropological CO_2 emissions will lead the world to a warming earth. The Paris Agreement sets a global goal to keep temperature increases over pre-industrial levels to 2°C, ideally 1.5°C. To meet the 1.5°C target, the world must reduce CO_2 emissions to net zero by the middle of the 21st century, and a deep transition in energy systems is required to achieve the net zero goal [1].

Net zero CO_2 emissions means lowering CO_2 emissions to the greatest extent possible and eliminating any residual emissions from the atmosphere. A net zero CO_2 emissions approach also revolves around countries probing their economic activities and determining strategies to reduce absolute emissions by reducing energy consumption, boosting energy efficiency [2], and restructuring the energy system for all energy-related needs: electricity, manufacturing, industrial activities, transportation, commercial and residential

* **Corresponding author**. Global Commons and Climate Policy, Kiel Institute for the World Economy, Kiel, Germany
E-mail addresses: hbchen@ujs.edu.cn (H. Chen), daluwei217@163.com (J. Lu), emmaserwaaobobisa@yahoo.com (E.S. Obobisa).

https://doi.org/10.1016/j.heliyon.2023.e22705
Received 6 May 2023; Received in revised form 7 November 2023; Accepted 16 November 2023
Available online 24 November 2023
2405-8440/

buildings [3]. Thus, the strive towards net zero CO_2 emissions has mainly been seen from a green investment lens, which places a focus on sustainable consumption and production patterns as well as access to affordable clean energy sources such as renewable energy, as detailed in the United Nations Sustainable Development Goals (SDG 7 & 12) [4]. In an effort to achieve this, renewable energy such as solar, wind, hydro, and bioenergy have grown in popularity recently in many nations as a result of their ability to reduce emissions. They are also recognized to have less of an impact on the environment and to produce energy for a longer time than fossil fuel energy sources [5]. This concludes the discussion of the possible benefits of using renewable energy sources in relation to net zero CO_2 emissions.

However, the process of producing renewable energy has a number of financial challenges, including infrastructure, operational, and startup expenses. According to researchers, financial development is critical in renewable energy generation and environmental damage [6,7]. In this regard, it has been determined that effective funding, risk management, and liquidity services require a well-developed financial system [8]. The financial market, through improving capital allocation, may aid in this process. Many economies are, therefore, implementing green investment strategies and switching investments from highly polluting projects to low-polluting projects in order to address the climate challenge [9]. By providing the funding needed for projects with low CO_2 emissions, financial tools such as green bonds can be extremely helpful in the fight against climate change [10]. Green financing, which contributes to a reduction in CO_2 emissions, is another controversial topic. According to studies, green investment is essential for attaining sustainable growth and lowering CO_2 emissions [11,12]. When used more broadly, the term "green investment" refers to financial contributions made to initiatives that address both carbon emission avoidance and sustainability [13]. The debt capital markets can raise money for projects with reduced CO_2 emissions and are renowned for encouraging investor involvement [14]. Nevertheless, other researchers warn against the latent capital crowding-out effect of financial sector development, which may inhibit research, and innovation, and stimulate CO_2 emissions [15]. Financial institutions also provide individuals, investors, and firms with low-cost borrowing with fewer restrictions as a result of growth in financial sectors, which increases the demand for energy and increases CO_2 emissions [16]. Hence, this study focuses on top emitters' efforts to achieve net-zero CO_2 emissions goals and analyzes how the utilization of clean energy and growth in financial sectors have influenced CO_2 emissions.

The study focuses on top emitter countries as they consume over 80 % of global fossil fuels, emit 70 % of global CO_2, and account for more than 50 % of the global population. Also, the top emitter setting was purposefully selected to allow the policy reorientation for the world's top nations to start a conversation in the global environmental policy arena. Furthermore, Figs. 1 and 2 illustrate that these major emitters are critical to reducing their global emissions. Thus, these figures emphasize the importance of commitment from these

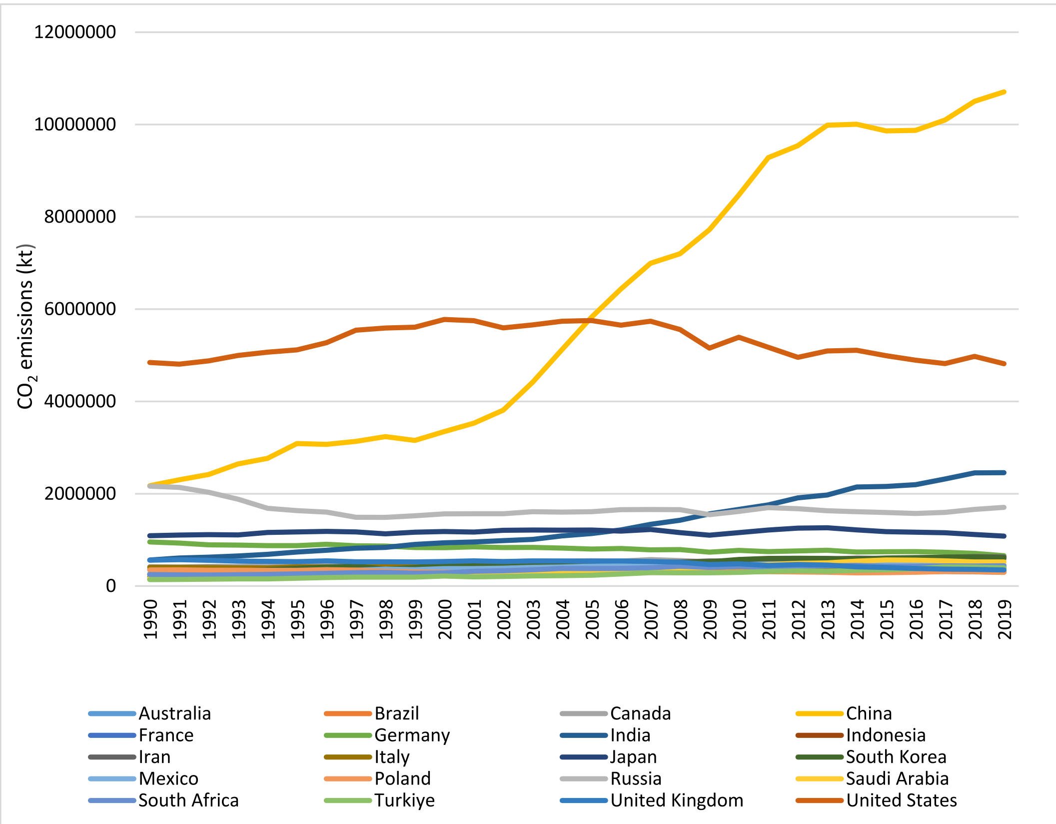

Fig. 1. CO_2 emissions (kt) in the top 20 emitter countries from 1990 to 2019.
Source: Authors' calculation from WDI

emitters in order to meet the Paris Agreement goals and focus on attaining net zero emissions through sustainable factors [17].

Although the importance of clean energy and finance in terms of their potential impact on carbon emissions has been extensively examined, the effort has been analyzed virtually in a vacuum, with few studies on the roles of clean energy and financial development toward net zero in top emitter countries. Additionally, scholarly literature has been unable to provide a definitive answer to whether financial sectors and renewable energy can help to achieve net zero CO_2 emissions in the top emitter countries. Given the highlighted environmental situation in these countries, a policy reorientation is to achieve the required net zero CO_2 emissions goals is needed. Financial development and renewable energy could be used as policy instruments in this process. The current study seeks to offer an SDG framework for reducing the harmful environmental externalities imposed by the top emitter countries' economic activity patterns based on these factors. The study contributes to the extant literature in various ways. First, this study expands the focus of extant studies by examining clean energy and financial development toward net zero emissions in top-emitter countries. Second, the study uses advanced second-generation panel models in addition to updated data.Though this study focuses on the top emitter countries, it is equally applicable to other countries seeking policy reorientation in order to achieve net zero emissions goals. The policy implication of this study can act as a model for other nations to follow, as it also attempts to achieve SDG 3, 4, 7, 8, 13, 15 and 17 goals.

