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Original Article

Does nuclear energy reduce consumption-based carbon emissions: The role of environmental taxes and trade globalization in highest carbon emitting countries

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ABSTRACT

This research examined consumption-based carbon emission reduction by nuclear energy consumption and environmental tax while considering the context of trade globalization in the highest five emitter nations from 1990 to 2020. This study used various empirical methodologies, including preliminary analysis to check the stationarity and cointegration, the CS-ARDL for long-run analysis, CCEMG, AMG for robustness, and the D-H causality test for short-term pairwise causation. The results indicated that nuclear energy consumption, environmental tax, and trade globalization help to mitigate consumption-based carbon emissions while economic growth and population density boost carbon emissions. Furthermore, the results also found two-way casual connection exists between nuclear energy consumption, population density, and consumption-based carbon emissions. Thus, the results emphasize the need for government policies that encourage nuclear energy and environmental tax as a strategy to reduce carbon emissions and achieve and maintain environmental development.

1. Introduction

The rapid environmental deterioration and climate change create substantial risks to the goals of sustainable development, environmental sustainability, and energy sustainability. The expansion of energy demand accompanied the emergence of automated manufacturing operations, necessitating large-scale energy consumption. Fossil fuels (oil and coal) have historically played an essential role in meeting the energy requirements necessary for production and driving economic growth globally, resulting in considerable CO_2 emissions [1]. This economic expansion and energy consumption upsurge greenhouse gas emissions, serious climate change, and environmental deprivation, posing a threat to humanity's survival [2]. Extensive scholarly research in energy and environmental economics has addressed these concerns and suggested using alternative energy sources. Although current electricity generation and other energy usages primarily rely on fossil fuels in selected nations, utilizing nuclear energy technologies and other renewable energy sources is expected to decrease future pollutant emissions and ensure a sustainable future [3].

Nuclear energy produces electricity through controlled nuclear reactions, which do not emit carbon emissions that contribute to climate change [4]. Nuclear power offers a reliable energy source with little CO_2 emissions, typically 15–50 g of CO_2 per kilowatt hour (gCO_2/kWh). In contrast, gas-fired power plants emit about 450 gCO_2/kWh, while coal-fired power plants emit a significantly higher 1050 gCO_2/kWh [5]. In addition, nuclear power's high energy density allows it to generate large amounts of electricity using minimal fuel. For example, a 1000 MWe coal-fired power plant uses about 2.5 million tons of coal yearly, while a 1000 MWe pressurized water nuclear power plant consumes around 27 tons of natural uranium as fuel, which is equivalent to over 18 million enriched uranium fuel pellets in more than 50,000 fuel rods.[1] The adequacy of uranium resources for ambitious nuclear energy policies depends on factors like nuclear expansion rate, reactor technology advancement, mining capabilities, exploration efforts, recycling, geopolitics, and public perception [6]. The global nuclear energy landscape is expected to undergo significant changes in the coming decades. As of January 1, 2021, there were 442 commercial nuclear reactors in operation across the globe, providing 393 GWe of power and using around 60,100 metric tons of uranium (tU) every year [7].

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[1] How is uranium made into nuclear fuel? Retrieved from: https://www.world-nuclear.org/nuclear-essentials/how-is-uranium-made-into-nuclear-fuel.aspx.

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Acronyms

CO_2	Carbon emissions
PD	Population density
SDGs	Sustainable development goals
AMG	Augmented mean group
$CBCO_2$	Consumption-based carbon emissions
IPCC	Intergovernmental Panel on Climate Change
NEC	Nuclear energy consumption
OECD	Organization for Economic Cooperation and Development
SH	Slope heterogeneity
CSD	Cross-section dependence
TGLOB	Trade globalization
ENT	Environmental Tax
MWe	Megawatt electrical
ECG	Economic growth
CS-ARDL	Cross-sectional augmented distributed lag
CCEMG	Common correlated effect mean group

Due to rising global energy demand and the need for sustainable and clean energy alternatives, nuclear capacity is anticipated to expand. By 2040, two scenarios are considered: a low-demand case with nuclear capacity remaining at 486 GWe and a high-demand case with capacity increasing to 931 GWe, representing a 70% growth from 2020 levels.[2] Consequently, annual uranium requirements for reactors are projected to range from 63,000 tU to 108,200 tU by 2040, depending on the specific demand scenario. The growth in nuclear capacity is not uniform across regions. East Asia, particularly China, is expected to experience the most substantial increase in nuclear capacity, with potential growth ranging from 35 GWe to 152 GWe by 2040 [7,8]. Other regions, such as the Middle East, Central and Southern Asia, and Africa, will also witness significant growth, totalling 27 GWe to 51 GWe collectively. In contrast, the European Union may experience a decrease in nuclear capacity by 2040, while North America's capacity could either decrease significantly or remain relatively stable, depending on various factors. However, nuclear energy's advanced reactor technologies enable superior environmental sustainability by conserving natural uranium resources, minimizing technical waste, and promoting energy independence through recycling and reducing environmental impact [9]. Fig. 1 plots the development of nuclear energy from 1965 to 2022 annually.

Furthermore, nuclear power facilities do not release CO_2 emissions during their operational phase and generate comparable CO_2 equivalent emissions per unit of electricity generation as wind power while being just one-third of solar power's emissions throughout their life cycle.[4] Therefore, nuclear energy has grown significantly due to its capacity to produce clean energy, reduce environmental effects, supply a carbon-free energy source, reduce reliance on fossil fuels, and reduce energy scarcity [10]. So, increased investment in secure and cost-effective nuclear power innovation and technology has the most capacity for green economic development. Despite the advantages of nuclear energy, the potential for environmental harm stemming from radioactive radiation and reactor accidents raises significant concerns [11]. This underlying environmental risk might trigger societal apprehensions. Furthermore, the progress of nuclear development has been hindered by anti-nuclear sentiments post the Fukushima disaster, particularly in Europe and other developed nations, leading to doubts about nuclear reactor management during extreme scenarios.

