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Investigation of displacement between main clean energy types: Evidence from leading developed countries through quantile approaches

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ABSTRACT

The role of energy transition has been developing under increasing negative impacts of environmental problems. Because there are various options, there is a displacement risk among alternatives. Therefore, it is critical to ensure that clean energy use (EU) alternatives do not displace others. Considering this critical point, the study investigates whether there is a displacement between types of renewable and nuclear energy. So, the study examines leading developed countries (Canada, France, United Kingdom, & United States) by considering impact of three main renewable energy use (REU) types (hydro-HEU, solar-SEU, wind-WEU) on nuclear energy use (NEU), using data from 1999/Q2 to 2023/Q4, and applying quantile approaches. The results reveal that (i) HEU (WEU) displaces NEU in Canada and United States (Canada); (ii) SEU mainly displaces NEU in the countries except United Kingdom; (iii) the higher displacing impact of REU types is seen in Canada, while it is partially displacement for France and United States, and almost no displacement for United Kingdom. Overall, the results demonstrate that all REU types have a certain displacement in Canada, whereas there are partial displacement for other REU types across the countries. Hence, a harmonized and comprehensive energy transition planning among clean energy types is critical.

1. Introduction

The earth has been experiencing a highly important climate change problem in recent years, which results from ecological deterioration. By considering environmental problems, which have been affecting negatively societies in all countries, policymakers at both national and international levels have been trying to take various measures, such as more stringent environmental policies, and ensuring energy transition, to make a slowing impact on climate change [1]. Consistent with such an environmental condition, the research and efforts regarding climatic and environmental issues have been progressing continuously [2].

Increasing emissions takes the leading role among all factors in terms of stimulating climate change. When data from the Energy Institute [3] and World Bank [4] is evaluated, it can be seen that a big share of carbon dioxide (CO_2) emissions comes from energy. Hence, the role of energy has been highly critical in combating climatic and environmental problems to make economics decarbonized [5]. Compatible with the propositions of internal institutions, such as the International Energy Agency [6], it is critical to rely on further clean energy sources to curb the negative impact of energy use that stimulates environmental degradation and causes climate change [7].

According to the contemporary literature, countries have various options for the replacement of fossil fuel energy. Within the context of energy transitioning efforts, countries can prefer to further use nuclear energy, while it is possible to rely on further use of renewable energy sources (e.g., hydro, solar, & wind) [8]. Either any of these clean energy types or a combination of them can be used based on the natural capability and preferences of countries in changing efforts of their

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current energy mix components.

In energy transitioning efforts, countries' natural resources capacity is naturally highly important. Either countries have rich fossil sources, are capable of using nuclear elements, or have rich resources for rare earth elements is critical due to their role in the selection of energy mix components [9,10]. Although all clean energy sources are potential alternatives in ensuring energy transition by replacing fossil fuel EU, nevertheless, it is clear that countries may not have the opportunity to benefit from all types of clean energy sources. While this necessity is related to the aforementioned reality, it also comes from the economic and financial capacities of countries. Because clean energy investments (especially nuclear power plants) require a large amount of investment, it is not possible for countries to financially support all clean energy investments at the same time [11]. For this reason, countries may have to make a selection between potential clean energy alternatives by considering their economic and financial conditions, natural resources capability including the access opportunities to nuclear and rare earth elements, current energy mix, and growth expectation in the EU for the coming years. This is the main cause of why there is a displacement risk among clean energy sources (i.e., between NEU and REU types) in addition to the displacement opportunity of fossil fuel energy by clean energy sources [12].

In reviewing the literature, it can be seen that the studies have mainly dealt with the displacement of fossil fuel energy by clean energy. Among all, Michaelides and Michaelides [13], Kramarz et al. [14], Greiner et al. [15], and Rather et al. [16] have investigated how clean (i.e., nuclear and renewable) energy has a displacing impact on fossil fuel energy. On the other hand, the current literature is not developed enough in terms of uncovering the potential displacement between clean energy sources. Naturally, there is some displacement research for clean energy sources (e.g., Ref. [12,17–19]), however, such studies have not made empirically to examine the displacement empirically, instead, they have presented only a conceptual point of view. By considering this condition of the empirical literature in investigating the displacement impact between clean energy sources, it can be stated that there is room for growth to make an empirical-based analysis of the issue by applying econometric approaches. Hence, much more precise analysis and evaluation regarding displacement impact from REU types to NEU can be performed.

Based on data from EI [3], there is a growing trend for REU types across many countries. On the other hand, data from EI [3] demonstrates that NEU has been an option for mainly highly developed countries due to the requirement of a large amount of financial resources to apply for a nuclear power plant. By considering these points, it can be highly suitable to consider developed countries in uncovering the displacement of REU types on NEU because most of the emerging countries do not have NEU, which prevents to consideration of such countries for empirical examination about the displacement between REU types and NEU.