The study's remaining sections are arranged as follows:A brief survey of the literature is given in Section 2. In Section 3,the models and data are provided. In Section 4, the empirical findings are presented and discussed. Section 5 offers the conclusion and policy implications.

2. Brief literature review

2.1. Renewable energy and CO_2 emissions

An essential topic on the environmental agenda is the connection between rising CO_2 emissions and climate change. Consequently, researchers and policymakers have begun to pay more attention to the measures for reducing CO_2 emissions. Since energy production and usage account for the majority of carbon emissions, they should be carefully examined. Energy sources such as renewables are designated as carbon-free when they come from a source like solar or wind that emits no carbon [18]. Therefore, the impact of renewable energy on CO_2 emissions has been objectively investigated in many countries. Most of the studies perceived that renewable

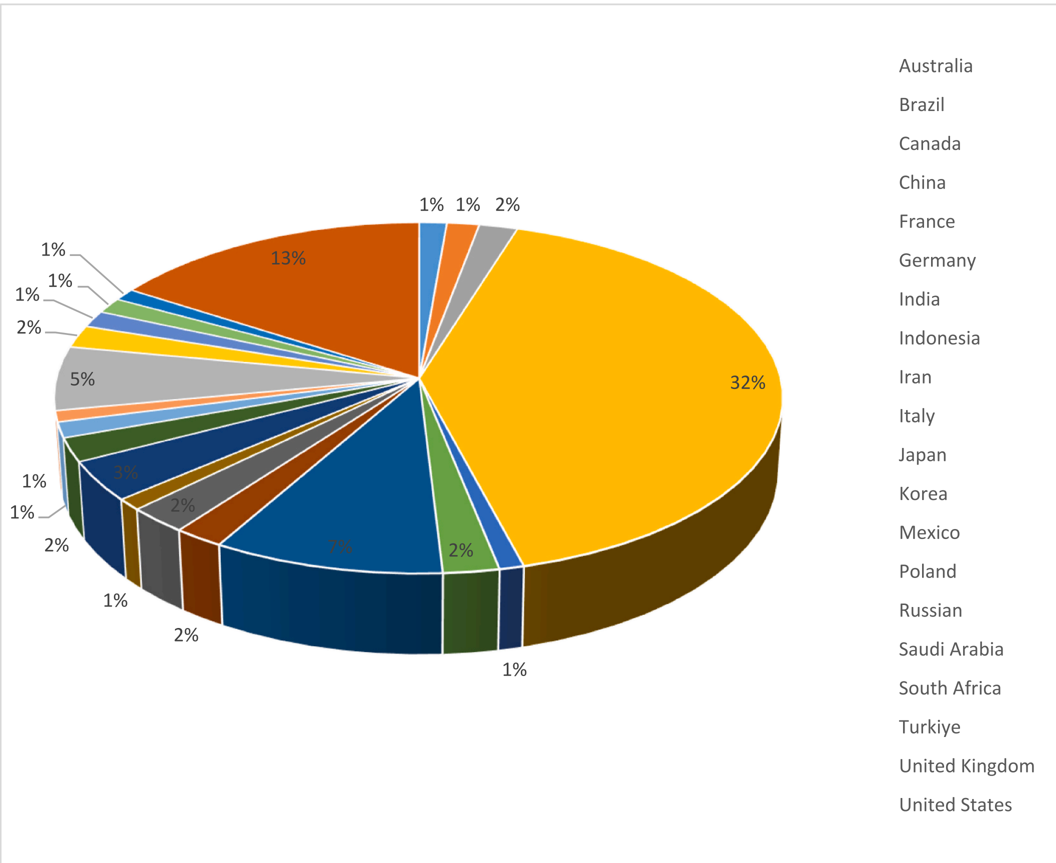

Fig. 2. Country share of global CO_2 emission in 2020.
Source: British Petroleum Statistics, 2021

energy enhances environmental quality through reduction of CO_2 emissions [11]. found that the utilization of renewable energy curtails CO_2 emissions in West African countries [19]. discovered that renewable energy reduces consumption-based CO_2 emissions and territory-based CO_2 emissions in the top 10 emitter countries [20]. highlight that renewable energy is the key enabler to achieving carbon neutrality or net zero emissions in the USA [21]. argued that strengthening environmental sustainability via renewable energy will help Turkey achieve carbon neutrality goals [22]. established that renewable energy is an important factor in reducing CO_2 emissions and fighting against climate change in African countries. Moreover [23], emphasized that increasing the development and deployment of renewable energy resources will aid in reaching net zero CO_2 emissions in N-11 countries. Thefore, the usage of renewable energy has the potential to enhance environmental quality as assessed by the long-term impact on CO_2 emissions [24].

Nevertheless [25], found renewable energy has an insignificant impact on the environment of South Korea [26]. observed that renewable energy usage causes countries' CO_2 emissions to increase [27]. presented data showing that the impact of renewable energy on CO2 emissions for 13 nations had varying results. For example, while investments in wind energy lower CO_2 emissions, investments in solar and bioenergy raise CO_2 emissions. Moreover, the scale impact lowers carbon emissions while the structure effect raises emissions due to greater renewable energy.

2.2. Financial development and CO_2 emissions

Growing recognition of the relationship between financial sector development and CO_2 emissions has prompted a global interest in evaluating approaches for carbon neutrality. According to academics, financial inclusivity makes money more accessible to businesses and individuals, which encourages them to invest in effective clean energy and technologies [8,28]. Therefore, environmental effects can be promoted by a more inclusive financial system [29]. [30] revealed that financial development improves the environmental quality of BRICS countries. [31] argued that increasing financing for net-zero emissions reduces CO_2 emissions and promotes the use of renewable energy. [32] acknowledges that the attainment of net zero emissions goals would entail a growth in green loans, bank financing, and green bank. [14] perceive that the development of sustainable finance will accelerate carbon neutrality in the U.S. [33] found that an increase in China's financial sectors aids in the reduction of CO_2 emissions which highlights the need to promote financial development to reduce CO_2 emissions while maintaining economic growth. However, increased financial sector development also encourages economic activity and industrialization, which might worsen environmental degradation [2]. Additionally, increased financial inclusivity will make credit more accessible to people, boosting household spending power on environmentally harmful products [6]. assert that financial development has a modest impact and can only explain a small portion of GHG emissions. According to [16], bank loan to the private sector raises overall CO_2 emissions as well as CO_2 emissions from the electricity and transportation industries in European countries. [34] highlight that financial development leads to environmental degradation in India through CO_2 emissions.

In summary, several studies have highlighted the importance of clean energy and financial development. Although the findings have been mixed and inclusive, there have been few studies on the role of clean and financial development toward net zero emissions in top-emitter countries. This study builds and expands on the findings of [2,35] to attend to the above issues.

