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Original Article

Asymmetric linkages between nuclear energy and environmental quality: Evidence from Top-10 nuclear energy consumer countries

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ABSTRACT

To lay a solid basis for prosperity and competitiveness, countries should achieve balance in the three fundamental aspects: energy availability, energy affordability and ecological balance. Nuclear energy has attracted international interest as one of the most crucial environmental quality strategies. The objective of this study is to analyze the non-linear link between nuclear energy and environmental quality in the top-10 nuclear energy consumer countries (USA, China, Russia, France, Canada, Spain, Sweden, South Korea, Ukraine, and Germany). Earlier research employed panel data methodologies to examine the linkage between nuclear energy and the environment, despite the fact that many nations did not independently demonstrate such a correlation. On the alternative, this study uses a novel approach known as 'Quantile-on-Quantile,' which allows for the analysis of time-series dependence in each country by giving universal yet country-specific insights into the relationship between the variables. Estimates show that the consumption of nuclear energy improves environmental quality by lowering ecological footprint in the majority of the nations studied at certain quantiles of data. Moreover, the data demonstrate that the degree of asymmetries between our variables changes by nation, emphasizing the importance of policymakers exercising caution when adopting nuclear energy and environmental quality regulations.

1. Introduction

One of the most well-known problems threatening the world is environmental pollution, which leads to environmental degradation. The primary causes of environmental deterioration are an ever-increasing human population, excessive financial development, and the use of natural resources and harmful technologies [1,2]. Environmental degradation is caused by a variety of factors, including deforestation, global warming, and pollution. The world community has recently focused on the environmental deterioration caused by global warming. Since the pre-industrial period, global warming has been seen as a severe threat due to an increase in the world's sea level, temperature, and desert expansion [3]. Energy use is main cause of carbon dioxide emissions (CO_2) in emerging economies. It is specific to mention that 85% of the CO_2 emissions from the world's power plants come from peat and coal [4]. It is significant to mention that countries like the USA, Japan, Germany, South Korea, South Africa, India, China, Poland, Australia, and Russia produce 84% of the world's coal-fired electricity, which results in yearly emissions of more than 8.5 Gt of CO_2 [5].

Nuclear energy (NE) is an effective approach for improving environmental quality (ENQ). To maintain the world temperature less than 2 °C above pre-industrial levels, the [5] suggests upgrading energy efficiency, demand management, carbon capture and storage, renewable energy (RE), and nuclear energy (NE). By 2050, NE is estimated to generate 15% of all yearly greenhouse gas emissions (GHG) reductions. The IEA [5] further illustrates contribution of NE to CO_2 reduction, stating that between 1970 and 2018, hydropower averted 87 Gt CO_2, NE evaded 66 Gt CO_2, and further renewable energies evaded 10 Gt CO_2. Nuclear energy consumption (NEC) has increased by more than 40% since a few years ago, representing for 12% of the global demand for electricity and 5% for primary energy [6]. When evaluating the current environmental impacts of economic advancement, the ecological measure has been specifically selected as a pollutant [7]. Climate change not only reduces biodiversity's benefits for people but also obliterates the

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earth's natural systems that sustain life [4].

The relationship of NEC and EF is challenging to investigate. Is it true that the NEC influences the trend of EF? Is the NEC's impact on the EF nonlinear? What occurs if the data sets are dispersed over several global regions? What are the likely effects of EF alterations caused by NEC? According to the literature, there are few empirical works that address these unresolved issues. There are several categories in which one might split the contribution of current study to preceding research. Numerous investigations into the NEC-ENQ have been initiated in recent years [4,8–10]. To the best of our knowledge, leading NE-consuming countries have not conducted any prior research on the asymmetric NEC-ENQ nexus. Most of the previous studies have taken CO_2 as an indicator of ENQ. However, we use EF as a proxy of ENQ.EF includes six types of bio productive land-use categories (such as carbon footprint, forest products, fishing grounds, crop land, grazing lands, and built up land). It can efficiently measure the ecological sustainability of the economy. Despite the fact that no such link was found in a wide variety of other nations, the NEC-EF relationship was shown in a prior study utilizing panel data methodologies. The Quantile-on-Quantile (QQ) technique is adopted in this study to provide evidence for the relationship between the variables that is both global and country-specific. Our single-country technique may offer authorities and policymakers crucial nation-related advice for achieving macroeconomic, political, and social aims ranked on the top, middle, or bottom quantiles of the variables since the link between the variables differs by country. At last, the findings of present study will open the way to further research on the relationship between the NEC and EF and its effects on other economies.

2. Literature review

The empirical study on the NE-ENQ association is divided into two categories. According to the first group, NEC enhances ENQ via lowering pollution [1,3,8]. The second group, on the contrary, argues that NEC has insignificant or positive effect on pollution [11–13].

