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Original Article

How do nuclear energy and stringent environmental policies contribute to achieving sustainable development targets?

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ABSTRACT

In order to achieve sustainable development that balances economic growth, environmental protection, and social well-being and ensures a sustainable future, strict environmental regulations and sustainable nuclear energy production may play a vital role. Empirical works are insufficient when measuring the effects of strict environmental policies and nuclear energy production on sustainable development. This research aims to close this gap by examining how environmental policy stringency and nuclear energy production contribute to sustainable development in the top 17 nuclear energy-generating countries between 1995 and 2021. The research uses the linear and nonlinear CS-ARDL and PMG-ARDL models to achieve this goal. The linear model suggests that environmental policy stringency and nuclear energy production contribute to long-term sustainable development. In the nonlinear model, a positive change in environmental policy stringency and nuclear energy production causes long-run sustainable development to grow, while a negative change in environmental policy stringency and nuclear energy production hinders long-run sustainable development. Furthermore, environmental technologies, human capital, financial development, trade liberalization, and research and development expenditures are crucial for fostering long-run sustainable development. In contrast, the natural resource rents hurt sustainable development. These findings suggest that policymakers should consider combining strict environmental regulations and nuclear energy in devising policies for sustainable development.

1. Introduction

Environmental deprivation, combined with rising greenhouse gas (GHG) emissions, has become a great concern for humanity, as these factors significantly impact human health and economic development. Environmental pollution has become a worldwide problem [1]. The United Nations (UN) in 2020 warned about the severity of the environmental catastrophes and predicted that these events will occur more often if the economies fail to meet their preferred environmental quality turnaround obligations. The UN further elaborated that if the world, as a whole, did not take care of these issues sincerely and aggressively enough to adopt suitable actions, the damage done by climate change would be more severe than the COVID-19 epidemic [2]. The countries are in the contest to achieve rapid economic development. Accordingly, energy consumption is on the rise, resulting in global warming and environmental change. According to the IEA [3] report, the energy sector accounts for 20 percent of GHG emissions and roughly 80 percent of carbon dioxide gas emissions. The IEA [4] report highlighted that the global energy sector's carbon emissions rose from 20,521 million tonnes in 1990 to 32,840 million tonnes in 2017.

Environmental policy stringency is one of the significant environmental policy tools employed to deal with environmental issues. A stringent environmental policy encourages sustainable development by minimizing negative externalities [5]. It is hard to endorse green technology for sustainable development without implementing strict environmental rules and regulations. Strict environmental policies are also vital in complementing other policies intended to reduce CO2 emissions, such as renewable energy development [6]. Thus, environmental policy

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stringency helps in reducing CO2 emissions, promoting green energy, and maintaining environmental sustainability. According to Elkins and Baker [7], environmental taxes can solve ecological problems through increasing clean energy utilization incentives. Literature introduced various kinds of environmental taxes, i.e., fuel, carbon, and energy taxes, to decrease environmental pollution [8]. The carbon tax is essential because it scrutinizes carbon emissions [9]. The effect of the carbon tax on CO2 emissions has been examined in most studies [10]. Some of these studies confirmed the positive role of environmental taxes in reducing carbon emissions [11].

Another important determinant is nuclear energy, which contributes to climate change mitigation and promoting sustainable development. It harnesses energy through nuclear reactions, generating heat that converts water into steam, driving turbines to produce electricity [12]. This form of energy can be derived from fusion, fission, or nuclear decay reactions [13], presenting a viable alternative to fossil fuels. Although it's not a perfect substitute for transportation, nuclear energy offers significant potential for powering vehicles and trains, making it a potent alternative to fossil fuels, especially in power generation. Prior studies documented that nuclear energy is rapidly substituting fossil fuel-based energy worldwide in developed and developing nations [14]. Transitioning from conventional energy sources to nuclear power is anticipated to alleviate the demand for crude oil and curb greenhouse gas emissions, thereby safeguarding the environment [15]. Several countries, including France, Russia, China, and India, have embraced nuclear energy as a key component of their energy strategies. The debate surrounding nuclear energy's acceptability and suitability continues, with limited efforts to assess its impact on sustainable development. This complexity arises from the multifaceted nature of nuclear energy [16]. On the one hand, it claims to lower greenhouse gas emissions, aligning with environmental sustainability goals. On the other hand, it poses risks such as potential environmental contamination and long-term radioactive hazards, highlighting the need to consider its pros and cons carefully.

Nuclear energy is widely believed to be a carbon-free and reliable source of energy, while environmental policy stringency plays a supportive role alongside other mitigating channels [17]. On the other hand, sustainable development is still a hot issue for world leaders and policymakers. Despite the success of nuclear energy and environmental policy stringency in dealing with the environmental aspect of sustainable development, their role is still a puzzle in achieving sustainable development's social and economic aspects. Therefore, the important research question in front of this analysis is how nuclear energy and environmental policy stringency help achieve sustainable development goals. Since nuclear energy is widely believed to be a low-carbon, sustainable, and reliable source of energy [18], its role is important in fulfilling the global energy demand without damaging the environment. Moreover, the role of environmental policy stringency can't be overlooked in controlling the negative externalities linked to economic activities [19]. Accordingly, the research questions this study wants to address are whether nuclear energy and environmental policy stringency help achieve sustainable development objectives.