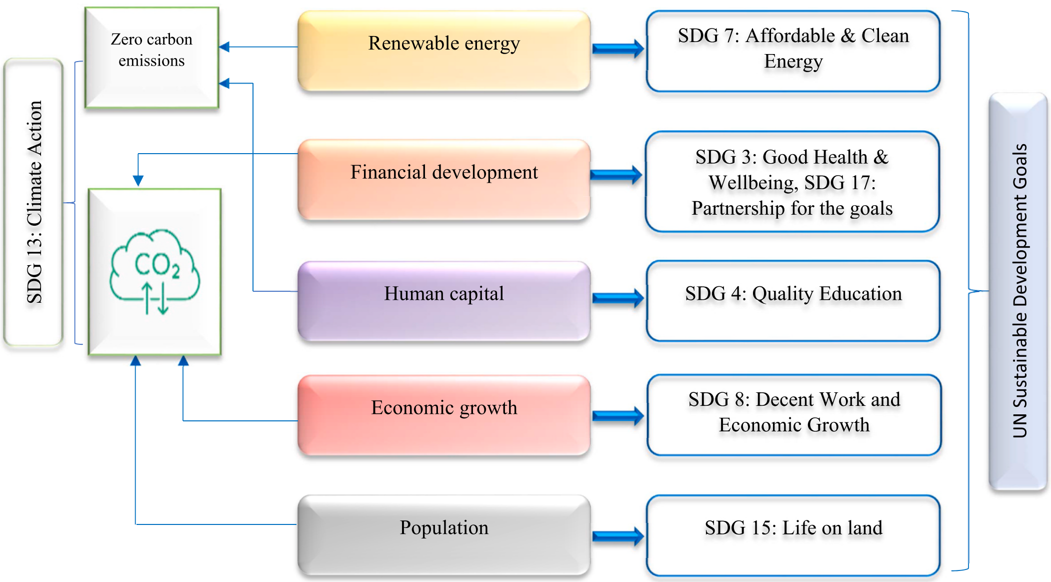

Fig. 3. Study framework.

3. Methodology

3.1. Model specification

This study aims to examine the relationship between renewable energy, financial development and CO_2 emissions in the context of the top emitters while observing the role of human capital, economic growth, and population. The United Nations (SDGs) 3, 4, 8, 7, 13, 15, 17 and the idea of sustainable economics, which focuses on human actions and environmental quality, serve as the framework for this research. It advocates for the importance of being concerned about sustainability and being aware of the potential consequences that human actions may have on the environment. Because environmental pollution is an undesirable outcome, identifying the causes

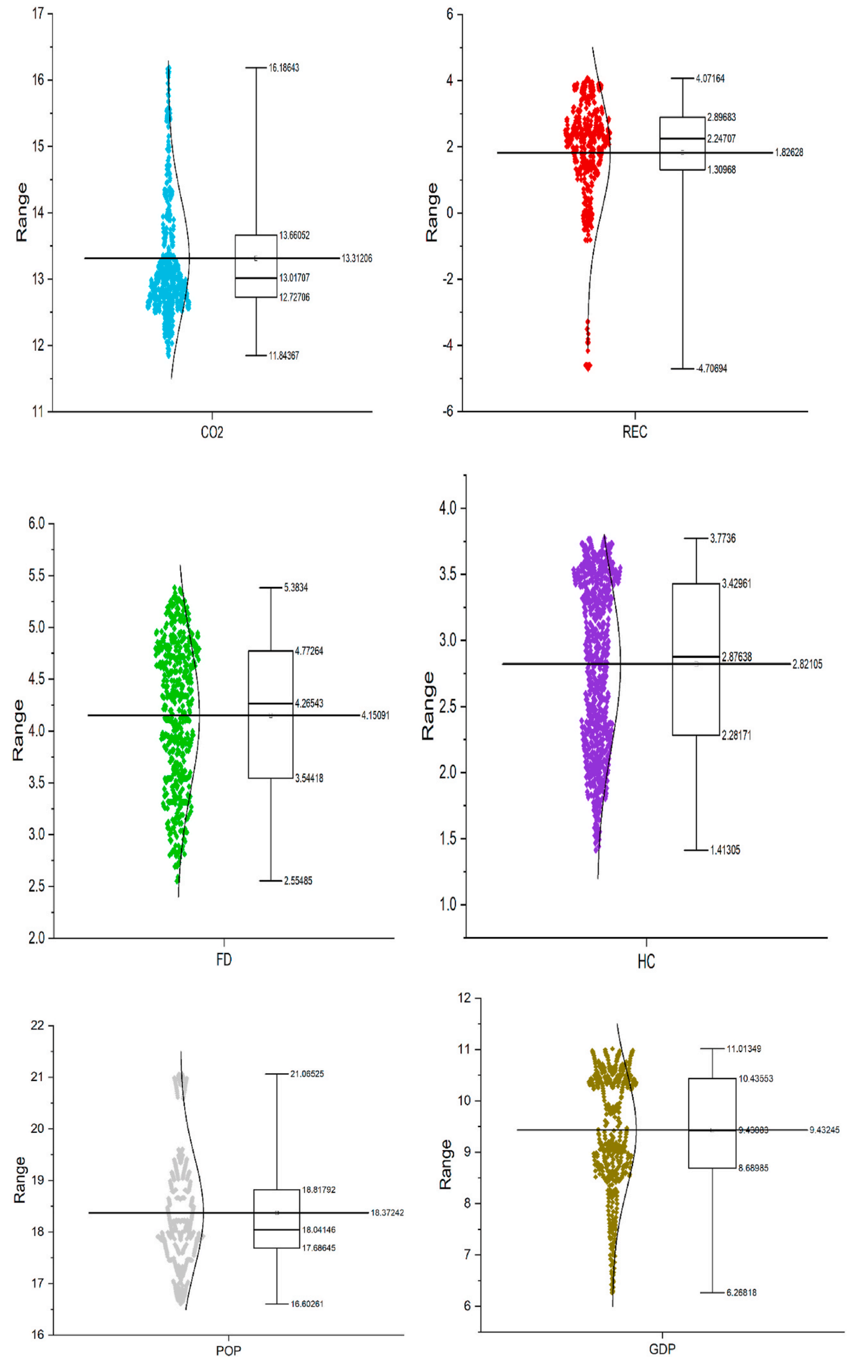

Fig. 4. Boxplot analysis of the variables.

and preventative measures is crucial. Therefore, it can be concluded that financial development and renewable energy have an impact on CO_2 emissions based on literature [17] and the situation in the top emitter countries. In controlling for human capital, economic growth, and population, we specified the following model:

$$CO_{2it} = f(REC_{it}, FD_{it}, HC_{it}, GDP_{it}, POP_{it}) \quad (1)$$

$$CO_{2it} = \alpha_0 + \beta_1 InREC_{it} + \beta_2 InFD_{it} + \beta_3 InHC_{it}, + \beta_4 GDP_{it} + \beta_5 InPOP_{it} + \mu_{it} \quad (2)$$

In Eqs. (1) and (2) shows carbon dioxide emissions (CO_2), renewable energy use (REC), financial development (FD), economic growth (GDP), and population (POP) respectively. α_0 is the unobserved country fixed effect, $\beta_1 - \beta_5$ are the long-run equilibrium coefficients, and μ_{it} is the error term. Fig. 3 shows the study framework.