The recent United Nations Climate Change Conference, COP27, held in Egypt, highlighted significant global temperature rise concerns. To achieve global carbon neutrality, COP27 set new objectives and reaffirmed nations' commitments to limiting temperature increases to 1.5 °C above pre-industrial levels.[5] Pursuing this objective, the conference has emphasized the significance of a sustainable energy mix, incorporating low-emission and renewable energy as diversified power sources and infrastructures. The COP27 conference places considerable emphasis on nuclear energy, as numerous nations advocated for heightened financial allocation towards nuclear power to mitigate atmospheric greenhouse gases and address the challenges of climate change. According to the IPCC, nuclear energy has been identified as a "low-carbon alternative" with the potential to mitigate global warming effectively [12]. During COP27, several nations, namely Egypt, the United Arab Emirates, and Poland, made new declarations regarding their further intentions to develop nuclear energy.

Similarly, it is essential to probe the impacts of government-implemented preventative measures, such as environmental taxes and carbon pricing through governmental legislation on environmental degradation, which is vital to mitigate CO_2 emissions [13,14]. According to economic theory, taxes fulfil the economic and environmental goals of government initiatives. Environmental taxes specifically aim to assign a price to environmental harm or negative externalities to guide production and consumption through clean energies, such as nuclear energy, toward more environmentally sustainable [15]. Recycling environmental taxes as subsidies for non-fossil energy sources is an economical strategy for addressing climate change issues [16]. This action can strive for environmental protection, boost the economy, and ultimately fulfil the sustainable development goals (SDGs). However, these nations have a chance to enhance environmental sustainability and economic growth without environmental degradation by implementing environmental taxes.

Furthermore, the impact of globalization, particularly the trade-related aspect, on climate change has been significantly underestimated despite the escalating rate of trade globalization [12]. Trade globalization can contribute to reducing consumption-based carbon ($CBCO_2$) emissions by boosting production efficiency, facilitating clean technology transfer, encouraging cleaner production methods, fostering competitiveness, and promoting the spread of nuclear and renewable energy technologies [17]. In addition, trade globalization stimulates green growth and productivity by growing worldwide demand for innovative and environmentally related technologies, resulting in more efficient production processes [18]. This efficiency can lead to reduced CO_2 emissions for each unit of output reforms. Due to the lack of strict environmental legislation, globalization might contribute to the transfer of emissions to nations that rely on nonrenewable energy sources, which can lead to increased carbon emissions [19].

Therefore, examining the connection between $CBCO_2$ emissions, nuclear energy usage, and globalization has become crucial because it has emerged as a critical factor in driving environmental developments [4,20,21]. However, previous research has overlooked the influence of environmental tax and trade globalization on $CBCO_2$ emissions in the top five emitter countries. Thus, this research is novel in filling the knowledge gap by thoroughly investigating the interactions between $CBCO_2$ emissions and nuclear energy consumption, incorporating environmental tax and trade globalization as crucial factors for sustainable development.

Based on the above discussion, this work makes several interesting and unique contributions to the existing literature. Firstly, it addresses a research gap by empirically exploring nuclear energy consumption and $CBCO_2$ emissions considering environmental tax and trade globalization

[2] The Nuclear Fuel Report: Global Scenarios for Demand and Supply Availability 2023–2040 Retrieved from: https://world-nuclear.org/our-association/publications/global-trends-reports/nuclear-fuel-report.aspx.

[4] How can nuclear combat climate change? Retrieved from: https://world-nuclear.org/nuclear-essentials/how-can-nuclear-combat-climate-change.aspx.

[5] More details can be found at: https://unfccc.int/event/cop-27.

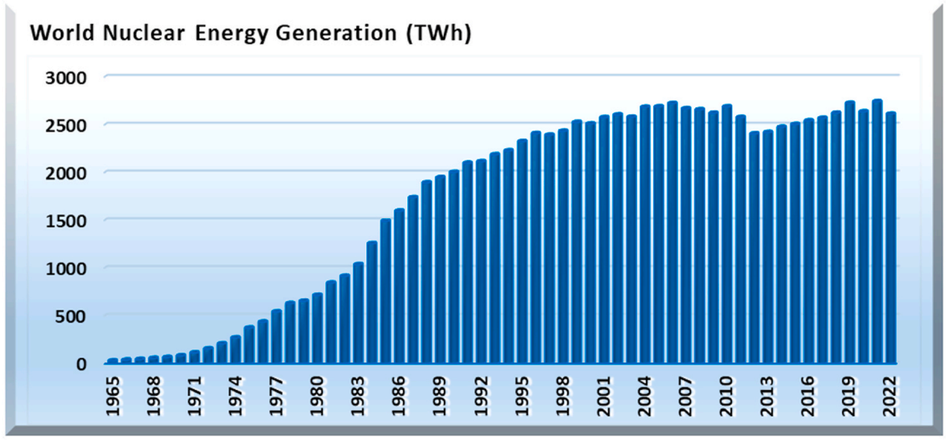

Fig. 1. Historical development of nuclear energy generation (Source: OurWorldInData.org based on Energy Institute Statistical Review of World Energy)[3].

in the highest five emitter nations from 1990 to 2020. By including these variables in the analysis, the study will help understand the factors influencing $CBCO_2$ emissions and provide facts regarding the prospective environmental benefits of nuclear energy consumption and environmental tax legislation. Secondly, this research checks the deepening effect of trade globalization on $CBCO_2$ emissions, which has been ignored in previous studies. The findings can inform policymakers and stakeholders about the potential role of trade globalization in promoting sustainable development through importing clean technology based on nuclear energy and reducing carbon emissions. Thirdly, this work applies CS-ARDL to find long-run connections and AMG, and CCEMG verifies it. Finally, the results can be used to design strategies and interventions to reduce $CBCO_2$ emissions and improve sustainable development.