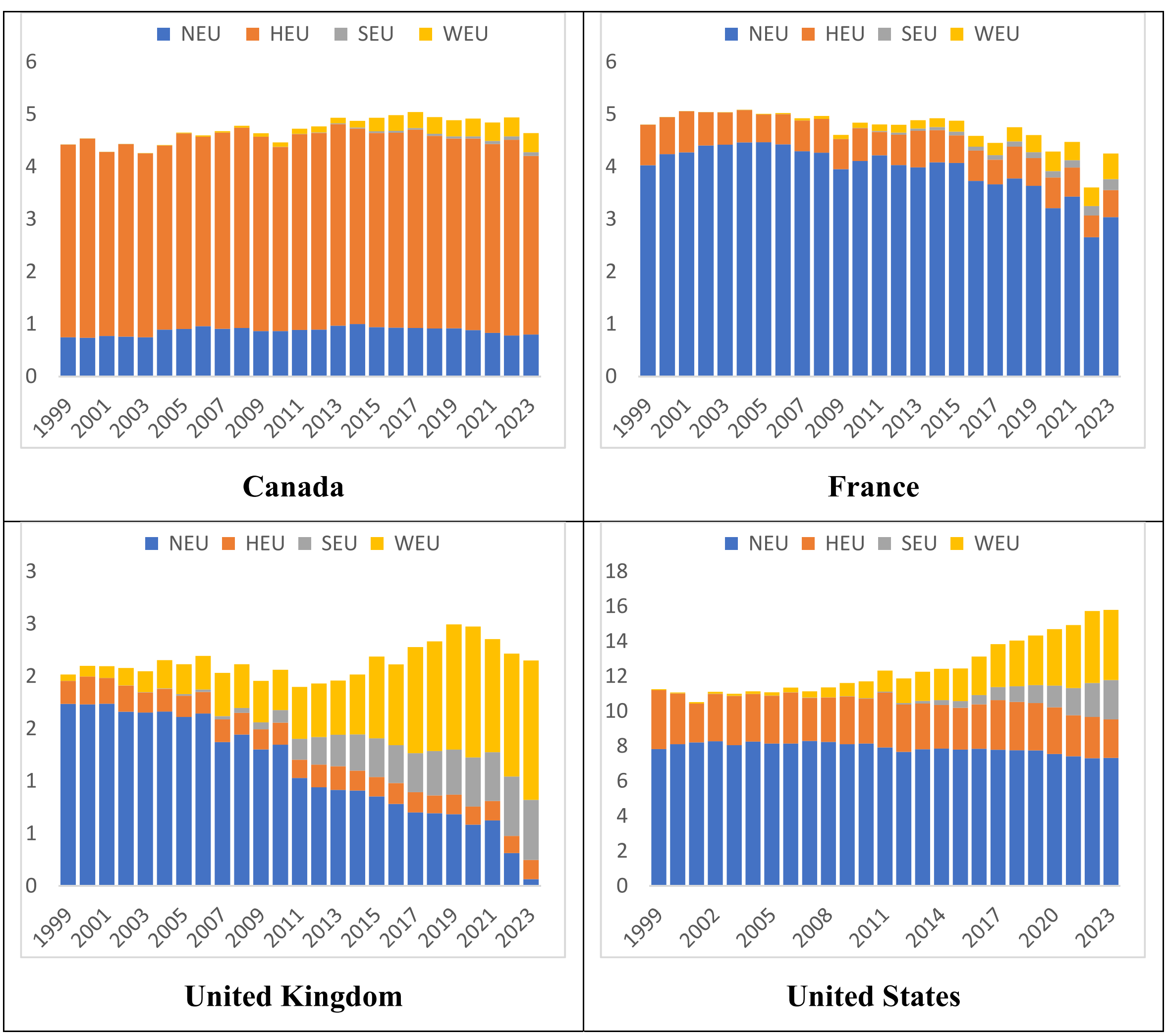

Fig. 1. Progress of EU in the Countries
Notes: The unit is exajoules.
Source: EI [3].

When evaluating developed countries, it can be seen that some countries and country groups, such as the G7 block, have a pioneering role from different points of view, such as the high amount of nuclear energy investments, energy transition efforts, and economic size. In G7 countries, however, some specific points (i.e., Italy ended NEU in 1987, and there is a lack of data on SEU for Germany and NEU for Japan in some years), should be considered [3]. So, consideration of the remaining four countries (namely, Canada, France, the United Kingdom, and the United States) for empirically uncovering the displacement between REU types and NEU can be possible. Accordingly, Fig. 1 demonstrates the progress of the EU at disaggregated levels in these developed countries.

According to Fig. 1, Canada has a high WEU share in the total energy mix. However, NEU has the highest share in the energy in France and the United States. Differently from those countries, NEU had a high share in the United Kingdom in the past, however, WEU has had a high share in the total energy mix in recent years. Thus, Fig. 1 presents that there are different trends in terms of the progress of energy mix components in the countries. Therefore, these countries are highly suitable to empirically analyze displacement between REU types and NEU across countries and levels of these EU types because their use has been changing over the years. So, it can be expected that the relationship between REU types and NEU can vary across the quantiles.

Taking into account the forcing impacts of climatic and environmental issues as well as the energy crisis, and energy transition efforts of the countries, and the empirical literature is underdeveloped, this investigation empirically analyzes the displacement between REU types and NEU in the leading developed countries in G7 block. That is why although there are some studies about the displacement impact of clean energy on fossil fuel energy, the empirical studies on the displacement between clean energy types are highly limited and no study has made an empirical analysis across developed countries and quantiles. Hence, there is a literature gap, and a new analysis by considering the aforementioned points can have the capability to fill in the gap.

Consistent with the motivation points explained above, the study searches for the answer to the following research questions how do REU types have a displacing impact on NEU? In this context, the study investigates leading developed countries, uses data between 1999/Q2 and 2023/Q4, and performs quantile approaches. Hence, the displacement impact of REU types on NEU can be empirically searched for across countries and quantiles. The results summarily show that the results demonstrate that all REU types have a certain displacement on NEU in Canada, whereas there are partial displacements for other REU types on NEU across countries.

The study provides some contributions to the literature. Firstly, the study uncovers displacement between REU types and NEU. Investigating the displacement between clean energy types is important because international parties, such as International Energy Agency, have been suggesting further use of clean energy to combat climate change and ensuring the nonexistence of a displacement between REU types and NEU is highly critical in this aspect. Secondly, the study empirically analyzes four leading developed countries. In doing so, the study performs novel quantile-based approaches on the most recent and longest accessible data to make a comprehensive analysis for a long time interval. Hence, the displacement between REU types and NEU is investigated across various level of these clean energy types by considering the possibility of quantile-based varying displacement. In this way, the study tries to obtain generalizable results on the issue that the article investigates. Moreover, with this empirical approach, the study considers potential differences between countries and across quantiles of the variables by making a country and quantile-based empirical analysis. Thus, the study demonstrates contributions by applying comprehensive empirical approach.

The following parts are located as such: Section 2 presents the literature review; Section 3 details the methods; Section 4 demonstrates the empirical results, discussion, and policy implications; and Section 5 concludes.

2. Literature review

Being influenced by the seminal studies of Kraft and Kraft [20] on the energy-led growth hypothesis and Grossman and Krueger [21] on the EKC hypothesis, the literature concerning economy-environment-energy has been developing day by day with the contribution of recent environmental problems and energy crisis that the world has faced. These studies have highly relied on investigating the relationship between different perspectives including economy, environment, and energy-related factors. Hence, it can be stated that the current literature has been highly dealing with the impact of such factors as economy and energy upon the progress of environment.

Whereas environmental economics, as well as energy economics literature, is highly rich, unfortunately, the research on the relationship between various energy types is somewhat quite rare, so the literature on this aspect is highly shallow. In case of examination of these types of studies, it can be seen that previous studies mainly focused on the displacement impact between fossil fuel energy and clean energy sources (e.g., Ref. [13–16]), whereas recent studies have considered the displacement among clean energy sources. When considering these studies, two types analyze the relationship between energy types theoretical-based and empirical-based studies.

Among theoretical-based studies, Sims et al. [22], Kaygusuz [23], Verbruggen [17], Forsberg [24], Karakosta et al. [18], McCombie and Jefferson [19], and Boccard [12] can be specified. The common specialties of these studies are that these studies have taken both NEU and REU together and discussed potential displacement among them. While these studies deal with an important point, however, they do not use any empirical prediction model to support their argument with empirical results.

Among empirical-based studies, Apergis et al. [25] examine selected 19 countries from 1984 through 2007 by using the panel causality approach and define that NEU has a declining impact on REU. Jin and Kim [26] analyze selected 30 countries from 1990 to 2014 by performing FMOLS, DOLS, and panel causality approaches and state that there is bidirectional causality between NEU and REU. Similarly, by using panel quantile regression, Gyamfi et al. [27] define the same result for E7 countries between 1990 and 2016. Nathaniel et al. [28] consider G7 countries for the period from 1990 to 2017 through using AMG, CCEMG, and panel causality approach and determine the similar result. With the same econometric approaches, Usman and Radulescu [29] define that there is unidirectional causality from REU to NEU for the period of 1990–2019. On the other hand, Saidi and Mbarek [30] consider selected 9 developed countries for the period of 1995–2013 through using FMOLS, DOLS, and panel causality approaches and conclude that there is no causality between NEU and REU. Thus, it can be that there is no clear consensus in the literature on the displacement between REU and NEU.

As examined above, the literature has not included empirical studies that analyze the displacement impact of REU types on NEU. Hence, it can be stated that based on the best knowledge, the relationship between REU types on NEU has not been empirically examined, which is a literature gap. By considering this gap, this research aims to empirically uncover between REU types and NEU. In this way, the researchers believe that this study contributes to the current knowledge by presenting empirical results about whether there is either a complementary or a displacing impact between these types of energy, which is highly critical for the energy transition policies of the countries.