3.2. Estimation techniques

The study initially tested for homogeneity, cross-sectional dependency (CSD), and stationarity. To examine the long-term relationships between the variables, the study conductedThe study used the cointegration test [36,37] to assess the long-term connections between the variables. Subsequently, the augmented mean group (AMG) estimator by Ref. [38] was employed to assess the long-term relationship between the variables. The capacity of these estimators to handle variables with cross-sectional dependency and slope heterogeneity issues sets them apart from other panel estimators. This estimator's method consists of two steps expressed in Eqs. (3) and (4):

$$\varphi Y_{it} = \gamma_i + \varphi_i \varphi X_{it} + \gamma_i f_t + \sum_{j=0}^{T} d_i \varphi D_t + \varepsilon_{it} \quad (3)$$

$$\widehat{\varphi}_{AMG} = \frac{I}{N} \sum_{i=1}^{N} \widehat{\varphi}_i \quad (4)$$

Where γ_i is the constant, the observables are represented by Y_{it} and X_{it}, φ denotes the first difference, $\widehat{\varphi}_{AMG}$ denotes the AMG estimator; ε_{it} present error term. In the empirical analysis that follows, correlations among cross-sections are addressed using a CCEMG technique by Ref. [39]. This method can deal with unobservable components as well as non-stationarity, cross-sectional dependence, and heterogeneous slopes. In Eq. (5), the CCEMG estimator is represented as:

$$CO_2^{i,t} = \varphi^1 \overline{REC}^{i,t} + \varphi^2 \overline{FD}^{i,t} + \varphi^3 \overline{HC}^{i,t} + \varphi^4 \overline{GDP}^{i,t} + \varphi^5 \overline{POP}^{i,t} + \gamma^i + W^{i,t} + \varepsilon^{i,t} \quad (5)$$

Where φ^i is the cross-sectional coefficients, γ^i is constant for each cross-section and ε is the error term.

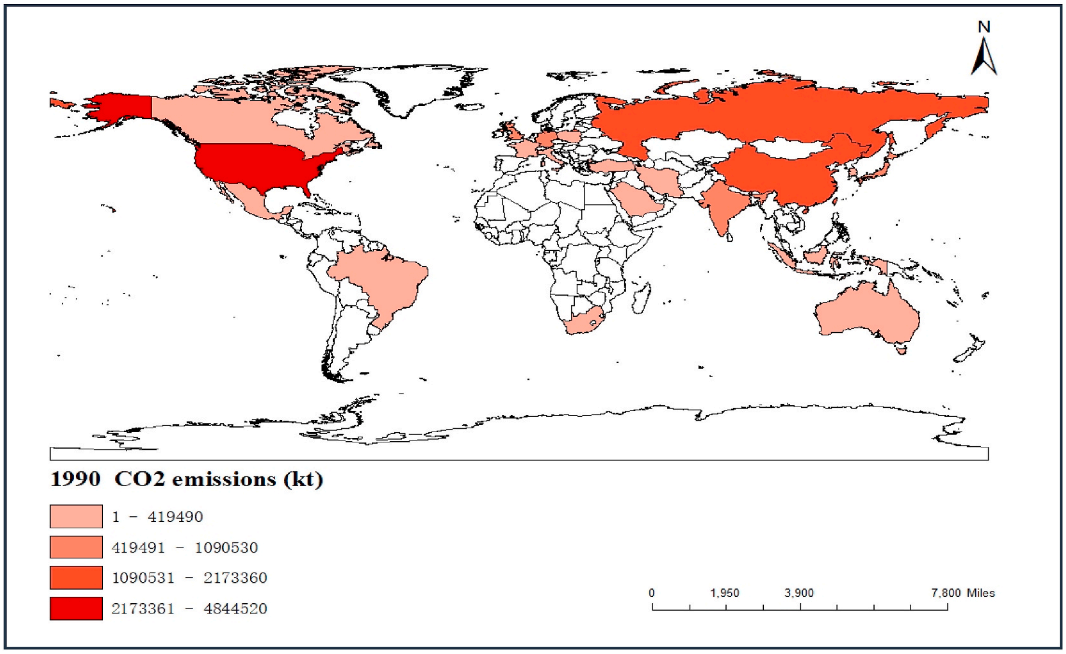

Fig. 5. Spatial distribution across the top 20 emitter countries in 1990.

3.3. Data description

The panel is made up of the top 20 emitter countries with yearly observations from 1990 to 2019 including Canada, China, France, India, Indonesia, Australia, Brazil, Germany, Iran, South Africa, Italy, Japan, United States, Korea, Mexico, Poland, Russia, Saudi Arabia, Türkiye, United Kingdom. These countries are among the top CO_2 emitters and exhibit a high level of clean energy, financial development, human capital, population, and economic growth. In this study, carbon dioxide (CO_2) emission is the dependent variable whereas, renewable energy consumption, financial development, human capital index, and GDP per capita are the independent explanatory variables. CO_2 emissions, renewable energy utilization, financial development, and GDP are sourced from World Development Indicators (WDI). Whereas the human capital index was gathered from Pen World Table version 10.0 DATA. Except for the human capital index, all the variables were transformed to their natural logarithm form. Also, a boxplot analysis of the variables is presented in Fig. 4. The spatial distribution for CO_2 emissions across the sample countries in 1990 and 2019 is shown in Figs. 5 and 6.

Table 1 reports the descriptive properties of renewable energy consumption, financial development, human capital, GDP, population, and CO_2 emissions (dependent variable) for the top 20 emitter countries from 1990 to 2019. As observed, CO_2 emission has a mean of 13.312 whereas renewable energy, financial development, humna capital, economic growth and population recorded a mean of 1.826, 4.151, 2.821, 9.432 and 18.372 respectively. The correlation matrix is presented in Fig. 7.

4. Results and discussion

4.1. Results of preliminary test

The analysis begins with the Pesaran CSD and homogeneity test, which is used to find CSD and homogeneity across the examined variables. Table 2 shows the results for the CSD test and heterogeneous slope coefficient. The findings validate the interdependence across nations by demonstrating that all of the variables are cross-sectionally independent at a 1% significance level. In addition, based on the results from the homogeneity test, the study rejected the null hypothesis for slope coefficients for the variables. These findings highlight the variables' diverse properties, implying that using traditional panel unit root and cointegration approaches will result in biased results.

After testing the CSD, it is crucial to run second-generation unit root tests (CIPS) to determine the degree of stationarity. Table 3 shows the results, which postulate that the null hypothesis of non-stationarity cannot be rejected in the cases at the level. Nevertheless, after accounting for the first difference, the null hypothesis is rejected for all variables. This demonstrates the stationarity of all the examined variables.

The result of the cointegration tests is reported in Table 4. The findings show that the null hypothesis of no cointegration can be rejected for all the tests. The existence of co-integration indicates that the regression findings are not fictitious and that long-term correlations between variables exist. Thus, the study concludes that all variables exhibit long-term cointegration.

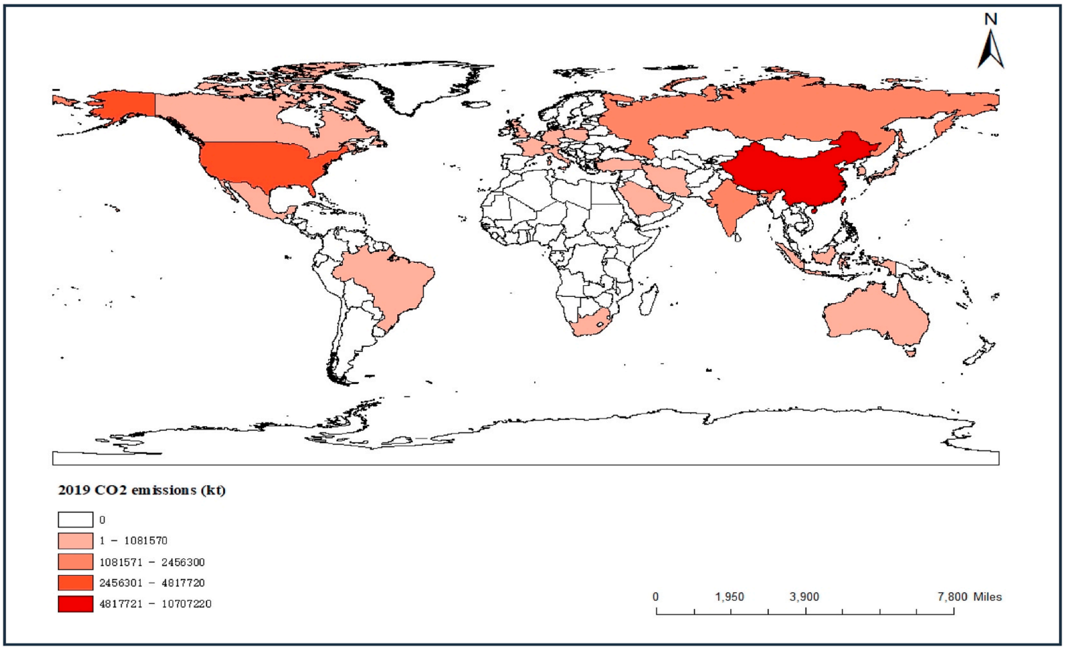

Fig. 6. Spatial distribution across the top 20 emitter countries in 2019.