The following is the study's structure: Segment 2 delivers a thorough overview of relevant studies, whereas the theoretical framework is explained in Segment 3. Segment 4 describes the data materials and econometric methodology applied. Segment 5 expresses the findings and conducts an in-depth discussion. Finally, Segment 6 provides the study conclusion.

2. Review of literature

2.1. Nuclear energy consumption and carbon emission

Environmental deterioration, climate change, and the need for energy consumption are now major concerns for human rights around the world. Growing energy consumption and demand are major problems in reducing atmospheric emissions during economic expansion [22]. Nuclear energy has become a possible solution to reduce carbon emissions and encourage better energy practices to address this issue [,23]. For instance, Kim [24] looked at the inspiration of nuclear energy on CO_2 emission and proposed that it is a more practical and long-term method of lowering carbon emissions in clean energy systems. Danish et al. [25] established that increasing investment in nuclear energy promotes energy efficiency, which boosts environmental sustainability and reduces CO_2 emissions in India. Similarly, Saidi and Omri [21] advised that OECD countries implement nuclear energy conservation to decrease the adverse environmental effects of energy usage by optimizing energy efficiency. Zhang et al. [26] found that nuclear energy considerably improves ecological sustainability and mitigates the harmful effects of CO_2 emissions in nuclear nations. Similarly, Pata and Kartal [27] realized that nuclear energy has improving impact on environmental quality in South Korea. Furthermore, nuclear energy boosts environmental quality by increasing energy efficiency.

Nathaniel et al. [28] claimed that the G7 region's NEC fosters environmental development and reduces CO_2. Additionally, it has promoted industrial and economic expansion. Naimoğlu [29] examined how nuclear energy affected CO_2 emissions in ten emerging economies and concluded that nuclear energy mitigates CO_2 and enhances environmental quality. Dong et al. [30] argued that nuclear energy is the most suitable opportunity for China's turn to a low-carbon energy system compared to other energy sources. Çakar et al. [20] noticed that nuclear energy-based innovation improves energy output and creates a cleaner atmosphere by lowering CO_2 emissions. Certain studies present different and opposite viewpoints. In contrast, Mahmood et al. [31] and Danish et al. [32] checked the inspiration on CO_2 emissions by NEC and concluded that nuclear energy is an inexpensive option, but NEC does not decrease CO_2 emissions and increases the influences of ecological deprivation.

2.2. Environmental tax and carbon emission

Environmental taxes are a powerful government policy legislation for lowering CO_2 emissions worldwide. Governmental organizations take action to reduce carbon-intensive activities to address urgent environmental issues by implementing some restrictive reforms such as environmental tax [33]. The association between CO_2 concentration and environmental tax measures is concerning because these taxes aim to reduce carbon emissions [34]. Sharif et al. [35] elaborated on this discussion in Nordic nations by arguing that environmental taxes play a vital role in reducing CO_2 emissions by increasing fossil fuel costs and reducing demand for them. Similarly, Bashir et al. [36] reviewed OECD nations and evaluated that environmental taxes efficiently improve environmental quality by decreasing CO_2 emissions. Depren et al. [37] explored the work of an ENT in the context of global warming and concluded that an environmental tax improves environmental sustainability and mitigates ecological deprivation in some Nordic nations. Hussain et al. [38] supported the idea that environmental taxes can successfully cut CO_2 emissions and prevent environmental damage.

Dogan et al. [39] argued that environmental taxes and energy sources with no carbon emissions are essential for lowering CO_2 emissions and promoting a better environment. To accomplish this, a proactive strategy that includes implementing environmental tax and nuclear and renewable energy sources is required. Xie and Jamaani [40] indicated that environmental tax significantly reduces carbon emissions and boosts environmental sustainability in G-7 nations. Silajdzic and Mehic [41] and Wolde-Rufael and Mulat-Weldemeskel [42] indicated that implementing environmental taxes might not be a popular way to lower CO_2 emissions.

[3] Nuclear energy generation. Retrieved from: https://ourworldindata.org/nuclear-energy.

2.3. Trade globalization and carbon emission

Globalization is the driving force behind the economic transformation to create prosperity worldwide and bridge the economic differences between countries. Trade globalization helps nations to become more connected and combined by exchanging commodities, services, capital, and information, posing environmental effects [10]. There is a shortage of studies examining how trade globalization affects carbon emissions. For example, Ahmed and Le [43] determined the connection among trade globalization and CO_2 emissions in six countries. Their study found that trade globalization helps to increase ecological sustainability by lowering emissions through exchanging clean technology in these countries. Zafar et al. [44] contend that people's movement, capital and the effective utilization of resources are critical components of globalization that help to maintain ecological quality. Similarly, Zaidi et al. [45] argued that increased trade globalization could improve environmental sustainability by promoting the spread of advanced technologies.

Murshed et al. [17] researched in Argentina and concluded the opposite result that trade globalization causes higher emissions levels in this country. Awosusi et al. [46] scrutinized the impression of CO_2 emissions by trade globalization and economic growth. Their findings indicated that TGLOB and economic expansion significantly upsurge CO_2 emissions. Sethi et al. [47] observed that globalization negatively impacts the environment's sustainability and mainly involves environmental deterioration due to higher energy usage and economic expansion.