Saidi and Omri [1] investigated the effects of NEC and RE on CO_2 in 15 OECD economies from 1990 to 2018. The estimates of Fully Modified Ordinary Least Squires (FMOLS) explored that investment in NE decreased CO_2 in the UK, Switzerland, Netherlands, Canada, Japan, and Czech Republic. Furthermore, the VECM technique results suggested that NE and RE minimized CO_2in the long-term. Ahmed et al. [3] examined the effect of NE, technical breakthroughs, RE, natural resources, and non-RE on carbon footprints. The findings revealed that NE and RE sources considerably contribute to an improvement in ENQ. In another study, Naimoğlu [2] investigated the effects of NE on CO_2 by employing autoregressive distributed lag (ARDL) technique with a dataset spanning from the years 1990–2019. The estimates of DOLS (Dynamic Ordinary Least Squares) and FMOLS demonstrated that NEC lowered CO_2. Similarly, Bandyopadhyay and Rej [14] also explored that NEC enhanced air quality. Nathaniel et al. (2021) observed the negative association among NEC on CO_2in G7 nations. In the same way, Usman and Radulescu [8] observed the impact of non-RE, RE, NE, on carbon footprint in the largest NE-generating nations from the year 1990–2019. The findings showed that the NEC and RE significantly improved ENQ.

Usman et al. [4] analysed the impacts of environmental-related technologies, and NE, RE on EF in Pakistan. The study used nonlinear ARDL approach. The research found that negative changes in NE raised CO_2 in the long-term, but inverse and direct variations in RE deployment considerably offset the environmental load. Syed et al. [9] found the effect of NE, GDP, and industrial productivity, on CO_2 in India for the years 1975–2018 by utilizing the asymmetric ARDL technique. The results showed that NE and CO2 had a nonlinear relationship in long run. In another work, Anser et al. [10] explored the impact of alternative and NE on CO_2 in a panel of 90 nations from the years 1995–2018. The findings revealed that alternate and NE initially boosted CO_2. At the same time, it diminished in the latter phases of NE expansion. Sharma et al. [7] looked at how RE affected EF in eight growing Asian economies. The estimations of CS-ARDL model observed that RE improved ENQ by reducing EF.

Another series of research indicates opposite findings about NEC-ENQ nexus. For example, Saidi and Mbarek [13] investigated the NE-ENQ relationship and discovered that NEC had an insignificant influence on CO_2 in developed economies. Similarly, Jin and Kim [12] explored the NEC-CO_2nexus for the panel of 30 economies from the years 1991–2015 and found an insignificant association among CO_2 and NEC. In the similar way, Sarkodie and Adams [11] observed a positive NE-GHG association in South Africa. However, Usman et al. [4] found that NEC is insignificantly associated with CO_2 in Pakistan.

3. Data and its description

This study explores NEC-ENQ nexus for the top 10 NE-consumer countries.[1] We use a dataset containing two variables. Nuclear energy consumption (NEC) is used as an explanatory variable. Our dependent variable is per capita ecological footprint (EF), which is taken as a proxy of ENQ. The Earth's carrying capability and its intrinsic futurist characteristic are described in the EF. It is also a gauge of ecological sustainability. Data is obtained from 1991 to 2020. The data related to NEC is taken from World Bank (https://databank.worldbank.org/) while the data for EF is taken from Global Footprint Network. At the beginning of the research, the taxonomy for the abbreviations and symbols used in this investigation is listed in Table 1.

4. Econometric technique

This section discusses the econometric technique utilized in this investigation. A cointegration test based on quantiles is used to evaluate the long-term link between NEC and EF. The Quantile-on-Quantile (QQ) method is adopted for econometric methodology.

4.1. Quantile cointegration (QC) test

If long-run relationships between variables are infrequent, using constant cointegration vectors may help traditional cointegration testing [15]. The data set's variable cointegration may change along distinct quantiles [16]. To reduce bias in estimation, we employ the quantile cointegration (QC) approach as suggested by Xiao (2009). Because endogeneity problems exist in conventional cointegration tests, Xiao [15] revised the earlier concept by adding fragmenting errors to lead-lag terms. If $\alpha(\tau)$ is a vector, then QC model, followed by Ref. [17], can be represented as follows:

$$X_i = \alpha + \alpha' Y_i + \sum_{k=-s}^{k} \Delta Y'_{i-k} \Pi_k + \nu_i \tag{1}$$

and

[1] USA, China, France, Russia, South Korea, Canada, Ukraine, Germany, Spain, and Sweden.

Table 1
The taxonomy of symbols and abbreviations.