3. Methods

3.1. Data and variables

In this research, displacement between REU types and NEU has been empirically investigated. In doing so, the study examines a total of four leading developed countries (namely, Canada, France, the United

Kingdom, & United States) because Italy ended the use of NEU in 1987, there is a deficiency in data on SEU for Germany and NEU for Japan in some years [3]. Hence, the displacement impact has been uncovered for the four countries.

Within the empirical examination, the study collects data of NEU, HEU, SEU, and WEU from EI [3], where the unit for all these variables is exajoules, for the period of 1999–2023. This is the most recent and longest accessible intersect data for the variables considered. Following the collection of yearly data, the study transforms data into quarterly frequency by applying a quadratic sum approach [31,32] and then calculates returns series by performing logarithmic differences [33]. Hence, the data from 1999/Q2 to 2023/Q4 is used in the empirical analysis.

3.2. Empirical methodology

Fig. 2 demonstrates the empirical methodology, which is used in this study, below:

After data was collected from the source of EI [3], this investigation first analyzes the main statistics. Secondly, the study examines correlations of the variables. Thirdly, the study applies the PP [34] test to examine the stationarity of the variables. Fourthly, the study performs the BDS test [35] to investigate the nonlinearity types of the variables. Fifthly, the study runs the QQ approach [36] to examine the impact of REU types on NEU across quantiles and countries. Sixthly, the study uses the GQ approach [37] to search for the causal impact of REU types on NEU across quantiles and countries. Lastly, the study applies the QR approach [38] to check the robustness of the QQ approach.

In the application of the empirical analyses through quantile approaches as consistent with the data types, the study uses Eqs. (1)–(3) below:

$$NEU = f\ (HEU) \tag{1}$$

$$NEU = f\ (SEU) \tag{2}$$

$$NEU = f\ (WEU) \tag{3}$$

Through the application of quantile approaches to the prediction models, which are presented in the equations above, the study searches for the displacement impact of REU types on NEU across quantiles in the leading developed countries.

4. Empirical results

4.1. Preliminary statistics

As the initial step of empirical methodology, the study examines the main statistics of the variables, which are reported in Table 1.

According to Table 1, the United States has the highest mean values concerning the countries. Following it, France and the United Kingdom have higher values, whereas Canada takes place at the end order. From the point of view of variations, the United States has again the leading position among the countries, whereas there are low variations for the variables in other countries. Moreover, all variables across the countries except for HEU in France and the United States as well as NEU in the United Kingdom have a nonnormal distribution.

As the second step of empirical methodology, the study analyzes the correlations between variables, which are reported in Table 2.

According to Table 2, NEU has a negative relationship with all REU types in Canada, which implies a displacement impact. Completely different, there is a positive relationship between all REU types and NEU in the United Kingdom. On the other hand, NEU has a positive (negative) relationship with HEU and WEU (HEU & SEU) in France (United States), while there is a negative (positive) relationship with SEU (WEU), in order.

As the third step of empirical methodology, the study analyzes the stationarity types of the variables, which are reported in Table 3.

According to Table 3, all variables are stationary at the level. As the fourth step of empirical methodology, the study uncovers the nonlinearity types of the variables, which are reported in Table 4.

According to Table 4, variables have different characteristics. In detail, HEU in the United Kingdom has a linear structure. NEU and HEU in Canada, HEU in France, NEU and WEU in the United Kingdom, and HEU in the United States have mixed structures. Other than these, all the remaining variables have a nonlinear type.

In the case of the overall evaluation of all preliminary statistics indicators, it can be summarized that most of the variables have a nonnormal distribution, there are various variation levels across the variables, all variables are stationary at the level, and all variables have a mixed (i.e., linear, nonlinear, &mixed) structures across the dimension. Therefore, quantile approaches (i.e., QQ, GQ, &QR), which are mainly nonlinear and successful in predicting the relationship between variables, are used to obtain highly estimative results as compatible with the literature [39].

4.2. QQ results

As the fifth step of empirical methodology, the study performs the QQ approach to uncover the impact of HEU on NEU across quantiles, which are presented in Fig. 3.

According to Fig. 3, there is a negative impact of HEU on NEU across all levels in Canada and the United States. Differently from those, in France and the United Kingdom, there is a positive impact of HEU on NEU at lower and higher levels, whereas there is a negative impact at

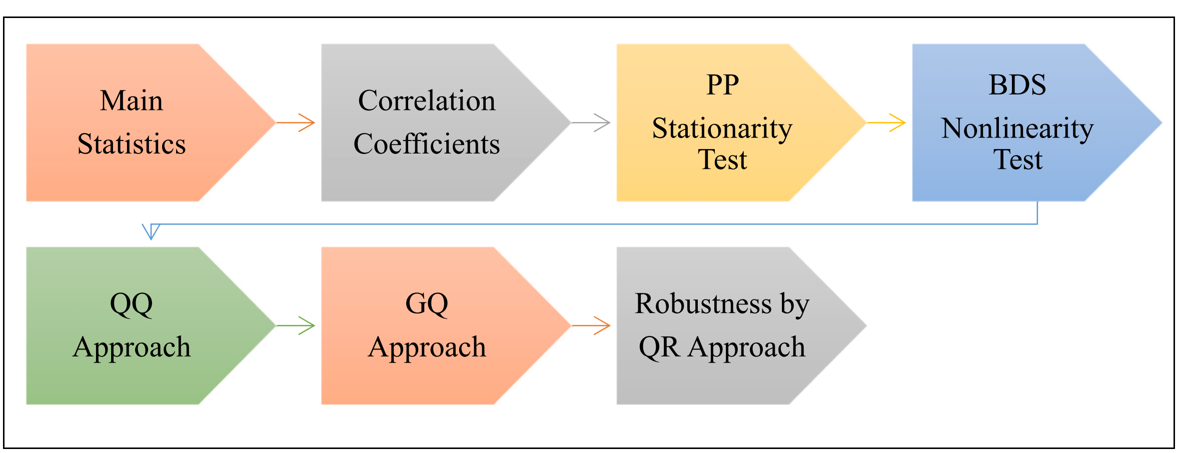

Fig. 2. Steps of empirical methodology.

Table 1
Main statistics.

Country	Variable	Mean	Median	Maximum	Minimum	SD	Skewness	Kurtosis	JB	Probability
Canada	NEU	0.22	0.22	0.25	0.18	0.02	−0.45	2.07	6.98	0.0304
	HEU	0.92	0.93	0.96	0.80	0.03	−1.09	4.95	35.17	0.0000
	SEU	0.00	0.00	0.02	0.00	0.01	0.94	2.64	15.11	0.0005
	WEU	0.04	0.03	0.09	0.00	0.03	0.44	1.47	12.85	0.0016
France	NEU	0.99	1.02	1.12	0.65	0.12	−1.22	3.95	28.45	0.0000
	HEU	0.15	0.15	0.20	0.10	0.02	0.16	3.12	0.50	0.7797
	SEU	0.01	0.01	0.05	0.00	0.02	1.04	3.07	17.76	0.0001
	WEU	0.04	0.03	0.14	0.00	0.04	0.72	2.57	9.38	0.0092
United Kingdom	NEU	0.16	0.16	0.25	0.08	0.04	0.05	2.22	2.55	0.2801
	HEU	0.01	0.01	0.02	0.01	0.00	−0.73	4.01	13.03	0.0015
	SEU	0.01	0.00	0.03	0.00	0.01	0.59	1.49	15.10	0.0005
	WEU	0.07	0.04	0.20	0.00	0.07	0.65	1.96	11.52	0.0032
United States	NEU	7.91	7.86	8.30	7.30	0.29	−0.53	2.33	6.46	0.0395
	HEU	2.65	2.68	3.42	2.12	0.26	0.40	3.37	3.25	0.1970
	SEU	0.46	0.05	2.35	0.01	0.66	1.44	3.92	37.84	0.0000
	WEU	1.48	1.24	4.18	0.05	1.33	0.58	2.08	9.13	0.0104

Notes: JB and SD denote Jarque-Bera and Standard Deviation, in order.