Ever since the UN unearthed its 2030 sustainable development agenda, the focus of researchers has shifted toward finding the factors that are helpful to fulfill this agenda. A growing body of empirical studies has shed light on various determinants of sustainable development such as renewable and non-renewable energy, ICT, human capital, governance, energy efficiency, and financial development, among others. However, the role of stringent environmental policy and nuclear energy as determinants of sustainable development has yet to be analyzed. Despite the significance of environmental policy stringency [20] and nuclear energy [17], contributors to environmental performance are just one dimension of sustainable development. Thus, we need empirical evidence to estimate the influence of environmental policy stringency and nuclear energy on sustainable development in the world's leading nuclear energy-producing economies.These economies include countries like the United States, France, China, Russia, Germany, etc., which are the major nuclear energy-generating economies and the world leaders in socio-economic development. In addition, the share of these economies in global CO2 emissions is enormous, and they are global leaders in implementing environmental rules and regulations. This research has made a significant contribution to addressing these gaps. Firstly, it untangles the effects of environmental policy stringency and nuclear energy on sustainable development. Secondly, the study offers a robust empirical analysis through the rigorous application of the CS-ARDL model. This approach provides both the long-run and short-run effects. Lastly, the findings of this study may hold crucial policy implications. Understanding the influence of environmental policy and nuclear energy on sustainable development in top nuclear energy-producing economies could help achieve sustainable development goals at the global level.

This paper includes several sections. Section 2 outlines the theoretical framework and model, while Section 3 justifies econometric techniques. Section 4 contains information about data and variables. Section 5 sheds light on the results and discussions. Last but not least, section 6 provides a conclusion and policy implications.

2. Theoretical framework and model

2.1. Theoretical framework and hypothesis development

It is widely believed that environmental policies try to protect the ecosystem and foster sustainable development by controlling irresponsible behavior of the countries and people towards the environment. Theoretically, environmental policies impact sustainable development in either way, i.e., positively or negatively, through the following two mechanisms. First, there is a "cost effect". This refers to an increase in the firm's total expenditures due to the implementation of environmental regulations because in order to step up their environmental governance efforts, they have to spend a lot of money to upgrade their manufacturing techniques in line with environmental standards [21]. The increased governance cost may significantly reduce the investment made by the firms in their production and operational activities, which impedes the firm's technical advancement and reduces the competitiveness of businesses' products [22]. Consequently, environmental policies through "cost effect" may harm sustainable development by swelling the production and governance costs of the firms.

The second is the "innovation compensation effect". In order to overcome the competitive disadvantage due to rising pollution control expenses and dwindling earnings, firms and enterprises spend more on technological development and try to improve product technology [23]. Next, entrepreneurs try to make eco-friendly and green innovations, improve their competitive position, and benefit from creative compensation. The efforts on behalf of entrepreneurs to innovate in terms of technology and products are more likely to provide economic and environmental advantages alongside enhancing production efficiency. As per the "Porter Hypothesis," appropriate environmental policies may ultimately overcome their costs, leading to a situation where economic and environmental objectives can be achieved simultaneously [24]. Thus, "innovation compensation effect," which emerges due to improved and strict environmental policies, may offset the governance cost and positively impact sustainable development.

Due to the severity of climate change and global warming, the targets of sustainable development are becoming more and more difficult to achieve. Therefore, researchers have investigated the role of clean energy and low-carbon energy sources in promoting sustainable development and limiting CO2 emissions. Nuclear energy is widely recognized as a low-carbon source of energy [25]. Carbon and other greenhouse gas emissions are considered the primary hurdles in the way of achieving sustainable development goals; therefore, cutting these emissions is the primary motive of the power sector. Energy produced by fossil fuels (e.g., coal, oil, gas) is considered one of the main factors contributing to carbon and other greenhouse gas emissions, which promotes the development of clean energy technologies [26]. Since nuclear energy is a part of clean energy, studies are on the rise that have examined the significance of nuclear energy in damaging the environment and promoting economic growth [27]. Compared to other renewable energy sources, nuclear energy is believed to be a carbon-free energy source, significantly contributing to the mitigation of CO2 emissions in the ultimate clean energy scenario [28]. Consequently, the role of nuclear energy is vital in achieving sustainable development goals. However, this notion is opposed by Sovacool et al. [29], who provided an alternative perspective on this relationship. The study highlights that nuclear energy does not help achieve sustainable objectives because it does not reduce carbon footprints and is incompatible with green energy sources. They further stated that nuclear energy initiatives may exacerbate carbon emissions, particularly in developing economies. Theoretical debate on the role of nuclear energy in achieving sustainable objectives is not conclusive; however, there is consensus among researchers and theorists that a definite linkage exists between nuclear energy and sustainable development objectives. Thus, the study hypotheses are as follows.

Hypothesis 1. Strict environmental policies stimulate sustainable development.

Hypothesis 2. Nuclear energy positively impacts sustainable development

2.2. Model formulation within theoretical boundaries

According to the command and control regulation theory [30], to achieve sustainability objectives, it is suggested that authorities should implement strict regulations and enforce them via the imposition of fines, penalties, and other measures. This theory's primary purpose is to ensure that regulated enterprises perform their operations according to environmental standards. This notion states that the major benefit of implementing environmental regulations is that they force industries to undertake measures to upgrade their production methods as per the prescribed environmental norms. The industry feels obligated to transition towards eco-friendly innovative products in response to environmental regulations. Further, the industry improves its manufacturing lines per the requirement of green development, which helps achieve sustainable development.