Table 1
Descriptive statistics.

Variables	CO_2	REC	FD	HC	GDP	POP
Mean	13.312	1.826	4.151	2.821	9.432	18.372
Median	13.017	2.247	4.265	2.876	9.431	18.041
Maximum	16.186	4.072	5.383	3.774	11.013	21.065
Minimum	11.844	−4.707	2.555	1.413	6.268	16.603
Std. Dev.	0.915	1.813	0.715	0.635	1.137	1.093
Obs.	600	600	600	600	600	600

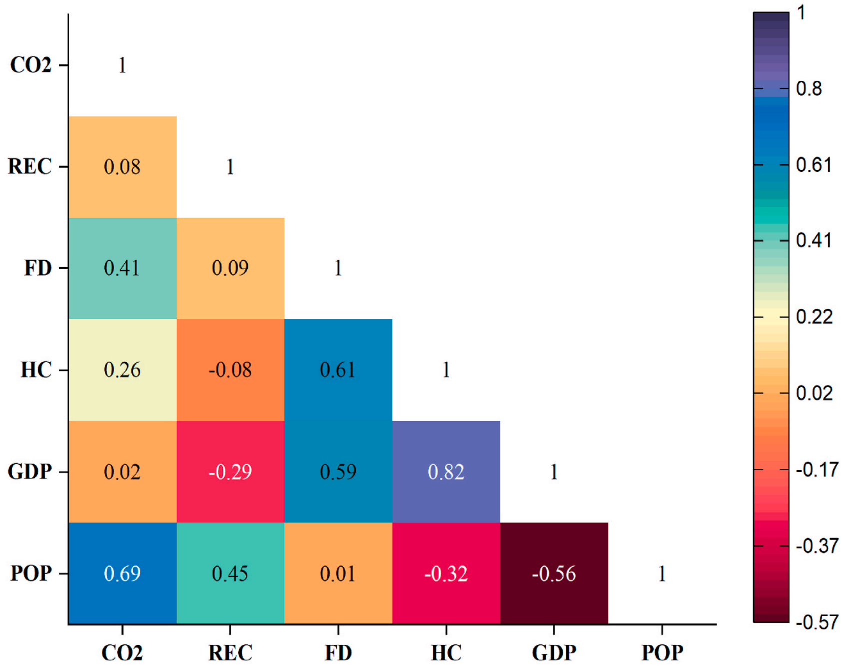

Fig. 7. Correlation matrix.

Table 2
Cross-sectional dependence and slope homogeneity test.

Variable	CSD-test	Correlation
CO_2	11.222 (0.000)***	0.680
REC	2.193 (0.028)**	0.570
FD	31.665 (0.000)***	0.710
HC	68.429 (0.000)***	0.910
GDP	64.194 (0.000)	0.850
POP	43.662 (0.000)	0.860
Slope homogeneity test		
Test	Statistic	
Delta	27.064 (0.000)***	
adj.	30.910 (0.000)***	

Note: ***, **, and * mean significance at 1 %, 5 %, and 10 %.

Table 3
Results of CIPS unit root test.

Variable	Level without trend	With trend	First difference without trend	With trend
CO_2	−1.901	−1.938	−4.659***	−4.838***
REC	−1.240	−2.568	−5.004***	−5.033***
FD	−1.549	−1.790	−3.840***	−3.916***
HC	−0.044	0.287	−1.352	−2.168**
GDP	−1.867	−2.295	−3.902***	−4.048***
POP	−1.248	−1.522	−1.830	−2.050**

Note: ***, **, and * mean significance at 1 %, 5 %, and 10 %.

Table 4
Panel cointegration.

Westerlund			Pedroni		
	Statistic	p-value		Statistic	p-value
Variance ratio	−2.4413	0.007**	Modified Phillips-Perron t	2.927***	0.001
			Phillips-Perron t	−2.185**	0.014
			Augmented Dickey-Fuller t	−1.920**	0.027

Note: ***, **, and * mean significance at 1 %, 5 %, and 10 %.

4.2. Regression analysis

Table 5 shows the results of the AMG estimates and a visual illustration is shown in Fig. 8. The empirical findings postulate a significant and negative impact of renewable energy utilization on CO_2 emissions with an estimated coefficient of −0.316. This would support the assumption that the increasing usage of renewable energy is good for the environment while also helping to reduce carbon emissions. In particular, this finding specifies that a 1 % surge in the utilization of renewable energy resources dampens carbon emissions by 0.316 %. Renewable energy has attracted global attention in the battle against climate change. Because its use is associated with lower CO_2 emissions, it is considered environmentally benign. In terms of output, it is likewise effective. In addition, the process of producing energy from renewable resources is less harmful to the environment than that of using fossil fuels. In the United States, China, and the EU which are among top emitter countries, significant efforts are being undertaken to embrace new renewable energy and low-carbon technologies in preparation for the 2050 net-zero route. The findings indicate that using renewable energy provides some environmental advantages to top emitter countries by lowering CO_2 emissions. Thus, realizing the goal of net-zero CO_2 emissions will require staggering upsurges in energy derived from renewable sources. This finding supports the empirical study of [17,19] who observed a similar validation for the negative connection between renewable energy usage and CO_2 emission in top emitters countries.

Likewise, the estimated coefficient (−0.064) of financial development shows a negative and significant impact on CO_2 emissions. Thus a 10 % increase in financial credit to the private sector reduces carbon emissions by 0.064 % which supports the study of [2,40].

Table 5
Results of long-term estimates (Dependent variable: **CO_2 emissions**).

	AMG		CCEMG	
Variable	Coefficient	P-value	Coefficient	P-value
REC	−0.316***	0.001	−0.249***	0.000
FD	−0.064*	0.090	−0.114**	0.015
HC	−0.160*	0.047	−0.744*	0.062
GDP	0.461***	0.000	0.449***	0.000
POP	1.605*	0.080	1.004**	0.010
Constant	−18.902	0.275	32.506	0.296
Wald-Test	62.78***	0.000	80.02***	0.000
Sigma	0.022		0.015	
Obs.	600		600	

Note: ***, **, and * mean significance at 1 %, 5 %, and 10 %.