Table 2
Correlation coefficients.

Country	Variable	NEU	HEU	SEU	WEU
Canada	NEU	1.00			
	HEU	−0.23	1.00		
	SEU	−0.39	0.04	1.00	
	WEU	−0.28	0.05	0.20	1.00
France	NEU	1.00			
	HEU	0.28	1.00		
	SEU	−0.06	−0.14	1.00	
	WEU	0.07	0.12	−0.01	1.00
United Kingdom	NEU	1.00			
	HEU	0.10	1.00		
	SEU	0.18	0.08	1.00	
	WEU	0.28	0.67	0.12	1.00
United States	NEU	1.00			
	HEU	−0.21	1.00		
	SEU	−0.16	−0.06	1.00	
	WEU	0.21	0.46	−0.02	1.00

Notes: Values denote correlation coefficients.

Table 3
PP stationarity test result.

Country	Variable	PP		Result
		I(0)	I(1)	
Canada	NEU	0.0000	–	I(0)
	HEU	0.0001	–	I(0)
	SEU	0.0004	–	I(0)
	WEU	0.0001	–	I(0)
France	NEU	0.0001	–	I(0)
	HEU	0.0000	–	I(0)
	SEU	0.0000	–	I(0)
	WEU	0.0003	–	I(0)
United Kingdom	NEU	0.0101	–	I(0)
	HEU	0.0051	–	I(0)
	SEU	0.0173	–	I(0)
	WEU	0.0777	–	I(0)
United States	NEU	0.0000	–	I(0)
	HEU	0.0000	–	I(0)
	SEU	0.0000	–	I(0)
	WEU	0.0000	–	I(0)

Notes: Values show the p-values. Barlett Kernel is used to define lag length.

middle levels. Hence, it is clear that there is a certain displacement impact of HEU on NEU in Canada and the United States, whereas there is a complementary impact at lower and higher levels in the case of France and the United Kingdom. In the present literature, some studies (e.g., Ref. [29]) have defined that REU has a causal impact on NEU, whereas some other studies (e.g., Ref. [26–28]) have concluded a bidirectional causality between REU and NEU. So, consistent with the literature, the study determines a displacement impact between HEU and NEU, while it differentiates across quantiles and countries.

Also, Fig. 4 shows the results of the SEU on NEU across quantiles in the countries.

According to Fig. 4, there is a negative impact of SEU on NEU across all levels in Canada. It is almost the same for the United States except for lower levels, where there is an increasing impact of SEU on NEU. In France, there is a positive impact of HEU on NEU at lower levels, whereas there is a negative impact at middle and higher levels. In the United Kingdom, there is completely positive impact of HEU on NEU. For this reason, it can be stated that there is a certain displacement impact of HEU on NEU in Canada and mostly in France and the United States, whereas there is a complementary impact across almost all levels in the United Kingdom. In the current literature, some studies (e.g., Ref. [29]) have defined that REU has a causal impact on NEU, whereas some other studies (e.g., Ref. [26–28]) have concluded a bidirectional causality between REU and NEU. So, consistent with the literature, the study finds a displacement impact between SEU and NEU, whereas the impact varies across quantiles and countries.

Moreover, Fig. 5 shows the results of the WEU on NEU across quantiles in the countries.

According to Fig. 5, there is a negative impact of WEU on NEU across all levels in Canada. Reversely, there is a positive impact of WEU on NEU across all levels in the United Kingdom and the United States. In France, there is a positive impact of WEU on NEU at lower and middle levels, whereas there is a negative impact at higher levels. Thus, it can be concluded that there is a certain displacement impact of WEU on NEU in Canada and partially in France, whereas there is a complementary impact across all levels in the United Kingdom and the United States. In the contemporary literature, some studies (e.g., Ref. [29]) have defined that REU has a causal impact on NEU, whereas some other studies (e.g., Ref. [26–28]) have concluded a bidirectional causality between REU and NEU. So, compatible with the literature, the study states a displacement impact between WEU and NEU, while it differentiates across quantiles and countries.

4.3. GQ results

As the sixth step of empirical methodology, the study performs the GQ approach to uncover the causal impact of REU types on NEU across quantile countries, which is reported in Table 5.

According to Table 5, there are causal impacts of REU types on NEU across various quantiles in the countries. Specifically, REU types have a causal impact on NEU across all quantiles except for 0.05–0.15,

Table 4
BDS nonlinearity test results.

Country	Variable	DS2	DS3	DS4	DS5	DS6	Result
Canada	NEU	0.0042	0.0437	0.1660	0.0326	0.0168	M
	HEU	0.0224	0.4470	0.5961	0.9237	0.4608	M
	SEU	0.0000	0.0000	0.0000	0.0000	0.0000	NL
	WEU	0.0000	0.0000	0.0000	0.0000	0.0000	NL
France	NEU	0.0000	0.0003	0.0013	0.0006	0.0000	NL
	HEU	0.6333	0.0284	0.0009	0.0504	0.3110	M
	SEU	0.0000	0.0000	0.0000	0.0000	0.0000	NL
	WEU	0.0000	0.0000	0.0000	0.0000	0.0000	NL
United Kingdom	NEU	0.0035	0.1132	0.3770	0.0866	0.0300	M
	HEU	0.8441	0.2618	0.1198	0.6898	0.9595	L
	SEU	0.0000	0.0000	0.0000	0.0000	0.0000	NL
	WEU	0.0935	0.9332	0.2428	0.8735	0.7281	M
United States	NEU	0.0000	0.0001	0.0046	0.0004	0.0002	NL
	HEU	0.0004	0.0202	0.1218	0.0125	0.0049	M
	SEU	0.0000	0.0000	0.0000	0.0000	0.0000	NL
	WEU	0.0000	0.0000	0.0000	0.0000	0.0000	NL

Notes: Values show the p-values. DS, L, M, and NL denote the dimensions, linear, mixed, and nonlinear, in order.