Although various studies are conducted on the connection between environmental indicators and nuclear energy consumption, a scarcity of literature that particularly discovers the affiliation between nuclear energy consumption and $CBCO_2$ emissions signifies an important gap. Furthermore, previous research has largely overlooked the crucial position of environmental tax and trade globalization in advancing environmental sustainability with nuclear energy studies in selected countries. In addition to the existing literature, multiple researchers provide contrasting and mixed findings influenced by data, time, region, variables, and methodology. Therefore, the present work intends to fill this gap in the existing body of knowledge by revealing novel linkages between $CBCO_2$ emissions, nuclear energy consumption, environmental tax, and trade globalization.

3. Theoretical framework and empirical model

This paper employs several exogenous variables, including nuclear energy consumption, environmental tax, and trade globalization, that have the potential to influence environmental sustainability. Nuclear energy represents more environmentally friendly energy that can help meet the growing demand for energy while reducing dependence on other energy sources. Undoubtedly, using nuclear-related technologies will help maintain a country's prestige, drive economic growth, and contribute to improvements in the environment and social development through high wages, healthcare, and educational and employment opportunities. Furthermore, nuclear-based electricity offers lower costs, contributes to energy security, provides modern energy solutions to end energy poverty, and helps reduce emissions associated with traditional forms of energy production. In selected countries, assessing the impression of NEC on environmental degradation is crucial for establishing appropriate climate and development policies.

Environmental taxes are typically designed to discourage activities that have negative environmental impacts, such as greenhouse gases, pollution of water and air, and destruction of ecosystems. The implementation of environmental taxes is tied to promoting economic growth and environmental protection. These taxes may alter consumer and investor behavior by incentivizing cost-effective and environmentally sustainable production methods, ultimately leading to a reduction in $CBCO_2$ emissions. To avoid these taxes, businesses and industries should invest in renewable and nuclear energy sources to upsurge energy output and reduce waste production. Therefore, it is essential to consider the environmental tax influence on $CBCO_2$ emissions.

Trade globalization describes the growing interconnection and reliance of economies around the world through international trade and investment. Trade globalization stimulates economic activities and production by growing worldwide demand for goods and services. Furthermore, trade globalization encourages the transfer of innovative and environmentally friendly technologies based on nuclear power, ultimately reducing $CBCO_2$ emissions. Considering the impact of trade globalization is vital when taking trade-adjusted carbon emission as a dependent variable.

Based on the theoretical foundations discussed above, this study employs the following fundamental functional form in panel data analysis to assess the dynamic relationship between $CBCO_2$ emissions, nuclear energy consumption, environmental tax, trade globalization, economic growth, and population density:

$$CBCO_2 = f(\mathrm{NEC}, \mathrm{ENT}, \mathrm{TGLOB}, \mathrm{ECG}, \mathrm{PD}) \tag{1}$$

where $CBCO_2$ emissions refer to consumption-based carbon emissions, NEC denotes nuclear energy consumption, ENT signifies environmental tax, TGLOB represents trade globalization index, ECG stands for economic growth, and PD pertains to population density. The study transformed the variables into logarithmic form to ensure accurate results. Logarithmic transformations of variables in Equation (2) address heteroscedasticity and enable the measurement of elasticity.

$$lnCBCO_{2it} = \lambda_0 + \lambda_1 \mathrm{lnNEC} + \lambda_2 \mathrm{lnENT} + \lambda_3 \mathrm{lnTGLOB} + \lambda_4 \mathrm{lnECG} + \lambda_5 \mathrm{lnPD} + \varepsilon_{it} \tag{2}$$

where the subscript i pertains to the cross-sections, while t represents time (1990–2020). The predicted residual ε_{it} represents deviations from long-run stability and $\lambda_1 - \lambda_5$ pertain to the long-run parameters of their respective variables.

4. Econometric methodology

4.1. Data and variables

A panel dataset containing the five most polluted countries was used to check the impact of nuclear energy, environmental tax, and trade globalization on $CBCO_2$ emissions from 1990 to 2020. Table 1 describe the variables, their measurement, and provide the sources of data. Table 2 presents a summary of descriptive analysis for selected variables. The Statistics include mean, median, standard deviation, skewness, kurtosis, and Jarque-Bera tests. The variable NEC has a higher standard deviation value than other variables, indicating that it is the most volatile variable in the statistical model.

4.2. Econometric approaches

4.2.1. Cross-sectional dependence(CSD) and slope heterogeneity (SH) analysis

Before proceeding with any empirical estimation of the panel data, assessing the presence of CSD and SH is critical. The growing connections of unobserved common shocks such as oil price shocks, financial crises, and socioeconomic networks can lead to cross-section dependence, making biased panel estimations of unit root and cointegration. Therefore, we employed the Pesaran [48] cross-section dependence test for reliable results in this panel. The test equation is assumed as follows:

$$CSD = \sqrt{\frac{2T}{N(N-1)}}\left(\sum\nolimits_{i-1}^{N-1}\sum\nolimits_{j=i+1}^{N}\rho_{ij}\right), N(0,1) \tag{3}$$

This selected panel has particular characteristics related to their economic, energy, demographic, and trade structures aside from CSD. Therefore, examining SH in a model is crucial before conducting additional empirical analysis. This work utilizes the SH test developed by

Table 1
Data sources and variables description.