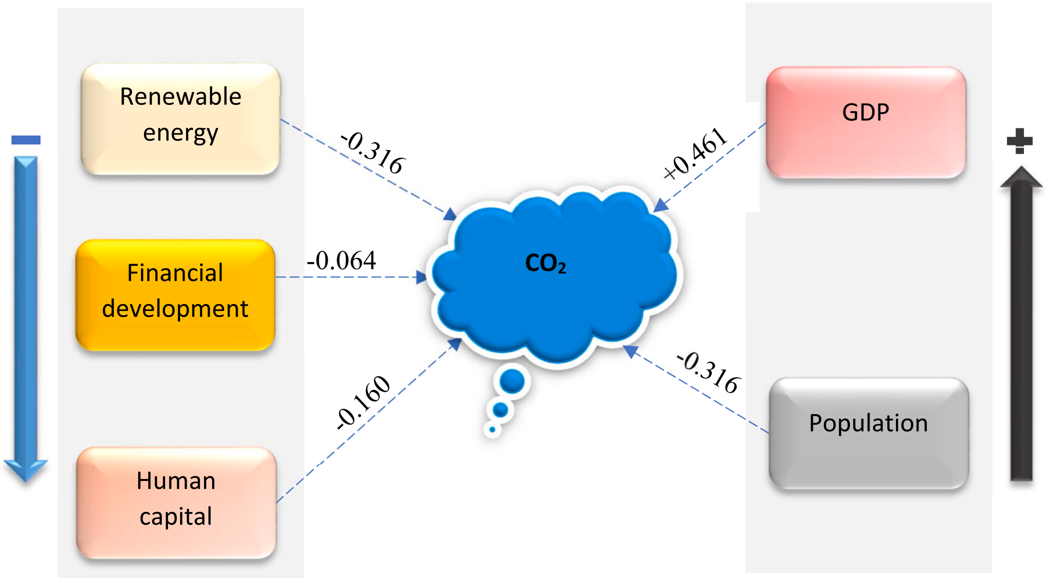

Fig. 8. Visual illustration of AMG long-run results.

Many top emitter countries are promoting the creation of long-term financial unions and green bonds as means of achieving net zero emissions through financial institution development. To accelerate decarbonization and provide resources for the world transition to net zero emissions, for example, over 550 of the world's most prestigious financial institutions representing 50 countries have united to join the Glasgow Financial Alliance for Net Zero (GFANZ). This finding shows that the availability of credit from the financial sector to the private sector increases investment in clean technology energies, thereby reducing emissions. It also suggests that these countries' financial institutions allocate a significant portion of their funding to new technologies and green initiatives. Ultimately, these measures boost energy efficiency and output while lowering emissions. Thus, ensuring the accessibility of financing for top emitter countries is critical in reaching net zero carbon emissions.

Moreover, human capital negatively and significantly impacts carbon emissions whereby a 10 % surge in human capital leads to a 0.160 % reduction in CO_2 emissions. The fact that many nations have recently encouraged environmental consciousness through research and environmental education, which encourages people to gain awareness of their surroundings, change their behavior and use eco-friendly products, maybe the reason for the effect of human capital that is visible in this data. Numerous economies have also started implementing sustainable development education programs and workshops about smart city initiatives, green technological innovation development projects, and teaching citizens about clean energy, energy conservation, and electric vehicles (EVs). This allows people to learn about environmental issues, acquire knowledge, skills, and experiences, and engage in sustainable activities to reduce CO_2 emissions. The studies of [41,42] reported that human capital dampens CO_2 emissions.

However, GDP appears to have a long-term positive impact on carbon emissions, as a 1 % rise in GDP correlates to a 0.461 increase in carbon emissions. Higher economic activity is typically accompanied by higher energy and natural resource usage. The findings of this study also show that as GDP levels rise, so does the need for environmental protection, emphasizing the necessity of developing environmental policies that may lower emissions even in times of economic expansion. Additionally, boosting resource allocation efficiency and implementing tools that can encourage consumers to choose renewable energy sources need to be at the forefront of the top emitter countries' sustainable agenda. Previous studies have also found a positive relationship between GDP per capita and CO_2 emissions [22,43].

Finally, there is evidence of a positive and significant link between population and CO_2 emissions. Specifically, the finding indicates that a 10 % increase in population causes CO_2 emissions to rise by 1.605 %. With the growing population globally, there is an increasing demand for energy. However, the conventional approaches to generating electricity are observed not to adhere to appropriate carbon neutrality norms. The intensive use of natural resources has therefore had a detrimental impact on the environment in the form of climate change and global warming because the burning of natural fuel products leads to CO_2 emissions. Thus, an increase in population leads to energy utilization and emissions. This supports prior studies [17,44]. The robustness findings from CCEMG corroborate the empirical findings from the AMG. The presented estimates derived from both approaches exhibit comparable trends with respect to significance and effect. Fig. 8 shows the visual illustration of the AMG long-run results.

4.3. Causality test

Table 7 displays the results of the [45] causality test, indicating which variables are agents of causation for other variables. All of the variables in the model show strong evidence of causation, most of which is bidirectional. The table shows a bidirectional causality between renewable energy use and CO_2 emissions which are line with study of [17]. Similarly, a feedback causality is established

Table 7
Causality results.

H_o	$W-Stats$	$\overline{Z}-Stats$	$p-value$	*Decision*	*Conclusion*
$REC \neq CO_2$	4.570	4.416	0.000	Reject H_o	$REC \leftrightarrow CO_2$
$CO_2 \neq REC$	4.737	4.726	0.000	Reject H_o	
$FD \neq CO_2$	6.006	7.080	0.000	Reject H_o	$FD \leftrightarrow CO_2$
$CO_2 \neq FD$	5.333	5.830	0.000	Reject H_o	
$HC \neq CO_2$	2.875	1.270	0.204	Accept H_o	
$CO_2 \neq HC$	5.809	6.715	0.000	Reject H_o	$CO_2 \rightarrow HC$
$GDP \neq CO_2$	3.477	2.387	0.017	Reject H_o	$GDP \leftrightarrow CO_2$
$CO_2 \neq GDP$	5.145	5.482	0.000	Reject H_o	
$POP \neq CO_2$	4.640	4.545	0.000	Reject H_o	$POP \leftrightarrow CO_2$
$CO_2 \neq POP$	8.928	12.502	0.000	Reject H_o	

Note: ***, **, and * mean significance at 1%, 5%, and 10%; ↔ bidirectional Granger causality and → unidirectional Granger causality.

between financial growth and CO_2 emissions, similar to the finding of [46]. Also, one incidence of unidirectional causality is detected from CO_2 emissions to human capital which supports the finding of [47]. Besides, there is a two-way causality between GDP and CO_2 emissions, population and CO_2 emissions which approves the findings of [48].

5. Conclusion and policy implications

Carbon emissions to the environment have grown dramatically over the last two centuries as a result of the increase in fossil fuel utilization linked with rapid and accelerating socioeconomic growth, which has unavoidably resulted in climate change. Due to the serious repercussions of climate change, enormous efforts have been made and many nations around the globe have announced and pledged to reach zero carbon emissions by 2050. Clean energy and financial development are proposed as critical factors to achieve net zero CO_2 emissions. Hence, using a dataset for the top 20 emitter countries from 1990 to 2019, this study examines the impact of renewable energy utilization, financial development, human capital, population, and GDP on CO_2 emissions. The empirical findings show that all the study variables are cointegrated. The long-run estimates indicate that renewable energy utilization, financial development, and human capital are significant in reducing CO_2 emissions in the quest for carbon neutrality goal. However, GDP and population increase CO_2 emissions.

The following recommendations and policies are provided based on the findings. The study findings suggest that renewable energy sources, financial development, and human capital can help top emitter countries transition toward a sustainable and net zero emissions economy. Practically, the results of this analysis suggest that encouraging businesses to make green investments in the area would be advantageous. Governments in the regions ought to give businesses more financial support in this regard. Import taxes on goods that will encourage clean energy should specifically be reduced. Tax incentives for businesses making green investments would also be beneficial. thus, the government might decide to provide tax rebates to companies that invest in renewable energy to lessen their reliance on fossil fuels. Governments must also make a financial commitment to investing in the development of renewable energy infrastructure and green technologies.