A sustainable environment can also be achieved with the help of more advanced technology and the implementation and adoption of green production ideas. The ecological moderanization theory [31] proposes that firms should be given incentives to implement ecologically responsible methods of market mechanisms, legislative procedures, and cultural beliefs. The main idea behind this theory is that instead of abandoning the processes that harm the environment, it is better to transform these processes as per the eco-friendly guidelines to make them low-carbon, like green industrial production via the use of renewable energy and nuclear energy technologies and innovations. Although nuclear energy is controversial in many aspects, it is widely believed to be a low-carbon source of energy [32]. The widespread adoption of nuclear can increase the share of low-carbon energy in the total energy mix of the nations. By increasing the use of low-carbon energy in industries can help transform their production processes into green and eco-friendly, which are instrumental in achieving sustainable development.

The human capital theory [33] postulates that in order to earn more income and enhance their job options, people must invest more resources in their education and skills development. Workers who are more interested in learning skills and work ethics that align sustainability and eco-management are more likely to have a favorable impact on sustainable development. According to this theory, human capital helps foster green technological development as well as eco-friendly industrial upgrades, resulting in sustainable growth [34]. Thus, as per this theory, investing more in human capital makes the transition toward sustainable development smooth and swift. In the context of green innovation theory [35], environmental technology is an important factor in the green economy. This theory also underscores the significance of collaboration between all concerned stakeholders, i.e., government and other regulatory bodies, in the development of green innovations and sustainable business practices.

The resource curse theory [36] postulates that countries with abundant natural resources, such as minerals, oil, and gas, tend to grow slowly as compared to the nations that don't have abundant natural resources. This is because accumulation of wealth and power related to natural resource rents may give rise to corruption and disproportionate distribution of resources that are hurdles to sustainable development [37]. The theory of sustainable finance highlights that the development of the financial sector can help achieve sustainable development objectives by using green investment and financial products. Financial development plays a vital role in the collection of funds and then helps transfer these funds to green projects. Growth of the financial sector has a crucial role in supporting R&D activities, entrepreneurial plans, and technological transfer [38], which is crucial for developing green innovations. Thus, the growth of the financial sector addresses issues related to the environment without giving up economic objectives by adopting green production and consumption practices [39].

Trade liberalization is crucial in fostering growth and development-related activities [40]. As a result of trade liberalization, consumers can enjoy a wide variety of products, while the producers can sell their items in a much bigger market. The comparative advantage theory states that international trade can bring several economic advantages. However, it can be detrimental to environmental sustainability. According to the pollution Haven Hypothesis [41], the developing economy becomes the house of dirty production and manufacturing activities due to weak environmental policies. Thus, international trade can impede sustainable development objectives if not complemented by strict environmental regulations. However, the pollution Halo Hypothesis states that international trade can help transfer technology from advanced to emerging economies that can contribute to sustainable development [42]. Therefore, the empirical model incorporates sustainable development as a function of stringency in environmental policy, nuclear energy, environmental technology, human capital, R&D, financial development, trade, and natural resources. This model is constructed under theoretical frameworks. The econometric representation of the model's functional form is provided in equation (1):

$$SD_{it} = \eta_0 + \eta_1 EPS_{it} + \eta_2 NEP_{it} + \eta_3 ET_{it} + \eta_4 HC_{it} + \eta_5 RD_{it} + \eta_6 FD_{it} + \eta_7 Trade_{it} + \eta_8 NRR_{it} + \varepsilon_{it} \tag{1}$$

Where sustainable development (SD) is dependent on environmental policy stringency (EPS), nuclear energy production (NEP), environmental technology (ET), human capital (HC), research and development (RD), financial development (FD), trade openness (Trade), natural resources rents (NRR). In this equation (1), 'i' represents individual cross-sectional units, while 't' signifies time periods. The symbol η_0 represents the constant term, and η 1, η 2, η 3, η 4, η5, η6, η 7, and η 8 represent the coefficients for each respective variable. The variable ε_{it} denotes the error term.

3. Econometric techniques

3.1. Cross-sectional dependence and slope homogeneity

In almost every study that has applied panel data, checking cross-sectional dependence has become a norm due to the high chances of dependency in the data across different cross-sectional units. One of the primary reasons recorded for this dependency is some concealed factors and interrelated shocks that may result in the presence of "error term, spatial dependence, and idiosyncratic pairwise dependency" in variations, regardless of any explicit arrangement of shared traits or spatial associations [43]. In the past two decades, the dependency between the nations has increased manifold due to their connection in the economic and financial spheres, leading to a high level of dependency in the cross-sections in the panel data. Therefore, before estimating the impact of EPS and NEP on SD, we need to do some preliminary tests. First of these tests is to see whether residuals in our data are cross-sectionally dependent; for this purpose, we employ the Pesaran [44] test.

In addition to cross-sectional dependence, the subsequent test is the test of slope heterogeneity of Pesaran and Yamagata [45], which is to check if there is consistency in slopes across the investigated panel units. Following the literature, this analysis employs the Pesaran and Yamagata [45] test of slope heterogeneity because it provides correct results if cross-sectional dependence exists instead of outdated tests like SURE that can't account for the issue of cross-sectional dependence [46].