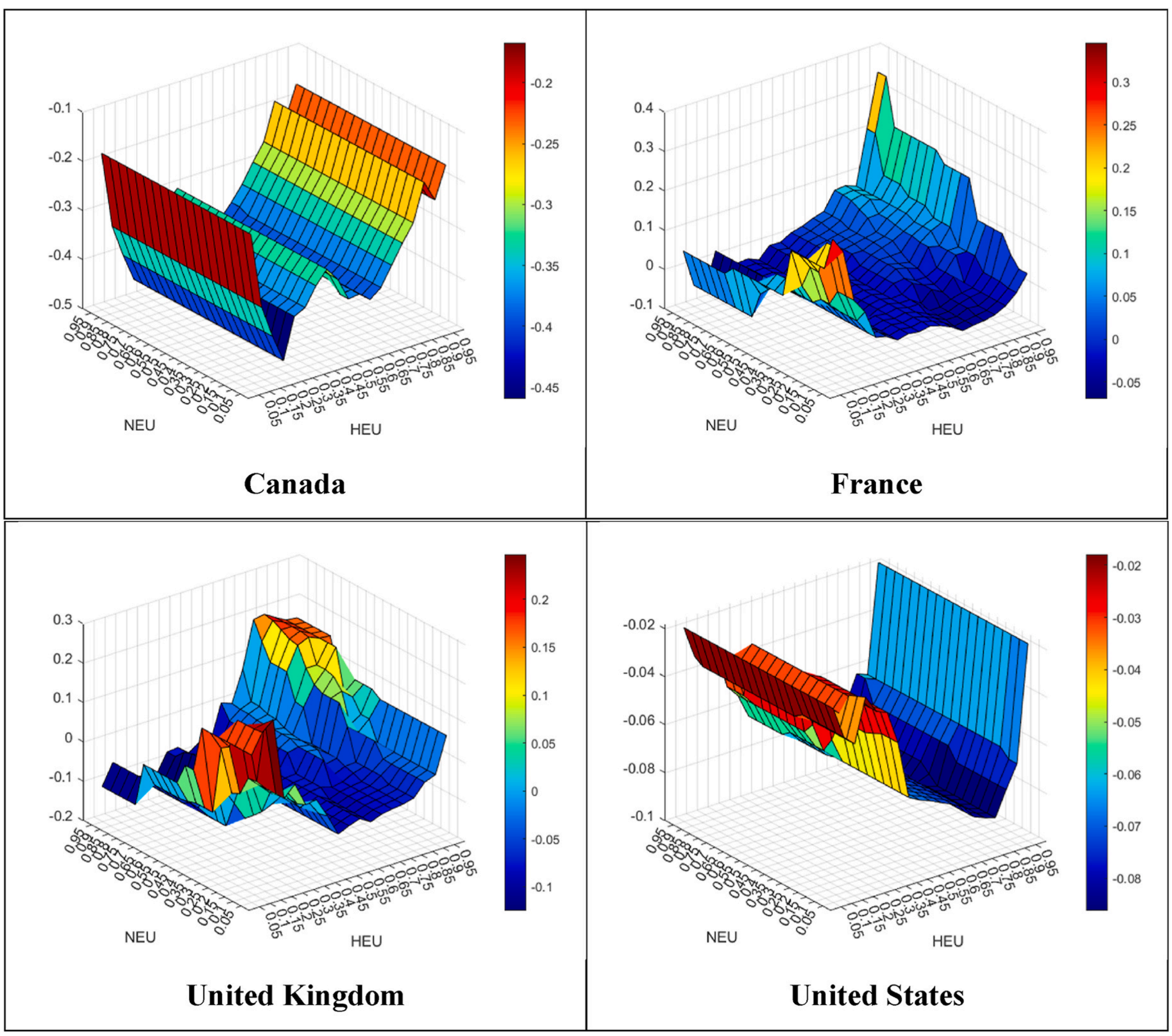

Fig. 3. QQ results for HEU impact on NEU

0.40–0.45, 0.55, 0.90–0.95 in Canada. In France's case, REU types have a causal impact on NEU across all quantiles except 0.05, 0.50, and 0.95. In the United States, REU types have a causal impact on NEU across all quantiles except for 0.05–0.15, 0.35–0.60, and 0.95. A bit differently, in the case of the United Kingdom, there is again a causal impact of REU types on NEU, however, the impact differentiates across REU types and quantiles. Hence, the GQ results show that there are certain causal impacts of REU types on NEU across quantiles and countries, which are consistent with the present studies in the literature (e.g., Ref. [26–29]) that have defined either unidirectional or bidirectional causality between REU types and NEU.

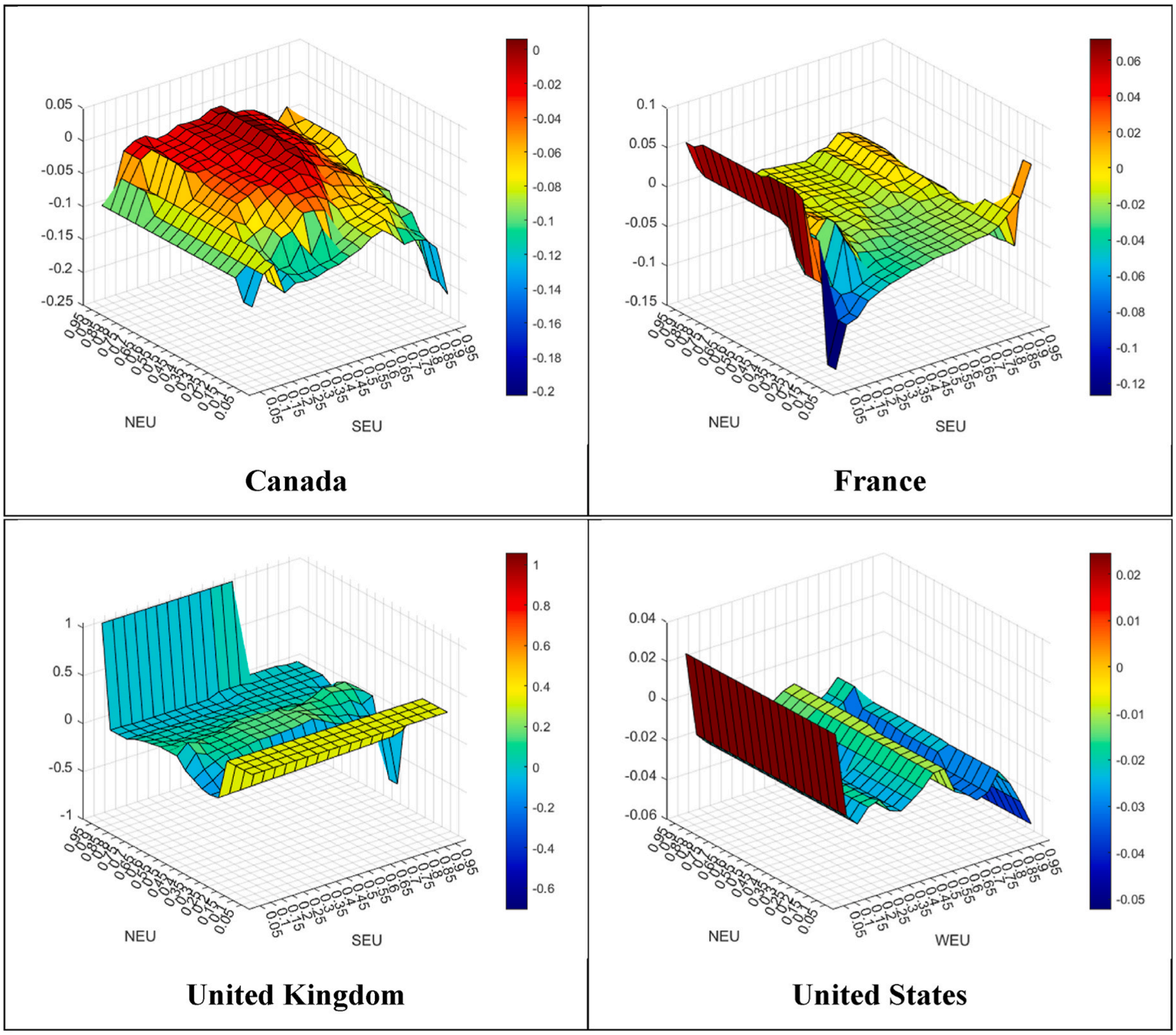

Fig. 4. QQ results for SEU impact on NEU

4.4. *Robustness check by QR approach*

As the last step of empirical methodology, the study performs the QR approach for a robustness check of the QQ results, which are detailed (summarized) in Annex 1–3 (Table 6).