Variables	Symbol	Unit	Source
Consumption-based carbon emission	$CBCO_2$	Metric tonnes of CO_2	Global Carbon Atlas[a]
Nuclear energy Consumption	NEC	Millions of tonnes of oil equivalent	British Petroleum[b]
Environment Tax	ENT	Percentage of GDP	World Bank[c]
Trade globalization	TGLOB	KOF Trade Globalization Index	KOF Swiss Economic Institute[d]
Economic Growth	ECG	GDP constant 2015 US$	World Bank
Population density	PD	People per square kilometer of land area	World Bank

[a] For data see: https://globalcarbonatlas.org/emissions/carbon-emissions/.
[b] For data see: https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html#tab_sr-2021.
[c] For data see: https://databank.worldbank.org/source/world-development-indicators#.
[d] For data see: https://kof.ethz.ch/en/.

Table 2
Descriptive analysis results (all variables in log form).

	$CBCO_2$	TGLOB	NEC	ENT	ECG	PD
Mean	3.358	1.625	2.431	0.163	12.40	2.106
Median	3.188	1.653	1.430	0.079	12.439	2.394
Std. Dev.	0.335	0.115	2.785	0.507	0.560	0.607
Skewness	0.364	−1.417	1.162	−0.230	−0.183	−1.297
Kurtosis	1.808	4.579	2.825	4.344	1.861	2.952
Jarque-Bera	12.613	68.013	35.114	13.045	9.251	43.481

Pesaran and Yamagata [49]. The SH analysis provides equations for the delta tilde (Δ_{SH}) and adjusted delta tilde (Δ_{ASH}) for testing purposes, which are as follows:

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

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

4.2.2. Unit root analysis

The outdated unit root analysis depends on the models' assumptions of slope homogeneity and CSD, which may provide inconsistent results. This study used two updated methods, cross-sectional Im-Pesaran-Shin (CIPS) and cross-sectional augmented Dickey-Fuller (CADF), recognized by Pesaran [50] to determine whether the variables are stationary, which deal with the issues of CSD and SH. The CIPS test uses a particular equation:

$$\Delta y_{it} = a_i + p_i y_{it-1} + \beta_i y_{it-1} + \sum\nolimits_{j=0}^{k} \gamma_{ij}\Delta y_{it-1} + \sum\nolimits_{j=0}^{k} \xi_{ij}\Delta y_{it-1} + \varepsilon_{it} \tag{6}$$

where α_i denoted the stochastic term, and k specified the lag order. The CIPS method attempts to detect the presence of stationarity by taking the first-order differences of the separate series and gradually increasing the lag numbers using the CADF methodology. The CIPS test statistic is as follows when compared to the CIPS statistics created using CADF statistics:

$$CIPS = \frac{1}{N}\sum\nolimits_{i-1}^{N} CDF_i(\mathrm{N},\mathrm{T}) \tag{7}$$

4.2.3. Cointegration test

To determine the long-term cointegration in a panel model, this study employs the panel cointegration test based on error correction developed by Westerlund [51]. The method entails estimating an equation using the variables' first differences while accounting for lagged differences and individual-specific effects. The benefit of this test over traditional cointegration techniques is that it solves cross-country reliance and heterogeneity issues in the selected dataset. The test equation of cointegration is written as follows:

$$ai(\mathrm{L})\Delta y_{i,t} = \gamma 1_{i,t} + \gamma 2_{i,t} + \beta_i\left(y_{i,t} - 1 - a_i x_{i,t} - 1\right) + \lambda_i(\mathrm{L})\nu_{i,t} + \eta_i \tag{8}$$

Where the symbol L represents the lag operator, while $\gamma\ 1i$ and $\gamma\ 2i$ are parameters that capture the long-term dynamics of the series. The term $\boldsymbol{\beta i}$'$xit-1$ represents the vector of independent variables in the previous period, and $\boldsymbol{\alpha i}$ is the error correction. This test employs four test statistics; the first two, G_t and G_a, are associated with group statistics, and the other two represent panel statistics expressed as Pt and Pa.

4.2.4. Panel long-run analysis

This work utilized the CS-ARDL method to inspect the influence of nuclear energy consumption, environmental tax, and trade globalization on $CBCO_2$ emissions while controlling for other variables, ECG and PD. This method is more robust since it addresses issues related to slope heterogeneity, cross-sectional dependency, and endogeneity [52]. Moreover, this method accounts for unobserved shared factors, autocorrelation, common correlation, and bias from small sample sizes, which can deliver biased and inconsistent findings. The CS-ARDL approach is chosen for this research because of its strong assumptions and effectiveness in addressing the above problem. The CS-ARDL econometric form is expressed as follows:

$$y_{i,t} = a_i + \sum_{j=1}^{x}\delta_{ij}p_{i,t-j} + \sum_{j=0}^{y}\xi_{ij}q_{i,t-j} + \sum_{j=0}^{z}\varphi_{ij}^{'}\overline{Z_{i,t-j}} + \varepsilon_{i,t} \tag{9}$$

In this model, Z = (p_i, q_i)' represents cross-sectional units with the endogenous variable p_i and independent variables q_i for each unit. Z signifies the lag length, and $\varepsilon_{i,t}$ denotes the residual.

This study used a common correlated effect mean group (CCEMG) developed by Pesaran [53] and an augmented mean group (AMG) coined by Eberhardt and Bond [54] estimation methods to verify the validity and reliability of the results attained from the CS-ARDL. These methods perform long-run predictions by taking CSD and SH into account. The results of these techniques can serve to confirm that the model's predictions are solid and accurate.