3.2. Unit root tests and cointegration test

Making true decisions regarding the stationary properties of the variables is crucial for selecting an appropriate regression approach. For instance, techniques like CS-ARDL and PMG-ARDL do not need variables to be stationary at the second difference or I(2); however, panel approaches, including AMG and DCCE require all variables to be integrated of order one or I(1) [47]. Two of the most famous panel unit root tests are the CIPS and CADF. These tests are employed in this analysis as they are famous for detecting correct stationary properties of the series used in the analysis, even if there are signs of cross-sectional dependence in selected series.

Determining the long-term nexus between EPS, NEP, and SD, also known as cointegration, is the last crucial step before we move towards our main estimation technique. The cointegration analysis is crucial because one of the study's main objectives is to estimate the long-run relationship between the selected variables, enabling policymakers to develop more effective strategies. Since the first-generation cointegration tests cannot handle issues such as cross-sectional dependence, slope heterogeneity, and structural breaks; thus, they may produce erroneous results. To deal with these issues, this study applies the Banerjee & Carrion-i-Silvestre [48] cointegration test, which has the power to deal with the issues of cross-sectional dependence, slope heterogeneity, as well as with unidentified changes in both the intercept and the slope in the cointegrated regression, which is not same across all cross-sections.

3.3. CS-ARDL

This study has applied Chudik and Pesaran's (55) CS-ARDL approach, which is a reliable and advanced procedure for analyzing the short- and long-run effects of EPS and NEP on SD. Several panel cointegration techniques have been proposed; however, the CS-ARDL surpasses all these techniques in providing accurate estimates. It possesses superior traits to counter issues like slope heterogeneity, endogeneity, and cross-sectional dependence. Moreover, the CS-ARDL is a robust estimator when the series we are working on are either I(0), I(1), or a mixture of both. To remove the cross-sectional dependence, this technique utilizes cross-sectional averages. The primary equation (2) representing the CS-ARDL is shown below:

$$\Delta SD_{i,t} = \varnothing_i + \sum_{l=1}^{p} \theta_{il}\Delta SD_{i,t-l} + \sum_{l=0}^{p} \theta_{il}^{'}X_{i,t-l} + \sum_{l=0}^{1} \theta_{il}^{'}\overline{Z}_{i,t-l} + \mu_{i,t} \tag{2}$$

Where $\overline{Z}_t = (\overline{SD_t}\,.\,\overline{Y_t})$ and $X_{it} = (EPS_{it} + NEP_{it} + ET_{it} + HC_{it} + RD_{it} + FD_{it} + Trade_{it} + NRR_{it})^{'}$, and X highlights the vector that caries all the regressors. Until we check the robustness of our main results by applying another econometric approach, our results are not authenticated. Following the literature, we used PMG-ARDL estimator of Pesaran et al. [49] to support our main technique, i.e., the CS-ARDL. The FMOLS and CCEMG methods do not yield short-term results but capture cross-sectional dependence. However, PMG-ARDL estimates both long and short-term results while ignoring cross-sectional dependence. Therefore, to compare short- and long-term outcomes, we employed PMG-ARDL. The PMG approach combines information across several panel units and allows for varying coefficients in these panel units. This technique handles the autocorrelation in the residuals by pooling data from several panel units to take advantage of the time and space characteristics of the panel data. In the PMG-ARDL, the dynamic impacts are incorporated by including a lagged response variable. This inclusion of a lagged response variable plays a critical role in controlling endogeneity by scrutinizing the link between the past and current values of the response variable. Moreover, it can successfully estimate the short and long-run nexus between the variables at once, and it can handle series that are either stationary or contain the unit root, i.e., either I(0), I(1), or their mixture. Both are efficient estimators in dealing with small samples. Therefore, the application of PMG-ARDL is justified alongside the CS-ARDL framework.

Checking asymmetry in the impacts of EPS and NEP on sustainable development is another goal of the analysis. To attain this goal, we separate the original EPS and NEP series into positive and negative series by implementing the partial sum technique of Shin et al. [50]. As a result, the nonlinear versions of CS-ARDL and PMG-ARDL have also been applied to reach this goal. A limitation of the linear models is that they cannot detect short-term unpredictability and structural breaks, a permanent feature of the long series. Likewise, Shin et al. [50] clearly stated that the linear models only efficiently capture the linear link between variables; however, the macro-variables in most instances move non-linearly. As a result, Usman et al. [19] shed light on the importance of nonlinear modeling by stating that variables or series that are impacted by human behavior are normally non-linear in nature. Further, non-linear models are much more powerful in explaining the link between the variables than linear ones [51]. In light of the limitations attached to the linear model, we also decided to apply the non-linear model. Implementing linear and nonlinear analysis side by side is as per the literature [52]. This helps us make a comparison between linear and non-linear estimates and lets us decide which results are more reliable and significant.

4. Data and descriptive analysis

The main goal of this study is to assess how environmental policy stringency and nuclear energy production impact the sustainable development of the top 17 nuclear energy-generating countries[1] between 1995 and 2021. Sustainable development (SD) is proxied by using adjusted net savings (ANS). Data on sustainable development is sourced from the World Development Indicators (WDI). This indicator is widely recognized as the most practical proxy for sustainable development [53, 54] as it is made up of several indicators covering the economic, social, and environmental aspects of sustainable development. In order to obtain adjusted net savings (ANS), the World Bank has made several adjustments in gross national savings (GNS), such as subtracting the use of produced capital, depletion of natural resources, CO2 emissions, adding the government spending on human capital, and divided them by the GNI. Thus, ANS is the best measure to represent sustainable development. Our independent variables include environmental policy stringency (EPS) and nuclear energy production (NEP). EPS refers to the environmental regulations related to emissions, pollution control, natural resource conservation, and overall environmental sustainability [55]. Our study measures it using the environmental stringency index that the OECD formulates. This variable is commonly used in energy and environment literature [56]. Nuclear energy production plays a pivotal

[1] China, USA, India, Japan, Germany, Canada, Brazil, France, Spain, Netherlands, Czechia, Belgium, Hungary, Finland, Switzerland, Sweden, Slovenia.