Additionally, to promote high environmental standards, financial sectors in top emitter countries should support green energy and low-carbon activities or projects. Likewise, government and financial institutions should support green energy and low-carbon projects and take carbon-reduction standards into consideration when constructing financial products. Banks, for example, can incentivize investments in energy-efficient technology by offering interest reductions and taking carbon-reduction standards into consideration when constructing financial products.

Economic growth, as objectively demonstrated, increases CO_2 emissions. Thus, economic models should be adjusted while engaging in environmentally friendly activities. To achieve net zero emissions by 2050, many countries will have to be reoriented – from incremental to structural change. Also, to achieve net zero by 2050, where the amount of greenhouse gases emitted is less than the amount removed from the atmosphere, top emitter countries must stop expanding fossil fuel production. To put an end to coal usage and accelerate the global transition from climate-changing fossil fuels to renewable sources.

Furthermore, the study revealed that human capital leads to a reduction in CO_2 emissions levels. Thus, one of the strategies for reaching net zero emissions may involve investing in human capital. The energy transition and net zero emissions goals can be achieved in top emitter countries through the promotion of environmental education and awareness.

CRediT authorship contribution statement

Haibo Chen: Writing - review & editing, Writing - original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Jiawei Lu:** Writing - review & editing, Writing - original draft, Visualization, Validation, Software, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Emma Serwaa Obobisa:** Writing - review & editing, Writing - original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

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.

Acknowledgments

Authors appreciate the financial support provided by the Philosophy and Social Sciences Excellent Innovation Team Construction Foundation of Jiangsu Province (No. SJSZ2020-20) and the Postgraduate Research & Practice Innovation Program of Jiangsu Province (No. KYCX22_3592).

References

[1] Peter C. Slorach, Stamford Laurence, Net zero in the heating sector: technological options and environmental sustainability from now to 2050, Energy Convers. Manag. 230 (2021), 113838, https://doi.org/10.1016/j.enconman.2021.113838.
[2] Emma Serwaa Obobisa, Achieving 1.5 °C and net-zero emissions target: the role of renewable energy and financial development, Renew. Energy 188 (2022) 967–985, https://doi.org/10.1016/j.renene.2022.02.056.
[3] Is Net Zero Carbon 2050 Possible?" Joule 4 11 (2020) 2237–2240. https://doi.org/10.1016/j.joule.2020.09.002.
[4] United Nations. United nations sustainable development goals. 2015. Retrieved from https://sdgs.un.org/goals.
[5] Obobisa, Emma Serwaa, An econometric study of eco-innovation, clean energy, and trade openness toward carbon neutrality and sustainable development in OECD countries. *Sustainable Development*, 1 (25) (2023) https://doi.org/10.1002/sd.2829.
[6] Boqiang Lin, Jude O. Okoye, Towards renewable energy generation and low greenhouse gas emission in high-income countries: performance of financial development and governance, Renew. Energy 215 (2023), 118931, https://doi.org/10.1016/j.renene.2023.118931.
[7] Appiah-Otoo, Xudong Chen Isaac, Jeffrey Dankwa Ampah, Does financial structure affect renewable energy consumption? Evidence from G20 countries, Energy 272 (2023), 127130, https://doi.org/10.1016/j.energy.2023.127130.
[8] Xinxin Wang, Zeshui Xu, Yong Qin, Marinko Skare, The global impact of financial development on renewable energy in a panel structural vector autoregression analysis, Sustain. Dev. 31 (3) (2023) 1364–1383, https://doi.org/10.1002/sd.2453.
[9] Xu, Xiaoyang, Yufan Xie, Emma Serwaa Obobisa, and Huaping Sun. 2023. "Has the establishment of green finance reform and innovation pilot zones improved air quality? Evidence from China." *Humanities and Social Sciences Communications* 10 (1):262. doi: 10.1057/s41599-023-01773-0.
[10] Zoaka, Joshua Dzankar, Daberechi Chikezie Ekwueme, Hasan Güngör, and Andrew Adewale Alola. 2022. "Will financial development and clean energy utilization rejuvenate the environment in BRICS economies?" *Business Strategy and the Environment* 31 (5):2156-2170. doi: https://doi.org/10.1002/bse.3013.
[11] Mohammed Musah, Bright Akwasi Gyamfi, Paul Adjei Kwakwa, Divine Q. Agozie, Realizing the 2050 Paris climate agreement in West Africa: the role of financial inclusion and green investments, J. Environ. Manag. 340 (2023), 117911, https://doi.org/10.1016/j.jenvman.2023.117911.
[12] Sanja Filipović, Noam Lior, Radovanović Mirjana, The green deal – just transition and sustainable development goals Nexus, Renewable and Sustainable Energy Reviews 168 (2022) 112759. https://doi.org/10.1016/j.rser.2022.112759.
[13] Meng Qin, Xiaojing Zhang, Yameng Li, Badarcea Roxana Maria, Blockchain market and green finance: The enablers of carbon neutrality in China, Energy Economics 118 (2023) 106501. https://doi.org/10.1016/j.eneco.2022.106501.
[14] Qin, Meng, Chi-Wei Su, Yifan Zhong, Yuru Song, and Oana-Ramona Lobonț. 2022. "Sustainable finance and renewable energy: Promoters of carbon neutrality in the United States." *Journal of Environmental Management* 324:116390. doi: https://doi.org/10.1016/j.jenvman.2022.116390.
[15] R. Wang, et al., The nexus of carbon emissions, financial development, renewable energy consumption, and technological innovation: what should be the priorities in light of COP 21 Agreements? J. Environ. Manag. 271 (2020) 111027.
[16] Xu, Baochang, Sihui Li, Ayesha Afzal, Nawazish Mirza, and Meng Zhang. 2022. "The impact of financial development on environmental sustainability: A European perspective." *Resources Policy* 78:102814. doi: https://doi.org/10.1016/j.resourpol.2022.102814.
[17] Umme Habiba, Xinbang Cao, Ahsan Anwar, Do green technology innovations, financial development, and renewable energy use help to curb carbon emissions? Renew. Energy 193 (2022) 1082–1093, https://doi.org/10.1016/j.renene.2022.05.084.
[18] Chinazaekpere Nwani, Ojonugwa Usman, Kingsley Ikechukwu Okere, Festus Victor Bekun, Technological pathways to decarbonisation and the role of renewable energy: a study of European countries using consumption-based metrics, Resour. Pol. 83 (2023), 103738, https://doi.org/10.1016/j.resourpol.2023.103738.
[19] Shahid Ali, Eyup Dogan, Fuzhong Chen, Zeeshan Khan, International trade and environmental performance in top ten-emitters countries: the role of eco-innovation and renewable energy consumption, Sustain. Dev. 29 (2) (2021) 378–387, https://doi.org/10.1002/sd.2153.
[20] Xi Yuan, Chi-Wei Su, Muhammad Umar, Xuefeng Shao, Oana-Ramona LobonŢ, The race to zero emissions: can renewable energy be the path to carbon neutrality? J. Environ. Manag. 308 (2022), 114648 https://doi.org/10.1016/j.jenvman.2022.114648.
[21] Shan Shan, Sema Yılmaz Genç, Hafiz Waqas Kamran, Gheorghita Dinca, Role of green technology innovation and renewable energy in carbon neutrality: a sustainable investigation from Turkey, J. Environ. Manag. 294 (2021), 113004, https://doi.org/10.1016/j.jenvman.2021.113004.
[22] Emma Serwaa Obobisa, Haibo Chen, Isaac Adjei Mensah, The impact of green technological innovation and institutional quality on CO2 emissions in African countries, Technol. Forecast. Soc. Change 180 (2022), 121670, https://doi.org/10.1016/j.techfore.2022.121670.
[23] Xuefeng Shao, Yifan Zhong, Wei Liu, Rita Yi Man Li, Modeling the effect of green technology innovation and renewable energy on carbon neutrality in N-11 countries? Evidence from advance panel estimations, J. Environ. Manag. 296 (2021), 113189, https://doi.org/10.1016/j.jenvman.2021.113189.
[24] Binlin Li, Nils Haneklaus, The role of clean energy, fossil fuel consumption and trade openness for carbon neutrality in China, Energy Rep. 8 (2022) 1090–1098, https://doi.org/10.1016/j.egyr.2022.02.092.
[25] Ugur Korkut Pata, Mustafa Tevfik Kartal, Impact of nuclear and renewable energy sources on environment quality: testing the EKC and LCC hypotheses for South Korea, Nucl. Eng. Technol. 55 (2) (2023) 587–594, https://doi.org/10.1016/j.net.2022.10.027.
[26] Muntasir Murshed, Behnaz Saboori, Mara Madaleno, Hong Wang, Buhari Doğan, Exploring the nexuses between nuclear energy, renewable energy, and carbon dioxide emissions: the role of economic complexity in the G7 countries, Renew. Energy 190 (2022) 664–674, https://doi.org/10.1016/j.renene.2022.03.121.
[27] Zikun Yang, Mingming Zhang, Liyun Liu, Dequn Zhou, Can renewable energy investment reduce carbon dioxide emissions? Evidence from scale and structure, Energy Econ. 112 (2022), 106181, https://doi.org/10.1016/j.eneco.2022.106181.
[28] Amine Lahiani, Salma Mefteh-Wali, Muhammad Shahbaz, Xuan Vinh Vo, Does financial development influence renewable energy consumption to achieve carbon neutrality in the USA? Energy Pol. 158 (2021), 112524 https://doi.org/10.1016/j.enpol.2021.112524.
[29] Dervis Kirikkaleli, Hasan Güngör, Tomiwa Sunday Adebayo, Consumption-based carbon emissions, renewable energy consumption, financial development and economic growth in Chile, Bus. Strat. Environ. 31 (3) (2022) 1123–1137, https://doi.org/10.1002/bse.2945.
[30] Joshua Dzankar Zoaka, Daberechi Chikezie Ekwueme, Hasan Güngör, Andrew Adewale Alola, Will financial development and clean energy utilization rejuvenate the environment in BRICS economies? Bus. Strat. Environ. 31 (5) (2022) 2156–2170, https://doi.org/10.1002/bse.3013.
[31] Haozhi Qi, Xucheng Huang, Sheeraz Muhammad, Green financing for renewable energy development: Driving the attainment of zero-emission targets, Renewable Energy 213 (2023) 30–37. https://doi.org/10.1016/j.renene.2023.05.111.
[32] Garima Vats, Mathur Ritu, A net-zero emissions energy system in India by 2050: An exploration, Journal of Cleaner Production 352 (2022) 131417. https://doi.org/10.1016/j.jclepro.2022.131417.