Symbols/Abbreviations	Description	Symbols/Abbreviations	Elucidation
QR	Quantile regression	CO_2	Carbon dioxide emissions
EF	Ecological footprint	h	Bandwidth parameter
NE	Nuclear energy	μ_t^θ	Quantile error term
NEC	Nuclear energy consumption	$Sup_\tau\lvert V_n(\tau)\rvert$	Value of supremum norm for the coefficients (α and γ)
RE	Renewable energy	τ	τ^{th} quantile of ecological footprint
ENQ	Environmental quality	GHG	Greenhouse gas emissions
QQ	Quantile-on-Quantile estimation	ρ_ϕ	quantile loss function

$$Q_\tau^x\left(X_i M_i^X, M_i^y\right) = \beta(\tau) + \alpha(\tau)' Y_i + \sum_{k=-s}^{s} \Delta Y'_{i-k} \prod_j + F_v^{-1}(\tau) \tag{2}$$

$\beta(\tau)$ has a constant parameter and is a drift term. $F_v^{-1}(\tau)$ stands for a conditional data distribution's quantile errors. Thus, the following equation illustrates the cointegration model's quadratic elements according to Ref. [15]:

$$Q_\tau^x\left(X_i M_i^X, M_i^y\right) = \beta(\tau) + \alpha(\tau)' Y_i + \delta(\tau)' Y_i^2 + \sum_{k=-s}^{s} \Delta Y'_{i-k} \prod_k + \sum_{k=-s}^{s} \Delta Y^2_{i-k} \prod_k + F_v^{-1}(\tau) \tag{3}$$

The QC cointegrating coefficients are obtained using null hypothesisH_0: $\alpha(\pi) = \alpha$ (as indicated by equation (3)). $Sup_\tau\left|V'_n(\tau)\right|$ is used as a test stat value for whole quantile distributions. The critical limits for the QC test are established using 1000 Monte Carlo simulation.

4.2. Quantile-on-quantile (QQ) methodology

The QQ mehodology is shown to be the most efficient strategy to build a relationship between the variables in this investigation because of the asymmetry of the data. The old quantile regression (QR) technique only looks at the simple conditional mean effects of the explanatory variable on the explained variable's quantiles. Sim and Zhou [18] designed the QQ strategy to explore a variety of relationships between the explanatory and explained variables in order to tackle some issues related to the QR methodology. The QQ model explores the effect of NEC quantiles over EF quantiles in order to address the dependency problem. Resultantly, the QQ tool is employed in current study to detect the NEC-EF connection faults that might be difficult to find taking other widely utilized methods like OLS and QR [16].

A non-parametrical model is used in its preliminary form, as shown below, followed by Refs. [1,8]:

$$EF_t = \alpha^\theta(NEC_t) + \mu_t{}^\theta \tag{4}$$

EF denotes per capita ecological footprint and NEC indicates nuclear energy consumption at time 't'. θ reflects the θ^{th}quantile of NEC. As we do not know anything about the NEC-EF connection, it is assumed that load factor $\alpha^\theta(.)$ is unknown. The quantile residual term is shown by $\mu_t{}^\theta$ along θ^{th}quantile.

Our model according to QQ approach can be written as follows:

$$EF_t = \frac{\alpha_0(\theta,\tau) + \alpha_1(\theta,\tau)\,(NEC_t - \ NEC^\tau)}{(*)} + u_t^\theta \tag{5}$$

Equation (5) illustrates how the θ^{th} quantile of NEC affects the τ^{th} quantile of EF. The element (*) implies the contingent to NEC quantiles. The α_0 and α_1 parameters that are doubly indexed in θ and τ, illustrate the quantile association among EF and NEC.

QQ performs better than other conventional time-series methods despite just having one explanatory variable (NEC) and being a bivariate tool [19]. Compared to other widely-used techniques, It is more reliable since it might predict the nonlinear connection between NEC and EF at both the lowest and top quantiles [18].

4.3. Robustness of the QQ technique

The QQ may give reliable estimates for various NEC quantiles, which might provide conventional QR estimations. Given that its quantile parameters are solely indexed by the θ^{th} NEC quantile, the QR model may predict how the θ^{th} NEC quantile (an independent variable) would change EF (a dependent variable). The QQ regression method, in contrast to the QR method, examines the relationship between the θ^{th} NEC quantile and the τ^{th} EF quantile and characterises the quantile parameters with the help of both θ and τ inducing to further comprehensive data. As a result, by averaging the QQ values along τ, the QR parameters may be ascertained. As suggested by Ref. [18], the slope coefficient of the QR model, represented by $\gamma_1(\theta)$, is applied to investigate the influence of NEC on varies EF quantiles, given as bellow:

$$\gamma_1(\theta) \equiv \overline{\widehat{\alpha}}_1 = \frac{1}{s}\sum_\tau \widehat{\alpha}_1(\theta,\tau) \tag{6}$$

The quantile range is denoted by τ = [0.05, 0.10, …, 0.95], and the total number of quantiles is given by s (s = 19). We can determine the accuracy of the QQ approach by comparing the expected QR parameters to the averaged QQ values.