Table 1
Descriptive statistics and definitions.

Variable	Definitions	Sources	Mean	Std. dev.	Min	Max
SD	Adjusted net savings, excluding particulate emission damage (% of GNI)	WDI	2.344	0.557	−0.431	3.336
EPS	Environment policy stringency index	OECD	2.320	1.116	0.000	5.056
NEP	Total energy production from nuclear (quad Btu)	EIA	1.196	2.019	0.000	8.459
ET	Environmental related technologies (total patents)	OECD	6.737	1.980	2.639	10.68
HC	School enrollment, secondary (% gross)	WDI	4.642	0.232	3.762	5.117
RD	Research and development expenditure (% of GDP)	WDI	2.029	0.851	0.488	3.874
FD	Financial development index	IMF	0.671	0.182	0.279	1.000
Trade	Trade (% of GDP)	WDI	4.201	0.617	2.750	5.151
NRR	Total natural resources rents (% of GDP)	WDI	0.949	1.423	0.008	9.648

role in mitigating climate change and fostering sustainable development [57]. Nuclear energy production (NEP) is measured by total energy production from nuclear in quad Btu and was previously used by Tugcu & Menegaki [58]. This data series is compiled from the EIA.

This study includes six control variables in the model such as environmental technology (ET), human capital (HC), research and development (RD), financial development (FD), trade openness (trade), and natural resources rents (NRR). Environmental-related technologies measure environmental technology in terms of total patents, and data is sourced from the OECD. Environmental technologies are vital in the development of a low-carbon economy; therefore, its role can't be overlooked in achieving sustainable development [59]. Human capital is assessed through gross percent of secondary school enrollment. Human capital significantly improves the efficiency of the production process, reducing resource wastage and mitigating environmental pollution [60]. Therefore, it's role is important in achieving sustainable development. Research and development expenditures are taken as percent of GDP, which are vital for fostering green innovations and energy-efficient techniques of production. This can enhance energy efficiency in every sector of the economy by promoting sustainable development [28]. Data series for human capital and research and development expenditures are taken from the WDI. Financial development is measured by an index, which the IMF formulates. Financial development helps achieve sustainable development objectives by providing financial capital for green ventures and renewable energy development [61]. Both series ' trade and natural resource rents are taken as a percentage of GDP, and data for both variables is collected from the WDI. Trade ensures the transfer of green technologies between partner countries, which helps achieve sustainable development [62]. Resource curse due to the natural resource earnings can adversely influence sustainable development objectives [63].

Data details and descriptive statistics are reported in Table 1. Descriptive statistics report the output for mean and standard deviations of variables. The mean scores are reported as: 2.344 for SD, 2.320 for EPS, 1.196 for NEP, 6.737 for ET, 4.642 for HC, 2.029 for RD, 0.671 for FD, 4.201 for Trade, and 0.949 for NRR. The S.D are displayed as: 0.557 for SD, 1.116 for EPS, 2.019 for NEP, 1.980 for ET, 0.232 for HC, 0.851 for RD, 0.182 for FD, 0.617 for Trade, and 1.423 for NRR.Table 2 presents the correlation matrix results for the variables under consideration, demonstrating the absence of multicollinearity issues within the model variables. Additionally, Table 3 reaffirms the absence of severe multicollinearity in the estimation, as none of the VIF values exceed 10.

5. Empirical results and discussion

Table 4 displays the results of the cross-sectional dependency analysis, which aims to assess whether there is any sign of interdependence or connection in our data set. Findings of the Pesaran [22] CSD test confirm that probability values attached to each of the variables (EPS, NEP, ET, HC, RD, FD, Trade, NRR) are less than 0.01, indicating a statistically significant cross-sectional dependence.These findings show that our dataset contains evidence of cross-sectional dependency. This highlights the need to use second-generation unit root tests like CIPS and CADF, which provide precise findings even if the cross-sectional dependency exists. Table 5 displays the findings of a slope homogeneity test. This test is based on two statistics: delta and delta-adjusted. The results confirm that both these tests are significant, confirming evidence of heterogeneity in the slopes of various cross-sections.

Table 6 displays the results of unit root testing for different variables. Two-panel unit root tests are employed to check the stationary properties of the variables. The results indicate that the variables are integrated either into order 0 (I(0)) or order 1 (I(1)). For instance, except for the variables FD and NRR, which are I(0), all other variables SD, EPS, ET, HC, RD, and Trade are I(1) as per the findings of both CIPS and CADF tests. However, the variable NEP is I(1) in CIPS, while I(0) in CADF.

After we observe the stationary qualities of the variables, the cointegration test is used to examine the validity of the long-run connection between the variables. For this analysis, we apply the Banerjee & Carrion-i-Silvestre [48] cointegration test that provides accurate results by accounting for cross-sectional dependence, slope heterogeneity, and unidentified changes in both intercept and slope in cointegrated regression that varies across cross-sections. Table 7 highlights the results of this test, confirming the cointegration between the variables in all three cases i.e. no deterministic specification, with constant, and with trend. Thus, we can confirm the existence of a valid long-run link between SD, EPS, NEP, ET, HC, RD, FD, Trade, and NRR.