[33] Lahiani, Amine. 2020. "Is financial development good for the environment? An asymmetric analysis with CO2 emissions in China." *Environmental Science and Pollution Research* 27 (8):7901-7909. doi: 10.1007/s11356-019-07467-y.

[34] Shahbaz, Muhammad, Muhammad Ali Nasir, Erik Hille, and Mantu Kumar Mahalik. 2020. "UK's net-zero carbon emissions target: Investigating the potential role of economic growth, financial development, and R&D expenditures based on historical data (1870–2017)." *Technological Forecasting and Social Change* 161: 120255. doi: https://doi.org/10.1016/j.techfore.2020.120255.

[35] Binlin Li, Nils Haneklaus, The potential of India's net-zero carbon emissions: Analyzing the effect of clean energy, coal, urbanization, and trade openness, Energy Rep. 8 (2022) 724–733, https://doi.org/10.1016/j.egyr.2022.01.241.

[36] Joakim Westerlund, Testing for error Correction in panel data, Oxf. Bull. Econ. Stat. 69 (6) (2007) 709–748, https://doi.org/10.1111/j.1468-0084.2007.00477.x.

[37] Peter Pedroni, Panel cointegration: ASYMPTOTIC and finite sample properties of pooled time series tests with an application to the PPP hypothesis, Econom. Theor. 20 (3) (2004) 597–625, https://doi.org/10.1017/S0266466604203073.

[38] Steve Bond, Markus Eberhardt, Accounting for Unobserved Heterogeneity in Panel Time Series Models, University of Oxford, 2013.

[39] M. Hashem Pesaran, Estimation and Inference in Large heterogeneous panels with a Multifactor error structure, Econometrica 74 (4) (2006) 967–1012, https://doi.org/10.1111/j.1468-0262.2006.00692.x.

[40] Jing Zhao, Ziru Zhao, Huan Zhang, The impact of growth, energy and financial development on environmental pollution in China: new evidence from a spatial econometric analysis, Energy Econ. (2019), 104506, https://doi.org/10.1016/j.eneco.2019.104506.

[41] Yao Yao, Kris Ivanovski, Inekwe John, Russell Smyth, Human capital and CO2 emissions in the long run, Energy Econ. 91 (2020), 104907, https://doi.org/10.1016/j.eneco.2020.104907.

[42] Jing Wang, Yubing Xu, Internet usage, human capital and CO2 emissions: a global Perspective, Sustainability 13 (15) (2021) 8268.

[43] Rahman, Mohammad Mafizur, Khosrul Alam, Eswaran Velayutham, Reduction of CO2 emissions: the role of renewable energy, technological innovation and export quality, Energy Rep. 8 (2022) 2793–2805, https://doi.org/10.1016/j.egyr.2022.01.200.

[44] Lamini Dauda, Xingle Long, Claudia Nyarko Mensah, Muhammad Salman, Kofi Baah Boamah, Sabina Ampon-Wireko, Courage Simon Kofi Dogbe, Innovation, trade openness and CO2 emissions in selected countries in Africa, J. Clean. Prod. 281 (2021), 125143, https://doi.org/10.1016/j.jclepro.2020.125143.

[45] Dumitrescu, Elena-Ivona, and Christophe Hurlin. 2012. "Testing for Granger non-causality in heterogeneous panels." *Economic Modelling* 29 (4):1450-1460. doi: https://doi.org/10.1016/j.econmod.2012.02.014.

[46] Aluko, Olufemi Adewale, Adefemi A. Obalade, Financial development and environmental quality in sub-Saharan Africa: is there a technology effect? Sci. Total Environ. 747 (2020), 141515 https://doi.org/10.1016/j.scitotenv.2020.141515.

[47] Muhammad Sheraz, Deyi Xu, Jaleel Ahmed, Saif Ullah, Atta Ullah, Moderating the effect of globalization on financial development, energy consumption, human capital, and carbon emissions: evidence from G20 countries, Environ. Sci. Pollut. Control Ser. 28 (26) (2021) 35126–35144, https://doi.org/10.1007/s11356-021-13116-0.

[48] Rubayyat Hashmi, Khorshed Alam, Dynamic relationship among environmental regulation, innovation, CO2 emissions, population, and economic growth in OECD countries: a panel investigation, J. Clean. Prod. 231 (2019) 1100–1109, https://doi.org/10.1016/j.jclepro.2019.05.325.