4.2.5. Panel causality estimation

The Dumitrescu and Hurlin panel causality (D-H) test was applied in this paper to analyze the direction of causation of variables and determine whether any of the variables under consideration may be used to forecast the position of the other [55]. The D-H panel causality method has gained extensive recognition for dealing with the issues of cross-sectionally dependent and heterogeneous panels. The D-H regression can be stated statistically as:

$$P_{i,t} = \alpha_i + \sum_{i=1}^{q}\gamma_i^n P_{i,t-i} + \sum_{i=1}^{q}\lambda_i^n \beta_{i,t-i} + \varepsilon_t \tag{10}$$

In the D-H equation, the constant, regression parameter, and autoregression coefficients are represented by $\boldsymbol{\alpha i}$, γ_i^n, and λ_i^n, respectively. The null hypothesis posits the nonexistence of a causal link in the panel dataset, whereas the alternative hypothesis suggests the existence of connections among variables. Fig. 2 shows the flow of the analysis followed in this study.

5. Results and discussion

Detecting any CSD and SH in panel data is essential to avoid biased findings from stationarity and cointegration tests. The results of the CSD and SH analysis are presented in Table 3. The findings of the CSD study provide compelling evidence to refute the null hypothesis of cross-sectional independence with a significance level of 1%. The observed results demonstrate that the dataset under study presents cross-sectional dependence. The empirical analyses of slope homogeneity's findings shows that H_0 was rejected at significance levels of 1% for both delta and adjusted delta values.

The subsequent phase involved examining panel data stationarity. This work used the CIPS and CADF stationarity tests, and the null hypothesis implies the presence of a unit root in panel data. Table 4 delivers the outputs of the CADF and CIPS models. The statistics rejected the H_0 of unit root for all variables at I(1), which indicates that $CBCO_2$, NEC, ENT, TGLOB, ECG and PD are not stationary at the level, but after the first difference becomes stationary.

Table 5 illustrates the outcomes of the panel cointegration analysis. The findings of G_t, G_a, P_t, and P_a test statistics could not reject the alternative hypothesis of the presence of co-integration at the 1%, 5%, and 10% significant levels. The results of this work deliver indications for long-term cointegration among the variables.

The findings of co-integration confirm the progress toward estimating long and short-term effects among variables. Table 6 exhibits outcomes of CS-ARDL for short and long-run relationships of determinate for this work. The CS-ARDL analysis shows that there is a substantial negative association between NEC and $CBCO_2$ emissions with a decision criterion of 1%. Specifically, long- and short-term findings specify that a 1 unit increase in NEC would result in a 0.056 and 0.08 unit decrease in $CBCO_2$ emissions in the short and long run, respectively. Nuclear energy substantially enhances environmental quality and promotes a sustainable environment in the selected countries. Nuclear energy has the potential to serve as a viable alternative to conventional energy sources and promote better environmental quality. It is cost-effective and has significant market potential to contribute to energy security and stimulate economic growth while reducing energy poverty by providing affordable, modern energy solutions. Building a more advanced nuclear energy infrastructure can help the economy by increasing tax income at the national and state levels, providing new employment possibilities, boosting productivity in the workplace, and boosting salaries in the community at large [3,29]. These outcomes are coherent with Adebayo et al. [56], Hassan et al. [4], and Sadiq et al. [57].

Regarding ENT, the investigation found that environmental tax significantly reduces $CBCO_2$ with −0.416 and −0.151 coefficient values in the short and long run, respectively. The negative association is a result of the taxes that are imposed on carbon-intensive goods. Environmental taxes can stimulate the adoption of clean energy sources through trade globalization and persuade businesses and households to deliberate the environmental impacts of their energy usage. This action leads to more efficient utilization of clean energy and ultimately contributes to general environmental protection policies. Therefore, environmental taxes should be implemented in combination with other environmental protection policies for maximum effectiveness [39]. These countries can reduce $CBCO_2$ emissions by promoting innovation without imposing heavy taxes on businesses to improve their environmental performance. Moreover, implementing environmental taxes leads to a rapid reduction

Table 3
Findings of CSD and SH analysis.

CSD analysis	CD test	p-value
$CBCO_2$	2.217**	0.027
NEC	2.843*	0.004
ENT	2.372 **	0.018
TGLOB	12.341*	0.000
ECG	13.696*	0.000
PD	3.925*	0.000
SH analysis	coefficient	p-value
Delta	8.677*	0.000
Adj. Delta	9.862*	0.000

Note: The statistical significance at 1% and 5% is symbolized by * and **, respectively.

Table 4
Findings of stationarity analysis.

	CIPS		CADF	
Variables	Level	1st difference	Level	1st difference
$CBCO_2$	−1.923	−3.579*	−1.081	−4.193*
NEC	−0.250	−3.601*	−1.558	−3.858*
ENT	−1.395	−4.702*	−1.481	−4.163*
TGLOB	−1.895	−4.352*	−0.945	−3.393*
ECG	−2.507	−4.029*	−1.247	−2.747*
PD	−0.691	−5.164*	−1.090	−5.194*

Note: The statistical significance at 1% is symbolized by *.

Table 5
Panel co-integration outcomes.

Statistic	Value	z-value	Robust p-value
G_t	−2.707	−1.117	0.050**
G_a	−10.164	−0.454	0.090***
P_t	−4.378	−0.140	0.040**
P_a	−18.592	−2.969	0.000*

Note: The statistical significance at 1%, 5% and 10% is symbolized by *, **, and ***, respectively.

