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Environmental benefits of nonrenewable energy efficiency and renewable energy intensity in the USA and EU: Examining the role of clean technologies

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ABSTRACT

Given that the United States of America and European Union are among the world's top greenhouse gas emitting economies, it poses yet to be answered questions on whether efficient utilization of nonrenewable energy sources or renewable energy intensification in these economies account for any environmental benefit. To answer these inherent questions, this study examines and compares environmental performances of the economies in response to nonrenewable energy efficiency, renewable energy intensity, and environmental-related technologies while controlling for natural resource rent and urban population over the period 1990–2019. By implementing the advantage of Kernel-Based Regularized Least Squares alongside robustness measures, the findings posit that nonrenewable energy efficiency, renewable energy intensity, and environmental-related technologies significantly mitigates greenhouse gas (GHG) emission in the economies. Importantly, while the three metrics show louder environmental impact in the EU, nonrenewable energy efficiency plays a louder and environmentally desirable role than the other two metrics. Conversely, natural resources and urbanization significantly hampers environmental sustainability by increasing GHG emission in the economies. Unfortunately, a terribly more damaging environmental impact arising from increased urbanization is noticeable in the EU. These findings afford concrete policy measures to be further devised for the USA and EU, and the entire globe given the foresight of net zero target.

Acronyms

ADF	Augmented dickey Fuller
CCE	Common Correlated Effects
CD	cross-sectional dependence
CO_2	Carnon Emissions
EU	European Union
ET	Environmental Technologies
DOLS	Dynamic ordinary least squares
FMOLS	Fully modified ordinary least square
GHG	Greenhouse Gas Emissions
IEA	International Energy Agency
NZE	Net Zero Emissions
NREE	Non-Renewable Energy Efficiency
NDCs	Nationally determined contributions
PP	Phillip Perron
SDG	Sustainable Development Goal
USA	United States America
UR	Urbanization

Introduction

Given the overarching benefit of energy efficiency, a 4 percent annual improvement in the global energy intensity is encouraged to safe the world from failing to attain the 2050 net-zero emissions target i.e the 2050 Net Zero Emissions (NZE) Scenario [25]. Keeping that in focus for the Stated Policies (SP) Scenario, it is also envisioned that global energy intensity should improve by 3.2 percent annually in the next decades to

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achieve the Sustainable Development Goal (SDG) 7 target. As a mechanism, series of mandatory policies are considered effective to drive down the energy-to-output conversion cost, i.e improving energy efficiency. In addition to the use of financial and fiscal incentives such as subsidies for buiding maintenance and purchase of electric vehicles, the strict adoption of codes and standards for energy performance, industry targets, and building energy are considered essential toward improving energy efficiency. With the SP Scenario (projection), the International Energy Agency [25] report shows that though the fastest improvements are noticeable among the Asian developing and emerging economies that could cause a 2.2 percent per annual improvement in global energy intensity between 2020 and 2030, yet that is not sufficient to meet the SDG) 7 target. Therefore, the NZE Scenario is found most suitable approach in meeting both the SDG 7 target and as well as the 2050 NZE target. However, the NZE Scenario is not attainable without adopting most stringent energy transition policies that include improvement in household and industrial sectors, energy efficiency standards, and adoption of electric vehicles for transportation.

Given this outlook, global coordination of energy efficieny policies through countries' nationally determined contributions (NDCs) is as important as the specific roles of the developed (regional) economies such as the United States of America (USA) and the European Union (EU). Attesting to countries' committment to improve energy efficiency, the USA and EU have consistently slowed their respective energy intensities by $\sim$ 2 percent every year since 2000, except in 2021 when the coronavirus (COVID-19) pandemic slightly inhibited the progress [20]. Amidst the annual improvement of $\sim$ 2 percent in energy efficiency, the energy mix of the two economies remained largely dominated by conventional energy sources, thus suggesting unabated challenges. For instance, the EU's energy mix as at 2020 is put at 35 percentt of petroleum products, 24 percent of natural gas, 17 percent of renewable energy sources, 13 percent of nuclear energy, and 12 percent of solid fossil fuels (European [18]. Meanwhile, for the USA, the country's primary energy sources is a mix of 36 percent of petroleum products, 32 percent of natural gas, 12 percent of nrenewables, 8 percent of nuclear energy power, and 11 percent of coal [43]. Evidently, from these economies' energy mix figures, it does indicate that fossil fuel and renewable energy sources are almost within thesame composition, although the EU demostrates slightly higher renewables capacity. Interestingly, these economies have equally cut greenhouse gas (GHG) emissions at least from 1990 emission level, thus informing on the environmental performance over time. Specifically, in the EU, GHG emission was mitigated by over 1.5 billion tonnes of CO_2 (carbon dioxide) between 1990 and 2020 ($\sim$32 percent reduction) across the sectors, with the exemption of transport sector which maintained a 7 percent increase in GHG emissions over the same period [46]. Relatively, with a 7 percent reduction in GHG emission over the same period [44], the USA clearly have more environmental challenges to contend with.