The linear short and long-run estimates utilizing CS-ARDL and PMG-ARDL methods are explained in Table 8. First, the long-run estimates are discussed. The long-run calculated coefficient associated with EPS has

Table 2
Correlation matrix.

	SD	EPS	NEP	ET	HC	RD	FD	TRADE	NRR
SD	1								
EPS	0.088	1							
NEP	0.286	0.056	1						
ET	0.355	0.047	0.597	1					
HC	0.117	0.310	0.044	−0.140	1				
RD	0.018	0.588	0.297	0.185	0.425	1			
FD	0.020	0.377	0.403	0.449	0.177	0.484	1		
Trade	0.175	0.357	−0.487	−0.608	0.360	0.055	−0.151	1	
NRR	0.184	−0.414	−0.097	0.124	−0.442	−0.399	−0.110	−0.320	1

Table 3
VIF results.

Variable	VIF	1/VIF
Trade	2.79	0.359
ET	2.70	0.370
RD	2.14	0.467
EPS	2.01	0.497
NEP	1.83	0.548
FD	1.75	0.573
HC	1.54	0.649
NRR	1.52	0.657
Mean VIF	2.03	

significantly and favorably impacted SD in CS-ARDL and PMG-ARDL models. More specifically, in the CS-ARDL and PMG-ARDL models, the SD will profit by 0.980 % and 0.282 % for every 1 % increase in EPS. This result validates hypothesis 1, and Porter's theory also backs the EPS result [24]. This theory suggests that stringent environmental regulations drive green innovation and competitiveness, achieving sustainable development.This outcome aligns with the conclusions drawn by D'Amato et al. [57], who observed a favorable influence of stringent environmental policies on sustainable development in China. Environmental policy stringency plays a pivotal role in fostering a stable and sustainable environment, enabling investments, encouraging innovation, and supporting environmental conservation. In addition to superior environmental performance, these changes caused by strict environmental policies also help promote new economic possibilities and develop some additional sectors, creating new jobs and promoting economic development. These empirical inferences are also backed by Mahalik et al. [20], who noted that environmental policy stringency is crucial in addressing sustainable development's environmental, social, and economic aspects, and the positive connection between these factors is justified. These policies are essential in accelerating progress toward achieving environmental, social, and economic sustainability goals [64]. High levels of environmental policy stringency provide a clear framework for businesses and investors by encouraging long-term investments in sustainable development projects. The empirical inferences noted that stringent environmental policies drive environmental innovations necessary for sustainable development. By setting high standards and encouraging research and development, these policies stimulate creativity and promote the invention of cleaner technologies and eco-friendly solutions. The research by Mihai et al. [65] supported our results and noted that stringent environmental policies reinforce social welfare programs by ensuring a healthy and safe community environment. This, in turn, promotes sustainable development.

Furthermore, a favorable correlation between NEP and SD is observed in the long run. Quantitatively, if the NEP improves by 1 %, the SD will increase by 0.748 % and 0.430 % in the CS-ARDL and PMG-ARDL models, respectively. Our result confirms hypothesis 2. This result is also supported by Grubler's Energy Transition Theory [66]. This result coincides with the research conducted by Kok & Benli [67], who noted a positive association between nuclear energy and sustainable development. This infers that nuclear energy reduces a country's dependence on imported fossil fuels, enhancing energy security. Energy security reduces the economic risks associated with energy supply disruptions and price fluctuations, ensuring a stable environment for sustainable development. The increased production of nuclear energy has the dual benefits of promoting environmental and economic performance. Indeed, nuclear energy plays a crucial role in achieving superior environmental quality, its success largely relies on the nation's economic categorization and socioeconomic factors that with the help of energy policy, promote sustainable development goals. Similar result is also found by Caglar [68] for UK. In order to address economic, social, and environmental hurdles, nuclear energy-based technological innovations may turn vital. Furthermore, recent research conducted by Bandyopadhyay & Rej [69] demonstrated that the nuclear industry generates green economic activities, providing both direct and indirect economic benefits that lead to sustainable development. The results also infer that nuclear energy facilitates the transition to industrialization and modernization by providing a reliable source of electricity. Nuclear power supports the growth of industries, infrastructure development, and urbanization. This transition is essential for overall sustainable development.

Similarly, we see that in some models, SD is positively and significantly connected to ET, HC, RD, and FD, while negatively and significantly connected to NRR. For example, a 1 % increase in ET leads to an increase in SD by 0.104 % and 0.149 % in the CS-ARDL and PMG-ARDL models. Likewise, for every 1 % rise in the HC, the SD improves by 0.998 % and 1.498 %; every 1 % increase in RD leads to an increase in SD by 1.415 % and 1.428 %; every 1 % rise in FD leads to a rise of 0.896 % and 0.918 % in SD, in the CS-ARDL and PMG-ARDL models, respectively. In contrast, in the CS-ARDL and PMG-ARDL models, a 1 % increase in NRR causes 0.519 % and 0.233 % fall in SD. In the short run, the estimates are mostly insignificant. However, the error correction terms are negatively significant, confirming that variables will converge toward long-run equilibrium at the pace of 25 % and 18 % per annum in the CS-ARDL and PMG-ARDL models, respectively.