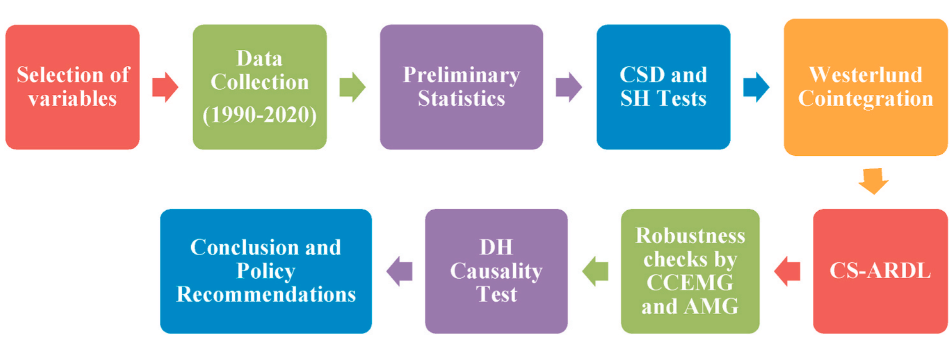

Fig. 2. Flow of the empirical analysis.

Table 6
CS-ARDL findings.

$CBCO_2$	Long run			Short run		
	Coef.	Std. Err.	P-values	Coef.	Std. Err.	P-values
NEC	−0.080**	0.044	0.040	−0.056**	0.027	0.030
ENT	−0.151*	0.058	0.009	−0.416***	0.223	0.062
TGLOB	−0.118*	0.121	0.003	−0.222*	0.275	0.004
ECG	0.541***	0.288	0.060	0.603**	0.244	0.014
PD	3.013***	0.990	0.070	1.066**	0.797	0.032
ECT(t-1)				0.722*	0.107	0.000

Note: The statistical significance at 1%, 5% and 10% is symbolized by *, **, and ***, respectively.

in the import and export of carbon-based products, which may negatively impact annual GDP growth but yield immediate environmental benefits by reducing $CBCO_2$ emissions. This perspective supports the findings by Dogan et al. [39], and Zhang and Zheng [16].

The CS-ARDL outcomes also described that trade globalization has a positive relationship with $CBCO_2$ emissions, signifying that a unit rise in TGLOB decreases the 0.222 and 0.118 unit of $CBCO_2$ emissions in the short and long run, respectively. The role of trade globalization in promoting environmental sustainability has become increasingly evident. Globalization facilitated by global trade and investment encourages structural reforms and the adoption of green industrial technologies, leading to increased productivity, higher incomes, employment opportunities, and poverty reduction. The expansion of global trade reduces trade barriers and boosts economic activity and output levels, driving economic growth and productivity [10]. These countries can promote environmental sustainability through trade globalization by importing more energy-efficient technologies to improve the industrial processes, ultimately decreasing the environmental tax and encouraging innovation in clean energy such as renewables and nuclear energy. Through connections with global partners, these countries also can enhance their economic activities, such as alleviating poverty, increasing employment, and expanding domestic income. This perspective is reliable with the results of Irfan et al. [58] and Murshed et al. [17].

The findings reveal that economic growth has a significant positive impact on $CBCO_{2.}$ Higher economic growth helps to upsurge CO_2 emissions in selected nations. These results illustrate that a 1 unit increase in economic growth results in a 0.603 and 0.541 units boost in $CBCO_2$ emissions in the short and long run, respectively. When a country's economy grows, the living standards of its people typically improve, leading to a rise in demand for domestic and imported goods [59]. The increase in consumption of products is accompanied by a corresponding increase in $CBCO_2$ emissions. Additionally, as industrial production increases to meet the higher demand for goods, which in turn requires more energy to produce and transport those goods and services, this also increases production-based CO_2 emissions. These results support the conclusions drawn by Adebayo et al. [60] and Saidi et al. [21].

Finally, population density's substantial positive coefficient values confirm that it significantly increases $CBCO_2$ emission in the selected

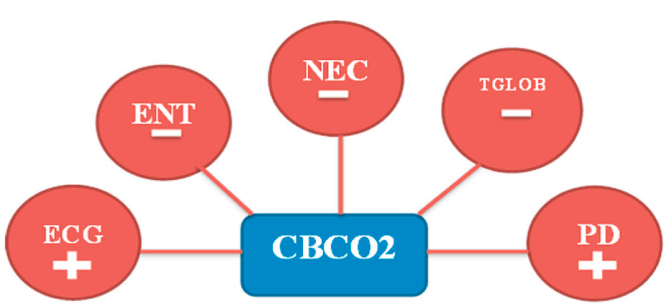

Fig. 3. Long-run analysis results.

panel. The findings indicate that a 1 unit increase of PD in 1.066 and 3.013 units boosts $CBCO_2$ emissions. Population density increases the demand for energy, transportation, housing, food, and other resources, ultimately increasing the consumption pattern in these countries. In highly populated cities, frequent traffic congestion leads to increased pollution and waste production, which harms environmental sustainability. Therefore, it is reasonable to attribute the negative impact of population density on environmental quality and increase consumption-based carbon emissions. These results are endorsed by Uzair Ali et al. [61]. This result contradicts with Sadiq et al. [57]. Fig. 3 is a visual representation of the CS-ARDL model results.

The robustness results of the AMG and CCEMG tests are presented in Table 7. The results of AMG and CCEMG confirm a negative and significant connection of trade globalization, nuclear energy, and environmental taxes with $CBCO_2$ emissions. Moreover, control variables, including ECG and PD, are positively and substantially affiliated with carbon emissions. The results are consistent and highly harmonized with the results of CS-ARDL.

The results of the D-H test show that there are causal associations between variations in Trade globalization, nuclear energy consumption, environmental tax, and consumption-based carbon emission across the five countries examined (see Table 8). The findings display a bidirectional causality between TGLOB and $CBCO_2$ emissions, indicating that this variable leads to development at the cost of environmental sustainability. Additionally, a bidirectional causal connection is observed among NEC and $CBCO_2$ emissions, signifying that this determinant increases environmental sustainability. Similarly, bidirectional causality among NEC and PD, TGLOB and PD, ECG and ENT, and ENT and PD. The outcomes also disclose the unidirectional causality between ENT, ECG to $CBCO_2$ emissions, ENT to NEC, and PD to ECG. The study's findings are important for policymakers creating regulations addressing nuclear power and the environmental impact of these nations.