As can be seen in graphs in Annex 1–3 and the summary reported in Table 6, the results of the QQ and QR approaches are above 89 %. Hence, the results of both QQ and QR approaches are highly identical, which reveals the robustness of the empirical results obtained from quantile approaches.

4.5. *Summary of the empirical results*

Following the completion of the empirical analysis, Table 7 summarizes the results.

As summarized in Table 7, there is certainly a negative relationship between REU types and NEU in Canada, which empirically reveals the displacement impact. Adversely, there is almost completely positive relationship between REU types and NEU in the United Kingdom, which empirically reveals the complementary impact. On the other hand, for both France and the United States, there are mixed conditions regarding the displacement impact of REU types on NEU, where displacement impact is much more powerful in lower quantiles and much weaker in middle and higher quantiles.

4.6. *Discussion and policy implications*

The results of the quantile approaches, which are summarized in Table 6 comparatively, imply that the empirical findings obtained are consistent across various empirical approaches and robust. Therefore, the study discusses various policy implications through considering the empirical results gathered from quantile approaches.

It is critical to consider the bivariate relationship between REU types and NEU. In this context, in the case of the HEU-NEU relationship, HEU has a certain displacement impact on NEU across all quantiles in Canada and the United States, where there is a competition for economic sources between HEU and NEU. So, these countries should care about the distribution of economic, financial, and natural resources between HEU and NEU. Accordingly, to prevent this negative displacement impact, both Canada and the United States should re-plan their energy mix, where HEU has a big share in Canada and a low share in the United States. By defining how big a share the policymakers are going to dream for the coming times, accordingly, they should allocate resources so that the displacement can be prevented. On the other hand, the case for the HEU impact on NEU is mixed for France and the United Kingdom. There is a complementary (substitute) impact of HEU on NEU across various low and higher (middle) quantiles. This determination implies that while lower and higher amounts of HEU and NEU have a supportive characteristic for each other, it may cause a displacement at the middle level, which is rather than the beginning or maturity level. Considering

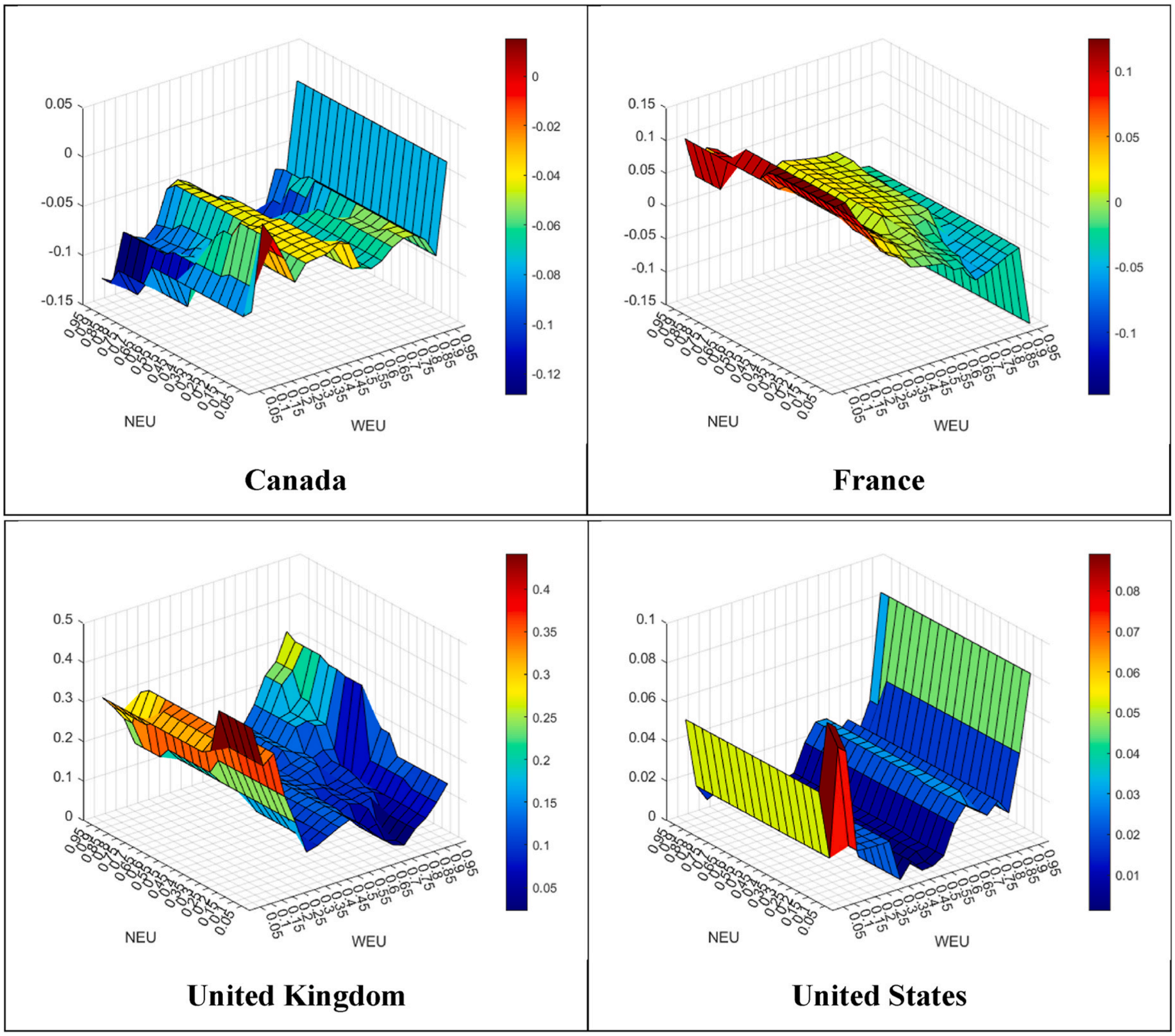

Fig. 5. QQ results for WEU impact on NEU

this fact, both France and the United Kingdom should care that they should have either below or higher levels of HEU from a threshold so that they can benefit from this level in ensuring the supportive impact of HEU on NEU. In this context, they should continuously follow up on the level of HEU in the total energy mix and make necessary arrangements for the allocation of economic and natural sources to ensure the achievement of enough HEU in the total energy mix.