5. Findings and discussion

This section contains a comprehensive overview of the investigation's preliminary and key findings.

5.1. Preliminary findings

Table 2 displays the descriptive analysis for NEC and EF. The rising trend in NEC in the economies we chose indicates an important change in the energy balance in favour of clean power.

Sweden has highest average NEC (46.02% of whole energy consumption), fluctuating from 41.42% to 50.45%.France comes second, with an NEC of 44.60% of whole energy consumption, varying from 38.19% to 49.60%. Canada is third, followed by Spain, Ukraine, and South Korea. On the other hand, the USA is much polluted country economically with respect to global hectares (gha), with an average EF ranging from 7.94 to 10.33. Germany is third, followed by Sweden and Canada. The outcomes derived from the JB (Jarque-Bera) test reveal that NEC and EF distributions are found not normal within whole economies, while Spain is an exception because there EF distribution is normally distributed. The non-normal distribution of data in our countries further

Table 2
Descriptive statistics for NEC and EF.

Nations	Mean	Max.	Min.	Std. Dev.	J-B Stats	ADF Level	ADFΔ
Section A: Nuclear Energy Consumption (NEC)							
Sweden	46.02	50.45	41.42	2.06	3.27*	−1.51	−5.64*
France	44.60	49.60	38.19	2.44	2.79*	−1.49	−4.62*
Canada	19.06	21.91	16.79	1.37	3.53*	−1.96	−5.80*
Spain	16.48	21.60	12.69	2.30	3.10*	−1.45	−4.30*
Ukraine	15.66	22.53	8.04	3.62	4.20*	−2.15*	−4.55*
South Korea	15.30	18.49	11.75	1.96	2.90*	−1.69	−4.80**
Germany	13.25	14.27	11.60	0.87	2.50*	−0.93	−6.77*
USA	10.58	11.87	9.42	0.73	3.65*	−1.35	−5.82*
Russia	7.01	8.24	4.89	0.98	2.76*	−1.67	−5.03*
China	3.56	7.10	0.98	2.29	2.37*	−1.71	−5.80*
Section B: Ecological Footprint per capita (EF)							
Sweden	6.25	8.33	5.30	0.54	14.29*	−4.32*	−6.75*
France	5.24	5.80	4.42	0.36	3.12*	−1.56	−5.71*
Canada	8.42	9.50	7.74	0.44	3.17*	−1.70	−4.46*
Spain	4.81	5.86	3.71	0.66	1.28	−1.70	−5.64*
Ukraine	5.09	6.20	1.20	0.59	3.49*	−1.88	−3.73**
South Korea	0.12	0.18	0.06	0.02	2.79*	−5.72*	−5.23*
Germany	5.47	6.36	4.67	0.40	3.70*	−1.86	−4.14*
USA	9.27	10.33	7.94	0.87	3.50*	−1.85	−5.15*
Russia	5.16	6.79	4.30	0.50	10.76*	−1.68	−5.72*
China	2.51	3.79	1.47	0.79	3.79*	−1.09	−5.71*

Note:* and ** denote significance level at1% and 5%, corresponingly

Table 3
Correlation between EF and NEC.

Country	Correlation	t-Stats	p.value
Sweden	−0.85	−18.30*	0.00
France	−0.70	−7.62*	0.00
Canada	−0.82	−4.90*	0.00
Spain	0.65	4.17*	0.00
Ukraine	−0.84	−10.60*	0.00
South Korea	−0.75	−9.36*	0.00
Germany	−0.68	−7.94*	0.00
USA	−0.77	−4.09*	0.00
Russia	−0.68	−9.32*	0.00
China	−0.76	−5.38*	0.00

Note:'*' depicts the significance at 1%.

strengthens the case for the QQ strategy, which is suited in such conditions [19]. The ADF test discloses that in the majority of the countries we chose, our data series are stationary at first difference. Resultantly, we pursued [19] and employed stationary data observations by converting them in the first differences.

In Table 3, correlation inspection shows that NEC and EF have adverse and strong link with each other, except for Spain. The countries with the greatest correlation coefficients are Sweden (−0.85), Ukraine (−0.84), Canada (−0.82), and the USA (−0.77), respectively.

5.2. Key findings

The QC test is shown in Table 4. Here, τ denotes the τ^{th} EF quantile. The stability of parameters is explained by the supremum norm coefficients (α and γ) derived with the help of equation (3).

The outcomes of the QC test show that the relationship between NEC and EF in long run differs by quantile in every economy. The coefficients' supremum norm values, which are bigger in respect of their critical levels (C1, C5, and C10), demonstrate a nonlinear long-run relationship between NEC and EF across all economies.