6. Conclusion and policy implications

Global warming has arisen as a major challenge confronting several countries in recent years. Many countries are pursuing alternative energy sources such as nuclear energy and environmental tax legislation to address the problem of rising greenhouse gas emissions while meeting their increasing energy demands. These alternative energy sources are crucial for providing energy security and strategic response to reducing carbon emissions and boosting a country's economy. Consequently, the primary intention of the paper is to scrutinize the impression of nuclear energy consumption, environmental tax, and trade globalization on $CBCO_2$ emissions in the top five carbon emitters nations. The stationarity tests of the second generation were utilized to confirm that the CSD and SH issues in the data existed. The empirical findings of CS-ARDL show that nuclear energy consumption, environmental taxation, and trade globalization have a negative connection with $CBCO_2$ emissions in both the short and long term. Moreover, it has been noticed that economic growth and population density increased the $CBCO_2$. The robustness tools AMG and CCEMG were used to produce results comparable to the CS-ARDL technique.

According to the detailed empirical analysis, this paper offers several policy suggestions for selected nations in this work. First, NEC has the potential to reduce $CBCO_2$ emissions in these nations, particularly in electricity production. These countries can reduce their dependence on unstable fossil fuel imports, grow energy security, and address the issue of global warming by increasing nuclear energy production. Therefore, these nations should work to increase their nuclear electricity-producing capacity while taking the necessary precautions to reduce any dangers to achieve this goal. Moreover, nuclear energy-based advanced technologies can present an attractive alternative for accomplishing economic, social, and environmental objectives in selected countries. Policymakers should prioritize research and development activities toward clean technology based on nuclear and renewable energy to overcome the

Table 7
Findings of CCEMG and AMG.

	CCEMG			AMG		
$CBCO_2$	Coef.	Std. Err.	P-value	Coef.	Std. Err.	P-value
NEC	−0.018*	0.002	0.000	−0.037**	0.053	0.048
ENT	−0.031***	0.053	0.055	−0.023**	0.040	0.043
TGLOB	−0.068*	0.082	0.004	−0.025*	0.265	0.009
ECG	0.197**	0.087	0.024	0.457*	0.120	0.000
PD	1.336***	2.820	0.063	1.109***	3.121	0.072

Table 8
Results of D-H panel causality.

Variables	$CBCO_2$	NEC	ENT	TGLOB	ECG	PD
$CBCO_2$	–	4.682**	2.265	4.898**	2.103	11.158*
		2.339	0.077	2.541	−0.073	8.398
		0.019	0.937	0.011	0.941	0.000
NEC	10.807*	–	1.876	1.137	2.201	4.491**
	8.069		−0.286	−0.977	0.018	2.160
	0.000		0.774	0.328	0.980	0.030
ENT	27.450*	4.734**	–	1.853	4.774**	6.175*
	23.640	2.388		−0.307	2.425	3.736
	0.000	0.016		0.758	0.015	0.000
TGLOB	6.737*	3.694	3.744	–	3.363	7.707*
	4.261	1.415	1.462		1.105	5.169
	0.000	0.156	0.143		0.268	0.000
ECG	39.209*	3.241	4.862**	2.595	–	17.232*
	34.642	0.990	2.507	0.387		14.080
	0.000	0.321	0.012	0.698		0.000
PD	9.840*	4.491**	5.797*	4.803**	2.761	–
	7.164	2.160	3.382	2.452	0.541	
	0.000	0.030	0.000	0.014	0.587	

Note: The 1st, 2nd' and 3rd values correspond to the W, Z, and P-values, respectively; the asterisks (*and **) show the significance levels of 1% and 5%, respectively.

issues associated with fossil fuel dependence and environmental degradation. The ultimate goal is to develop a sustainable energy system that promotes economic growth while protecting the environment for future generations.

Second, economists highlight that environmental taxes are critical in minimizing the serious effects of pollution. Governments and policymakers should impose major taxes on carbon-containing items and stimulate the formation of new firms and technology based on nuclear and renewable energy sources. Tax collections should be directed towards environmental awareness programs, donations, and education to promote environmentally friendly practices in these countries. Moreover, Govt must implement an environmental tax to deter behavior resulting in CO2 emissions and encourage businesses and industries to select production and consumption practices prioritizing low-carbon alternatives. The transport sector in these nations contributes significantly to CO_2 emissions, an organized tax system should be introduced to minimize the consumption of fossil fuels and encourage the use of low-emission automobiles. This will assist selected countries in meeting their objective of sustainable development goals.

Third, these nations should prioritize ecological concerns through trade globalization, which is critical for achieving global sustainability. Decision makers and governments should implement environmental rules, such as limiting CO_2 emissions, regulating trade activities that consume energy and emit pollutants, and managing technology transfers. Simultaneously, policymakers should have greater participation in regional and global markets to encourage importing technology based on nuclear and renewable energy resources and investment in sustainable manufacturing and energy. These actions will help maintain eco-efficiency and improve environmental quality while boosting global economic growth and development.

Although the analysis provides compelling and convincing outcomes, it has limitations. Therefore, it highlights the need for further research to build upon these findings and explore the topic in greater depth. Firstly, future investigations could explore alternative energy sources and the means to meet their growing demand by developing new policies and providing financial support. Secondly, future studies should consider additional environmental indicators, such as load capacity factors and ecological footprint. Finally, it would be intriguing to assess the environmental implications of nuclear energy in both other developing and developed nuclear-based nations.

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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.

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