In the case of the SEU-NEU relationship, there is a certainly displacement impact of SEU and NEU in Canada. Hence, Canada should again ensure a balanced distribution of its sources between SEU and NEU harmoniously consistent with the energy mix targeted for the coming years. Conversely, the United Kingdom has the capability that there is a supportive relationship between SEU and NEU. Hence, they can rely on further increase of SEU to support the progress of NEU. Hence, they can ensure that the share of both SEU and HEU in the total energy mix will continue at the same levels. On the other hand, France and the United States have a mixed condition for the impact of SEU on NEU. It requires these countries to decide upon the desired energy mix for the coming period. Accordingly, they should take necessary measures in balancing with the EU from solar and nuclear sources by considering that there is a displacement impact across the middle and higher levels.

In the case of the WEU-NEU relationship, Canada has a certain displacing impact on WEU and NEU. Therefore, Canada should ensure a balanced distribution of its sources between WEU and NEU in an appropriate and compatible manner with the energy mix goal for the upcoming times. Conversely, there is a certain complementary impact of WEU and NEU in the United Kingdom, the United States, and at lower and middle levels in France, which enables these countries to supporting the progress of both WEU and NEU simultaneously. Hence, they can have the opportunity to supporting new investments through various measures, such as financial incentives, long-term purchasing agreements, and credits, in any of these areas, where they make an increasing impact is also another one.

Also, it is important to consider country-based cases. Among the countries under the investigation, unfortunately, Canada has the worst condition because there are displacing impacts from REU types (i.e., HEU, SEU, & WEU) to NEU. These conditions force Canadian policymakers to distribute to sources (i.e., economic & natural) among clean energy alternatives. Conversely, the United Kingdom can benefit from almost all REU types in supporting the progress of NEU because there are complementary impacts. From this point of view, the case of France and the United States is mixed, where the United States can benefit from WEU across all levels in supporting the progress of NEU and France can benefit from REU types across some specific levels. So, the countries should consider at which levels they have EU from renewable and nuclear sources. Accordingly, they can re-plan their energy mix predictions across the years so that they can prevent a displacing impact between clean energy sources in their efforts into energy transition [8].

Moreover, it is significant to consider quantile-based variations. The

Table 5
GQ results.

Country	Causality Path	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90	0.95
Canada	HEU⇒NEU	1.00	0.12	0.08	0.03	0.02	0.02	0.03	0.09	0.76	0.03	0.18	0.02	0.02	0.02	0.02	0.02	0.02	0.83	1.00
	SEU⇒NEU	1.00	0.12	0.08	0.03	0.02	0.02	0.03	0.20	0.76	0.03	0.18	0.02	0.03	0.02	0.02	0.02	0.02	0.83	1.00
	WEU⇒NEU	1.00	0.12	0.08	0.03	0.02	0.02	0.03	0.09	0.76	0.03	0.18	0.02	0.03	0.02	0.02	0.02	0.02	0.83	1.00
France	HEU⇒NEU	0.08	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.89	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	1.00
	SEU⇒NEU	0.08	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.89	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	1.00
	WEU⇒NEU	0.08	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.89	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	1.00
United Kingdom	HEU⇒NEU	1.00	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.21	0.56	0.55	0.02	0.02	0.02	0.02	0.06	0.02	0.02	0.24
	SEU⇒NEU	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.62	0.23	0.35	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.08
	WEU⇒NEU	1.00	0.17	0.09	0.02	0.02	0.02	0.08	0.08	0.80	0.20	0.18	0.03	0.02	0.02	0.02	0.32	0.17	0.91	1.00
United States	HEU⇒NEU	1.00	0.18	0.06	0.02	0.02	0.02	0.12	0.14	0.14	0.14	0.62	0.14	0.03	0.02	0.02	0.02	0.02	0.02	1.00
	SEU⇒NEU	1.00	0.18	0.06	0.02	0.02	0.02	0.12	0.14	0.14	0.14	0.62	0.14	0.03	0.02	0.02	0.02	0.02	0.02	1.00
	WEU⇒NEU	1.00	0.18	0.06	0.02	0.02	0.02	0.12	0.14	0.14	0.14	0.62	0.14	0.03	0.02	0.02	0.02	0.02	0.02	1.00

Note: Numbers represent p-values. The null hypothesis is that the first variable does not granger cause the second variable.

Table 6
Summary of the QQ and QR comparison.

Country	Correlation (%)		
	HEU on NEU	SEU on NEU	WEU on NEU
Canada	99.82	93.20	94.29
France	91.17	94.31	98.78
United Kingdom	89.63	91.23	94.27
United States	98.61	99.75	98.42

Table 7
Summary of the results.

Country	Variables	Impact of REU Types on NEU at		
		Low Quantiles	Middle Quantiles	Higher Quantiles
Canada	HEU on NEU	–	–	–
	SEU on NEU	–	–	–
	WEU on NEU	–	–	–
France	HEU on NEU	+	–	+
	SEU on NEU	+	–	–
	WEU on NEU	+	+	–
United Kingdom	HEU on NEU	+	–	+
	SEU on NEU	+	+	+
	WEU on NEU	+	+	+
United States	HEU on NEU	–	–	–
	SEU on NEU	+	–	–
	WEU on NEU	+	+	+

Notes: + and - denote the increasing and decreasing impact, in order.

empirical results show that the impact of REU types on NEU can be differentiating across various quantiles for certain REU types. For instance, HEU impact on NEU in France and the United Kingdom, SEU impact on NEU in France, and WEU impact on NEU in France and the United States changes across quantiles. Hence, assuming the relationship between REU types and NEU as linear may be a big mistake for the countries, which may cause harmful results on the energy transition policies of the countries. Accordingly, the countries should consider the nonlinear impact of REU types on NEU for better planning.

Furthermore, it is possible to state that there is no similar solution for all countries. Instead, each country should consider its conditions that are highlighted by the empirical results. That is why because there may be structural variation in energy generation and use across quantiles. Even so, it may be valid across economic sectors. Hence, structural change in energy generation and use over the years should be also taken into account within the scope of energy transition planning. Also, it is critical for the countries to work on energy efficiency [40] and the structure of the electricity grid [41]. That is why because these points are directly related to the use of energy across various areas and sectors in the economies. Therefore, these are highly effective in terms of energy transition policies of countries, where clean energy sources are included.

By relying on the empirical results, a set of policy implications has been argued above. Hence, the investigations present quantile-based insights through applying comprehensive theoretical and empirical approaches. Thus, it can be aimed to be helpful to the policymakers of the countries under the empirical examination by discussing various issues among main clean energy types so that they can structure their macro energy transition plans by considering displacement. Consistent with the empirical findings and policy implications discussed, it is critical to make energy transition plans harmonized and benefit from main clean energy types as much as it is possible for the countries. In this way, the countries can get the highest benefit from the use of clean energy types in trying to be carbon-neutral, slow down climate change, and curb CO_2 emissions resulting from energy use.

5. Conclusion

Under the adverse impact of climate-related issues as well as the forcing impact of the recent energy crisis, the energy transition issue has become highly important for all countries. Compatible with the developing societal interest in these issues, all countries have been trying to be carbon neutral by ensuring a clean energy transition. So, countries and policymakers have been aiming to stimulate further use of clean energy alternatives to replace fossil fuel ones. In this way, countries expect some potential benefits, such as using further clean energy, lowering the use of fossil fuel energy, curbing CO_2 emissions, decreasing environmental degradation, slowing down climate change, and ensuring decarbonization of economies and sectors.