Fig. 1 demonstrated the $\alpha_1(\theta, \tau)$ as slope estimations, that illustrate the dominance of the θ^{th} quantiles of NEC over τ^{th} EF quantiles in selected countries along numerous values regaring θ and τ. The powerful and inverse effect of NEC on EF is shown **in France**. The lowest to upper-mid NEC quantiles and all EF quantiles are combined in the localities, and NEC and EF have a strong and inverse association. The NEC is thought to improve ENQ by lowering EF at lower to upper-middle levels of NEC, according to this predominantly powerful and inverse connection. A weak inverse NEC-EF link is also shown in the regions, connecting overall EF quantiles holidng the medium high to high NEC quantiles (0.80−0.95). **In Germany**, there is a considerable negative link between the NEC and EF. The regions that connect all of the NEC quantiles holding medium low to highest EF quantiles establish a strong inverse relationship between EF and NEC (0.35−0.95). This very strong inverse relationship showed that in the lowest, middle, and top ranks of NEC, EF is minimized, which improves ENQ [1,20]. endorse this strong inverse NEC-EF association in France and Germany.

In **Sweden** the powerful inverse effect of EF on NEC is dominant. A powerful inverse bond across NEC and EF is existed between the localities, which join lower-mid to higher NEC quantiles (0.35−0.95) along whole EF quantiles. The instant powerful and negative connection referred as the NEC boosts the ENQ by lowering EF at well levels of NEC. Though, a weak and inverse NEC-EF link is produced in the zones that blend lower NEC quantiles (0.05−0.30) along entire EF quantiles. The USA is most affected negatively by NEC's influence on EF. The zones provide a strong negative NEC-EF association that connects all NEC quantiles to bottom to highest EF quantiles (0.50−0.95). This mainly stroung and inverse association denoted that, at medium levels of NEC, lowering EF enhances ENQ. The strong inverse NEC-EF association in Sweden and the USA is aligning with [3], who claimed that NEC decreased carbon footprint.

Inverse and powerful effect of NEC on EF is remarkable in **China**. The sectors, which connect lower-middle to upper-mid NEC quantiles (0.35−0.80) with full EF quantiles, exhibit a strong and inverse relationship across NEC and EF. This powerful and negative link demonstrated how NEC lowers EF at healthy levels, which raises ENQ. Higher NEC quantiles (0.85−0.95) are connected to all EF quantiles in the sections. However, this NEC-EF relationship is weak and inverse. Additionally, a powerful positive link among NEC and EF can be seen in the zones that connect lower NEC quantiles (0.05−0.30) along all EF quantiles. The insant especially powerful positive correlation demonstrated how the NEC reduces ENQ by increasing EF during times of low NEC. NEC has a significant and inverse effect on EF in **Russia.** The vicinities that blend all NEC quantiles with lower-middle to higher EF quantiles produce a considerable negative link between NEC and EF (0.50−0.95). This particularly powerful and negative relation suggested that the NEC decreases EF at the healthy levels of NEC while increasing ENQ levels. The strong negative NEC-EF nexus in China and Russia is backed by the studies of [1,20].

In **Ukraine,** NEC has a considerable negative impact on EF, which is predominate. The lower to high-middle and top NEC quantiles (0.05−60 & 0.85−0.95) are joined with whole EF quantiles by a notable and negative relationship among NEC and EF across the regions. This particularly powerful negative union implied that, at healthy levels of NEC, the NEC enhances the ENQ by reducing EF. In **South Korea,** the negative and strong effect of NEC on EF is predominant. The sections integrate all EF quantiles with the bottommost to moderate and upper-mid to highest NEC quantiles (0.05−0.50 & 0.70−0.95), resulting in a strong and inverse association between NEC and EF. This especially powerful negative union suggested as the NEC upgrades the ENQ by lowering EF at well grades of NEC. Though, a strong and positive NEC-EF connection is also seen among localities, that join high-middle NEC quantiles (0.55−0.65) along whole EF quantiles. In **Canada**, NEC has a significant and negative impact on EF. A powerful and

Table 4
Findings of QC test (NEC and EF).

Nations	Coefficients	$Sup_{\tau}\|V_n(\tau)\|$	C1	C5	C10
Sweden NEC vs. EF	α	6247.60	5684.90	4687.50	3780.78
	γ	3281.96	2694.71	2182.70	1848.40
France NEC vs. EF	α	8325.20	5284.23	3134.05	2522.37
	γ	179.60	112.41	55.88	39.33
Canada NEC vs. EF	α	3940.93	3770.27	248.50	205.95
	γ	167.72	156.81	49.08	45.78
Spain NEC vs. EF	α	1837.70	1547.79	1046.78	994.89
	γ	960.77	688.61	497.73	346.80
Ukraine NEC vs. EF	α	7117.36	3496.14	3085.19	2229.30
	γ	606.41	302.86	217.15	118.12
South.Korea NEC vs. EF	α	8750.53	6712.11	4771.12	1476.80
	γ	398.17	204.61	105.09	99.11
Germany NEC vs. EF	α	6,8581.33	58,366.33	57,305.24	54,880.74
	γ	2472.64	1483.21	1446.48	1432.10
USA NEC vs. EF	α	7144.36	3492.10	3082.11	2225.39
	γ	605.45	303.88	213.20	120.13
Russia NEC vs. EF	α	7014.35	3295.13	3185.18	2125.30
	γ	612.40	310.85	218.16	116.12
China NEC vs. EF	α	537.40	325.35	294.70	238.57
	γ	280.90	198.80	124.70	98.30