Table 9 provides the nonlinear short-and long-run estimates using

Table 5
Slope homogeneity test.

	Delta	p-value
$\hat{\Delta}$	10.61***	0.000
$\hat{\Delta}_{adjusted}$	13.40***	0.000

Table 6
Panel unit root tests.

	CIPS		CADF	
	I(0)	I(1)	I(0)	I(1)
SD	−1.256	−3.990***	1.015	−12.01***
EPS	−0.786	−5.273***	0.345	−17.90***
NEP	−1.635	−5.611***	−3.037***	
ET	−0.682	−2.595***	0.129	−8.795***
HC	−1.289	−3.952***	1.038	−11.91***
RD	0.009	−3.221***	3.367	−8.406***
FD	−2.613***		−5.222***	
Trade	1.770	−4.945***	−16.51***	
NRR	−2.365***		−4.212***	

Table 7
Banerjee & Carrion-i-Silvestre cointegration test.

No deterministic specification	−5.211***
With constant	−4.244***
With trend	−5.879***

Table 4
Cross-section dependence test.

	SD	EPS	NEP	ET	HC	RD	FD	Trade	NRR
Pesaran's test	4.257***	10.03***	5.757***	9.992***	4.148***	0.640	10.52***	7.490***	9.010***
Prob	0.000	0.000	0.000	0.000	0.000	0.522	0.000	0.000	0.000
off-diagonal elements	0.326	0.378	0.363	0.347	0.425	0.398	0.4	0.331	0.334

Table 8
Linear CS-ARDL and PMG-ARDL

	CS-ARDL				PMG-ARDL			
Variable	Coef.	Std. Err.	z-stat	P > z	Coef.	Std. Err.	t-Stat	Prob.*
Long-run								
EPS	0.980***	0.229	4.280	0.000	0.282***	0.040	7.117	0.000
NEP	0.748***	0.176	4.253	0.000	0.430***	0.163	2.630	0.009
ET	0.104**	0.051	2.032	0.043	0.149*	0.076	1.953	0.052
HC	0.998***	0.361	2.766	0.006	1.498***	0.408	3.674	0.000
RD	1.415***	0.336	4.211	0.000	1.428***	0.213	6.707	0.000
FD	0.896**	0.374	2.397	0.017	0.918***	0.330	2.781	0.006
Trade	0.291	0.212	1.374	0.170	0.215	0.200	1.076	0.283
NRR	−0.519***	0.174	−2.982	0.003	−0.233***	0.054	−4.311	0.000
Short-run								
D(EPS)	0.019	0.229	0.080	0.933	0.093	0.069	1.337	0.182
D(NEP)	0.144	0.140	1.029	0.304	0.665	1.391	0.478	0.633
D(ET)	1.126	0.850	1.330	0.185	0.020	0.121	0.167	0.868
D(HC)	0.120	0.430	0.279	0.781	0.633	1.201	0.527	0.599
D(RD)	0.064	0.524	0.120	0.902	0.375	0.337	1.114	0.267
D(FD)	0.382	0.322	1.188	0.236	0.236	0.289	0.815	0.416
D(Trade)	0.760	2.217	0.340	0.732	0.531	0.405	1.312	0.191
D(NRR)	0.447	1.956	0.230	0.819	1.086	1.116	0.972	0.332
C					-3.441***	0.824	−4.176	0.000
ECM(-1)	−0.250***	0.097	−2.582	0.010	−0.179***	0.040	−4.429	0.000

Note: ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

the CS-ARDL and PMG-ARDL approaches. Once again, we consider long-run estimates first. The SD in the CS-ARDL and PMG-ARDL models has been positively and considerably affected by the long-run estimated coefficients linked to EPS_POS and EPS_NEG. More precisely, for every 1 % rise in EPS_POS, the SD will benefit by 0.959 % and 0.305 % in the CS-ARDL and PMG-ARDL models, respectively, and for every 1 % rise in EPS_NEG, the SD falls by 0.081 % in the CS-ARDL model. Moreover, a long-term positive connection between NEP_POS and SD and NEP_NEG and SD is shown. In the CS-ARDL and PMG-ARDL models, the SD will rise by 0.387 % and 0.356 % if the NEP_POS increases by 1 %, while the SD models fall by 0.160 % for every 1 % rise in EPS_NEG in the CS-ARDL model. In addition, SD has a negative and significant relationship with NRR but a positive and significant relationship with ET, HC, RD, FD, and Trade. For instance, in the CS-ARDL and PMG-ARDL models, a 1 % increase in ET causes a 0.432 % and 0.245 % rise in SD, respectively. Similarly, in the CS-ARDL and PMG-ARDL models, the SD increases by 1.126 % and 1.472 % for every 1 % increase in HC; the SD improves by 0.403 % and 1.043 % for every 1 % increase in Trade. However, the SD increases by 0.642 % and 0.610 %, only in the CS-ARDL model, for every 1 % increase in RD and FD, respectively. In contrast, a 1 % increase in NRR results in a fall in SD by 0.099 % and 0.079 % in the CS-ARDL and PMG-ARDL models, respectively. The estimations are mostly insignificant in the short term except for the estimates of D(EPS_POS), D(RD), and D(Trade) are positively significant. The error correction terms in the