Countries have mainly two options (i.e., renewable & nuclear energy sources) to ensure energy transition. Naturally, there are various options within the scope of renewable energy. On the other hand, hydro, solar, and wind are the main renewable alternatives that have been used over the years, whereas some other new types of renewable (e.g., biofuel) have recently emerged. By considering that the economic and natural sources of countries are limited, which requires the distribution of these sources among alternatives, this study examines leading developed countries to determine whether there is a displacement between main renewable energy types and nuclear energy. Accordingly, the study examines four leading countries (namely, Canada, France, the United Kingdom, & United States) by considering the main renewable and nuclear energy types (i.e., HEU, SEU, WEU, & NEU), using data from 1999/Q2 to 2023/Q4, and applying quantile approaches. In this way, the study empirically and comprehensively investigates the displacement through considering country and quantile-based differentiating impact of REU types on NEU.

The study determines the complete displacement impact of all REU types on NEU for Canada cases across all quantiles as well as the varying impact for the remaining countries across various quantiles. While the study presents new insights about the displacement between REU and NEU, it achieves consistent results with the current literature (e.g., Ref. [26–29]), however, extends the knowledge upon the displacement between clean energy types across countries and quantiles.

Considering the empirical results, the study discusses various policy implications for each clean energy type for the countries examined. Also, the study empirically reveals that there is no opportunity to apply global policies to ensure energy transition. Instead, each country should consider its own condition and re-structure energy transition planning by considering displacement risk between clean energy alternatives. Hence, they can have the opportunity to ensure energy transition by preventing displacement through comprehensive energy transition planning.

By focusing on the four leading developed countries, the study tries to present fresh insights into the displacement between clean energy alternatives. Nevertheless, the study has some limitations. Considering the content of the study, it can be suggested that future research can either deal with emerging countries or consider examining both developed and emerging countries together in a comparative way. Also, further disaggregated level components of renewable energy can be included in new studies because there are recently emerged alternatives (e.g., biofuel). Besides, a potential displacement only between renewable energy types can be analyzed. Moreover, other variables, and some other critical points that may be effective on the displacement between clean energy alternatives, such as environmental factors, economic drivers, and structural variation in energy structure, can be considered in the formulation of future research. Furthermore, much higher-frequency data and other econometric (e.g., time and frequency-based; machine learning algorithm-based) approaches can be used in new studies. Hence, the empirical literature on the displacement between clean energy alternatives can be extended further.

CRediT authorship contribution statement

Mustafa Tevfik Kartal: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Project administration, Investigation, Formal analysis, Conceptualization. **Shahriyar Mukhtarov:** Writing – review & editing, Writing – original draft. **Nigar Hajiyeva:** Writing – original draft.

Disclosure statement

The authors certify that they have NO affiliations with or involvement in any organization or entity with any financial interest (such as honoraria; educational grant; participation in speakers' bureaus; membership, employment, consultancies, stock ownership, or other equity interest; and expert testimony or patent-licensing arrangements), or non-financial interest (such as personal or professional relationships, affiliations, knowledge or beliefs) in the subject matter or materials discussed in this manuscript.

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Data will be made available on request.

Ethics approval and consent to participate

Not applicable.

Consent for publication

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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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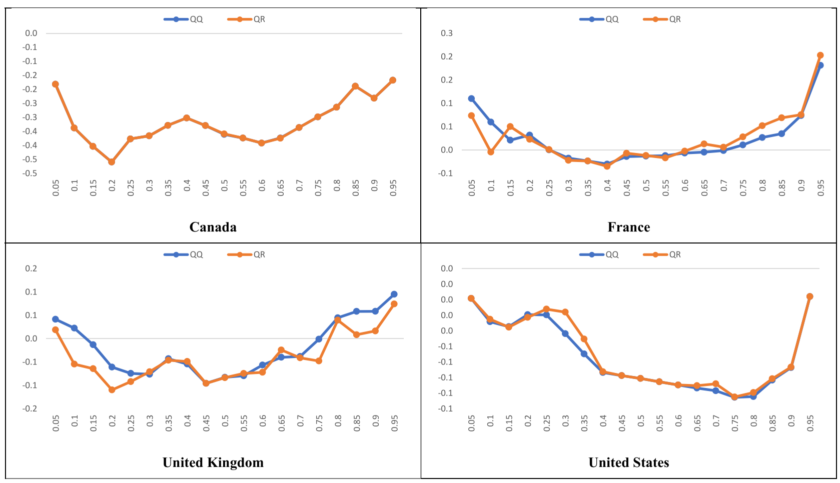
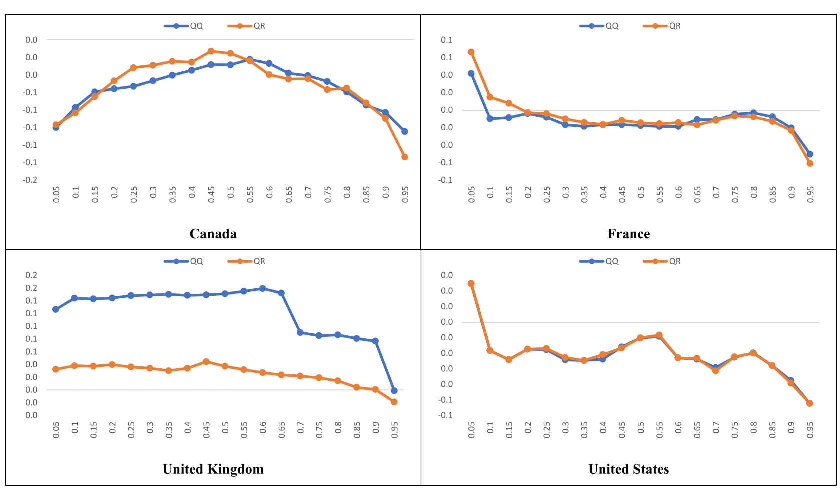
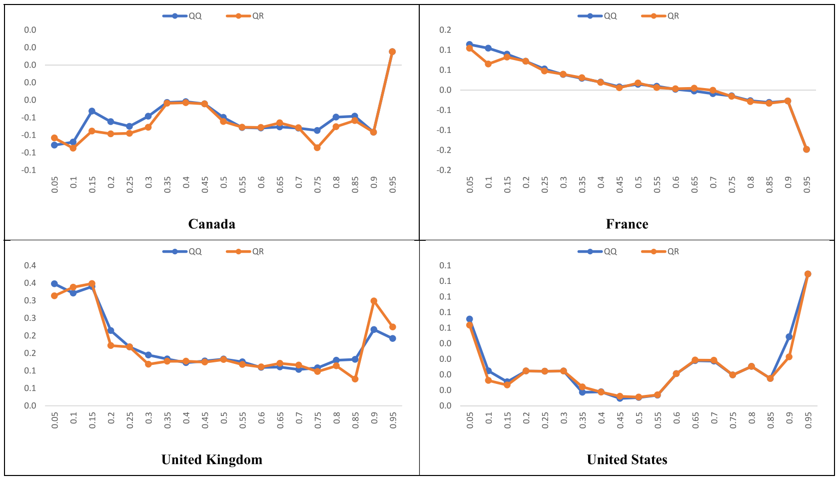
Annex 1. QQ and QR Comparison for HEU Impact on NEU



Annex 2. QQ and QR Comparison for SEU Impact on NEU



Annex 3. QQ and QR Comparison for WEU Impact on NEU



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