Note: An equally-spaced grid of 19 quantiles (0.05–0.95) is employed to analyze the t-statistic values. Values for supremum norm of both α and γ (parameters) with their critical bounds are given at 1%, 5%, and 10% levels of significance denoted by C1, C5, and C10, respectively.

negative NEC-EF connection is found across the areas, which unite bottom to mid-upper NEC quantiles (0.05–0.75) along whole EF quantiles. The instant incredibly powerul adverse connection made it clear that NEC decreases EF at low to high levels, boosting ENQ. However, the zones also show a strong and positive NEC-EF correlation that links higher NEC quantiles (0.80–0.95) with all EF quantiles. The powerful inverse impact of NEC on EF in South Korea and Canada is consistent with the empirical study of [2].

In **Spain**, there is a complex link between NEC and EF. The zones exhibit a strong inverse NEC-EF relationship that links all of the NEC quantiles to the moderate to upper EF quantiles. The instant predominantly powerful negative links shown that the NEC reduces EF at mid-to high-grades of NEC, which enhances ENQ. However, there is a powerful positive union among NEC and EF that connects all of the NEC quantiles to the lower to mid EF quantiles (0.05–0.50). This especially powerful positive correlation demonstrated how the NEC degrades ENQ by maximising EF when NEC levels are low to moderate. The result is in line with the work of [4], which shows a time-varying relationship between NEC and ENQ.

5.3. Verification of the robustness of the QQ methodology

We now evaluate the QQ and QR estimations to see if they coincide. The conclusions of the preceding QQ are supported by Fig. 2. It is demonstrated that the average slope coefficient QQ estimates across all nations exhibit a similar pattern to the QR estimations.

Fig. 2 depicts inverse link between NEC and EF in top-10 NE-consumer economies. However, Spain shows mixed results. Furthermore, our data show that the link between EF and NEC varies across all nations. The magnitude of the coefficients reveals why NEC has a considerably higher influence on EF in the USA and Canada but a much lesser impact in South Korea and Ukraine.

5.4. Discussion of findings

Estimates show an inverse link between NEC and EF in mostly nations. In eight out of ten countries, NEC has been identified as a cause of reduced EF, as have other empirical research, such as [1,3,8], which imply that NEC enhances ENQ. Our findings of a negative NEC-EF association are consistent with those of [1] for OECD countries [21], for G7 economies [8], for top NE-producing countries [4,7], for Asian economies., all of which suggest that NEC increases ENQ. Our findings, however, differ from earlier research. Previous studies took into account certain variables (positive, neutral, or negative) throughout the sample data distribution. Conversely, this study suggests that diverse indicators (positive or inverse) might be drawn throughout a broad scope of quantiles of the whole data distributions. Additionally, the data will assist authorities and policymakers in our selected nations in developing policies at various NEC and EF levels.

Spain shows mixed association between NEC and EF. The findings are corroborated with the study of [4], which demonstrates a temporally variable link between NEC and ENQ and shows how variations in position, time, and season may prevent NEC from steadily improving ENQ. Furthermore, increasing NEC may have a detrimental impact on ENQ depending on regional and macroeconomic factors. Several factors might explain this mixed association such as investment behavior, economic cycles, population increase, technological improvements, and energy use. Similarly, the positive relationship between NEC and pollution is consistent with [11].

The effect of NEC changes significantly between nations and quantiles due to multiple reasons. Upper EF quantiles, for instance, imply a foremost NEC-EF connection in the mostly nations (i.e., USA, Germany, France, Russia, South Korea, Canada, and Spain).This suggests that when the levels of EF are high, NEC enhances ENQ [10]. assert that the degree of NEC is first harmful to ENQ and thereafter becomes advantageous, like Spain's findings. For instance, when it comes to population, economic growth, and technology, Germany and the United States are superior to the other specific economies. Avoiding this type of variability might bring out incorrect results. The NEC and EF slope coefficients imply that the link varies based on the direction and size of economic shocks as well as the economic stage (boom or bust) that impacts NEC. The NEC-ENQ association is not consistent throughout the highest and lowest data quantiles. Additionally, the vicinities we selected have particular difficulties that panel data methodologies cannot tackle. So that we could completely understand each economy's distinct characteristics, we extensively examined each economy.