Table 9
Nonlinear CS-ARDL and PMG-ARDL

	CS-ARDL				PMG-ARDL			
Variable	Coef.	Std. Err.	z-stat	P > z	Coef.	Std. Err.	t-Stat	Prob.*
Long run								
EPS_POS	0.959***	0.118	8.130	0.000	0.305***	0.045	6.780	0.000
EPS_NEG	0.081**	0.033	2.486	0.014	0.023	0.154	0.147	0.883
NEP_POS	0.387**	0.160	2.414	0.017	0.356*	0.210	1.695	0.087
NEP_NEG	0.160*	0.089	1.797	0.073	0.137	0.267	0.515	0.607
ET	0.432***	0.147	2.940	0.004	0.245***	0.050	4.948	0.000
HC	1.126**	0.471	2.391	0.018	1.472***	0.264	5.567	0.000
RD	0.642**	0.319	2.014	0.045	0.034	0.109	0.312	0.755
FD	0.610**	0.246	2.484	0.014	0.214	0.329	0.650	0.516
Trade	0.403*	0.223	1.806	0.072	1.043***	0.183	5.689	0.000
NRR	−0.099***	0.030	-3.307	0.001	−0.079***	0.021	−3.678	0.000
Short Run								
D(EPS_POS)	0.273***	0.082	3.341	0.001	0.149***	0.050	3.010	0.003
D(EPS_NEG)	0.480	0.636	0.760	0.450	0.180	0.342	0.526	0.600
D(NEP_POS)	0.011	0.021	0.528	0.598	0.609	2.461	0.247	0.805
D(NEP_NEG)	0.017	0.025	0.681	0.497	0.825	2.051	0.402	0.688
D(ET)	0.135	0.211	0.640	0.519	0.038	0.091	0.418	0.676
D(HC)	0.148	0.124	1.194	0.234	0.710	1.801	0.394	0.694
D(RD)	0.965**	0.462	2.088	0.034	0.606*	0.333	1.817	0.071
D(FD)	0.517	0.930	0.560	0.578	0.346	0.401	0.864	0.388
D(TRADE)	0.357	1.009	0.350	0.723	0.916**	0.413	2.217	0.028
D(NRR)	1.065	2.708	0.390	0.695	0.942	0.606	1.555	0.121
C					1.876***	0.649	2.889	0.004
ECM(-1)	−0.181***	0.028	−6.446	0.000	−0.193***	0.069	−2.807	0.005

Note: ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

CS-ARDL and PMG-ARDL models are negatively significant, indicating that the variables will converge at 18 % and 19 %, respectively, toward long-run equilibrium during the last year.

6. Conclusion and policy recommendations

Understanding the relationship between stringent environmental policy, nuclear energy, and sustainable development is crucial for shaping effective policies, ensuring energy security, and fostering social, economic, and environmental sustainability. In this regard, the present study examines the impact of environmental policy stringency and nuclear energy on sustainable development in the case of top nuclear energy-producing economies.Data has been collected for 17 top nuclear energy-producing economies from 1995 to 2021. The study reports the following results applying the linear and nonlinear CS-ARDL estimation method. The linear model suggests that environmental policy stringency and nuclear energy production contribute to long-term sustainable development. In the nonlinear model, a positive change in environmental policy stringency and nuclear energy production causes long-run sustainable development to grow, while a negative change in environmental policy stringency and nuclear energy production hinders long-run sustainable development. Furthermore, environmental technologies, human capital, financial development, trade liberalization, and research and development expenditures are critical for fostering long-run sustainable development. In contrast, the natural resource rents hurt sustainable development. Most of these factors do not significantly influence sustainable development in the short run.

The study's outcomes lead to the following policy implications. First, policymakers in major energy-producing economies must enact and impose stringent environmental strategies to promote sustainable development. In order to reap full benefits, these policies must be implemented consistently for a long period of time. Policymakers must be careful of abrupt policy changes to avoid decreased investment and unpredictability. Further, policymakers must participate in strategic planning to promote sustainable development by setting achievable goals and designing a sound regulatory system. Sustainable development options can be further enhanced by promoting collaboration between research organizations and industries. Second, to increase nuclear energy generation, policymakers must focus on proposing ecological laws by keeping waste administration, emissions control, and water preservation in mind. Nuclear power plants must operate within the accepted environmental norms and standards. Third, investing in nuclear technology is a viable policy option to increase its generation due to several benefits of increasing safety, fostering efficiency, and improving waste management of nuclear power plants. Lastly, during the legislative procedure for nuclear energy, policymakers must keep an eye on the needs and demands of nuclear power plants. Policymakers should focus on several points during this legislation process, such as safety, ecological protection, and accepted international norms. Improved supervision of nuclear power plants has several benefits but is not limited to increasing public confidence, mitigating nuclear energy threats, and increasing nuclear energy production.

While this analysis offers valuable insights, notable limitations warrant consideration. Firstly, the research ignores country-specific analysis, which is crucial for policymakers to develop effective strategies for individual nations. Future research should prioritize in-depth, country-specific analyses. Second, the study considers the adjusted net savings as a measure of sustainable development. Some other indicators, as highlighted in the literature, such as HDI, green growth, etc., may also be used as measures of sustainable development in future studies to empirically analyze the response of these varying indicators to changes in environmental policies and nuclear energy. Third, the analysis is performed by gathering data across 17 nuclear energy-consuming economies, including developed and developing economies with different socio-economic and political environments. Future analysis must consider this issue and perform a comparative analysis in developed and developing economies for more interesting findings.

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CRediT authorship contribution statement

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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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