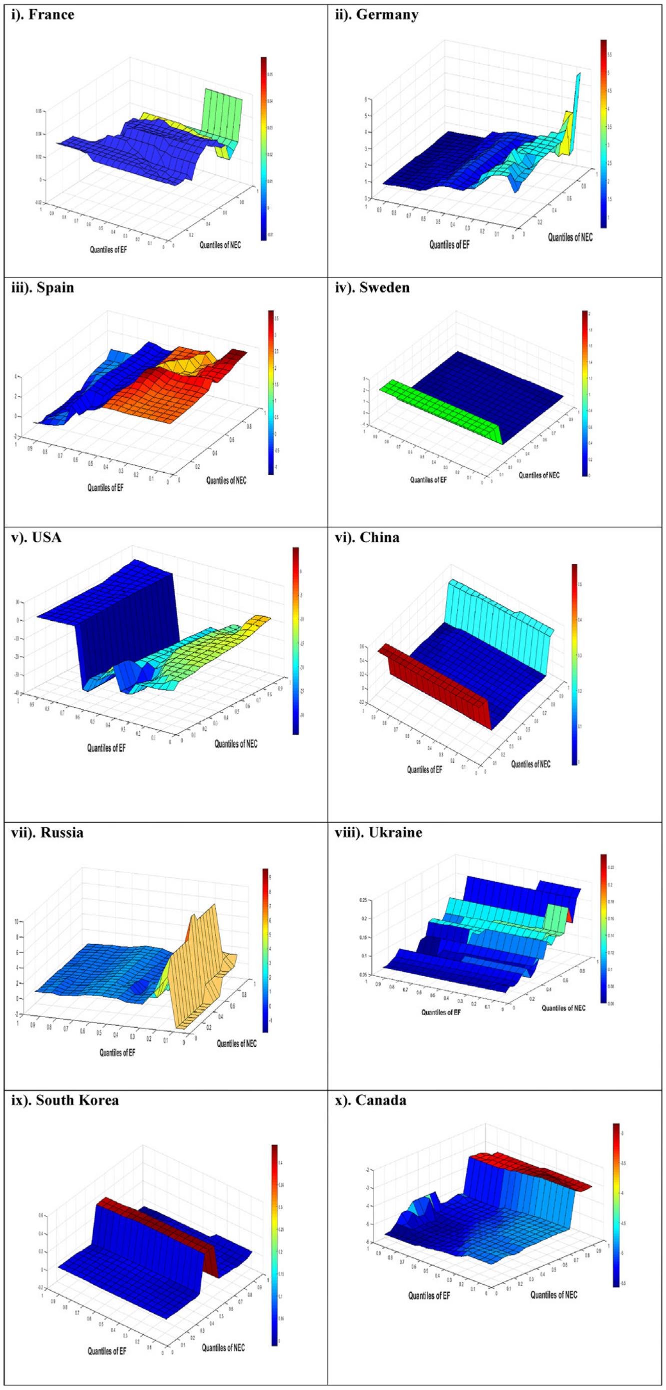
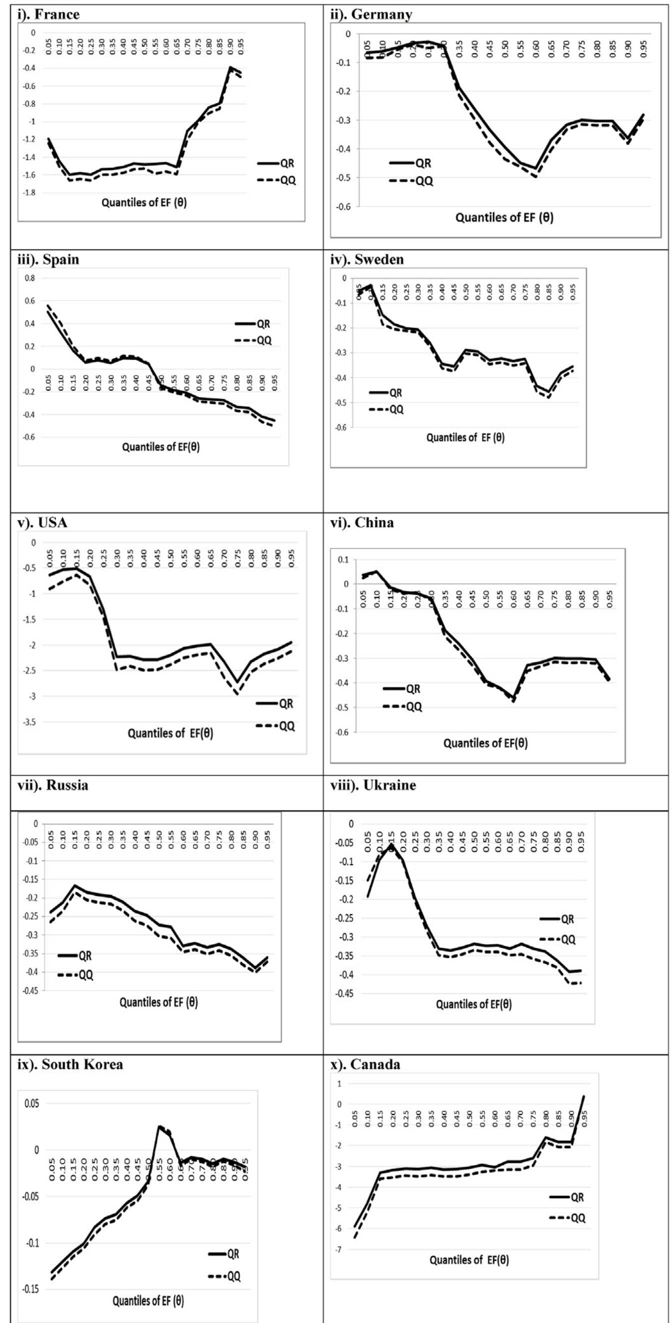


Fig. 1. QQ estimates of the slope coefficient$\alpha_1(\theta, \tau)$ Effect of Nuclear Energy Consumption (NEC) on Ecological Footprint (EF)

Note: Estimations regarding slope coefficients a_1 (θ) are plotted along with z-axis, with the NEC quantiles along with x-axis and the EF quantiles along with y-axis. The slope coefficients are shown on the right on a colour scale from red to blue, with red being the biggest value and blue representing the smallest. Dark blue indicates a strongly negative correlation between NEC and EF, whilst dark red indicates a strongly positive connection. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)



Note: The estimations for the typical QR parameters and the averaged QQ parameters are presented against different EFquantiles.

Fig. 2. Verification of the Robustness regarding QQ Technique by analysing QQ and QR tool

Note: The estimations for the usual QR parameters and the averaged QQ parameters are presented parallel to different EF quantiles.

6. Conclusion and policy recommendations

The asymmetric relationship between NE and ENQ in the top ten NE consumption nations was investigated in this study. EF is used as a proxy for ENQ. According to QQ estimations, NEC raises ENQ by reducing EF across the majority of the localities examined at certain quantiles of the data distribution. Furthermore, the data show that the degree of asymmetries between our variables differs by country, underscoring the necessity for policymakers to adopt NE and ENQ rules with prudence.

We propose several major policy implications of this research based on the empirical findings. The findings show that NEC lowers EF. This implies that adequate environmental actions are needed to reduce the EF. While taking into account NE's huge potential in this regard, there must be significant efforts made to improve energy efficiency and reduce the amount of fossil fuels in the energy mix. More crucially, the significance of NEC suggests that our chosen nations are on pace to being carbon-free and achieving long-term ecological sustainability. Government and policymakers should focus on increasing NE production, and each country should devote more funding for infrastructural development in the NEC. To ensure a sustainable future, it is suggested that developing nations increase the proportion of NE in their energy mix, manage their natural resources wisely, and keep an eye on the rate of urbanisation.

Due to the prevalence of criminal actions involving natural resources, such as exploitation and logging, stronger rules and more public awareness are needed to put a stop to this nefarious behavior. Furthermore, while addressing national energy concerns, politicians should focus on natural resource mining methods by forcing firms that collect mineral resources to employ energy-efficient technology in their processes. Furthermore, smart infrastructures and hybrid electric vehicles may be deployed to convert urban traffic to green mobility. Environmental consciousness and rising educational reform techniques will eventually enjoy the rewards of long-term ecological sustainability. Although NE is a less expensive energy source, it has drawbacks including safety hazards that are permanent in nature. As a consequence, appropriate safety and security measures are also required in terms of safety regulations. In additional to the above, this study suggests that the variables have an asymmetric connection. Policymakers should thus take into account the asymmetric nature of the link between the variables before passing any judgement on policy.

Finally, the study's substantial shortcomings will create the hindrance in the way of more research into this topic. Due to the QQ regression's shortcomings, we picked solely EF, neglecting its subcomponents (such as fishing grounds, carbon footprint, forest products, grazing lands, crop land, and built up land). These ENQ estimates may be used in future investigations to analyze that how the findings alter due to changing environmental conditions. Micro-level (firm-level) data should be used to investigate the effect of NEC on EF in order to provide more compelling empirical findings. It is suggested that further research be done on renewable energy sources such solar, wind, geothermal, and biomass. Another significant flaw in this work is the application of the bivariate QQ tool that restricts the insertion of other independent variables influencing the NEC-EF association. Hence, in order to properly comprehend the linkage with the further explanatory factors, we could utilise multivariate approaches to improve our empirical model in the future (such as Quantile ARDL).

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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