Therefore, the queries that glaringly ensue from the above motivation are from the environmental sustainability and energy efficiency dimensions of these economies. All nations including the EU and the USA are required by the recent concluded COP27 in Sharm el-Sheikh to create a special fund for damage and loss, preserve an unambiguous commitment to keep 1.5 °C within reach, hold institutions and businesses accountable, mobilise more financial support for emerging economies, and shift towards implementation. Specifically, the objective of the study is conceived from the questions about the environmental performances related to: (i) the criticality of conventional energy source efficiency, (ii) intensification of renewable energy sources, (ii) the role of environmental-related technologies, and (iv) the comparative evidence from the USA and EU in respect to the two previous questions. The choice of the case (the USA and EU), among the several reasons provided above, is also because the economies are the world leading polluters, have the most ambitious net zero targets, and almost share the same capacity additions of renewables [26]. Moreover, energy efficiency is arguably a potent and unavoidable approach in navigating the NZE target. In novelty, while the role(s) of nonrenewable and renewable energy profiles in environmental quality are well-covered in the literature, there is a questionably sparse attention on the criticality of the efficient utilization of nonrenewable energy sources and intensification of renewable sources. This investigation is vital because it further probes whether investment in energy efficiency technologies designed for nonrenewable energy sources is still worth undertaken given the increasing adoption of renewable and clean technology development. Thus, by providing a country-level investigation through an empirically econometric approach, the result is positioned to provide a concrete addition to the body of knowledge and useful guide for policy makers.

The other parts of the study are arranged such that the selected and related studies are briefly discussed in section 2. In section 3, the utilized variables and empirical methods are highlighted while the result are presented in section 4. The discussion of the results and summary of the study are respectively presented in sections 5 and 6.

Literature review

Generally, as documented in the literature, energy efficiency and renewable energy both provide vital and desirable solution in driving environmental sustainability. For instance, Özbuğday and Erbas [36] employed the estimator approach of common correlated effects (CCE) which account for heterogeneity and cross-sectional dependence (CD) for 36 countries over the period 1971–2009 to investigate the effect of renewable energy and energy efficiency on CO_2 emissions. In the study, energy efficiency index was constructed such that the panel result reveals that CO_2 emission is significantly mitigated by energy efficiency in the long run. Moreover, by accounting for the impact of renewable energy while controlling for other factors, CO_2 emission is also mitigated by a statistically significant degree. Similalry, Akdag and Yıldırım [5] estimated energy efficiency as ratio of Gross Domestic Product (GDP) to total domestic primary energy consumption and examined its impact of aggregate GHG emission in the panel of 28 EU countries (EU-28) and Turkey over the period 1995–2016. By using the combination of Granger causality by Emirmahmutoglu and Kose [17] and long-run estimator of fully-modified and dynamic ordinary least square (i.e., FMOLS and DOLS), the result shows that GHG emission decline significantly with increase in energy efficiency in the panel. Additionally, the country-specific result further implies that energy efficiency Granger causes GHG emissions in Austria, Bulgaria, Estonia, Germany, Hungary, Iceland, Italy, Latvia, Netherlands, Norway, and Poland.

Mirza et al. [34] is another study that examined the contribution of renewable energy and energy efficiency on carbon emission mitigation. This study is based on the case of 30 developing countries while controlling for the effects of structural shift, income and industrialization over the examination period 1990–2016. The result shows that energy efficiency has larger influence to reducing CO_2 emission across the selected panel than structural shift that arises from economic activities. Renewable energy utilization also mitigate CO_2 emission while income and industrialization are causing more urge of carbon emission. While Mirza et al. [34] is based on cross-sectional autoregressive distributed lag (CS-ARDL) and other mean-value estimation approaches within the Environmental Kuznets curve (EKC) framework, Awan et al. [9] applied panel quantile regression approach but also within the EKC framework. A broader case is being considered in Awan et al. [9], that is a panel of 107 countries over the period 1996–2014. The result shows that energy efficiency mitigates CO_2 emission across the quantiles with its impact is minimal at the higher quantile of CO_2 emission. Additionally, while also validating the EKC hypothesis, the result illustrates that renewable and non-renewable energy mix respectively reduce and increase the surge of CO_2 emission across the quantiles.

While most studies such the above-discusssed ones used total primary energy in computing energy efficiency index, other studies also deployed different energy sources in measuring the specific energy efficiency/saving potential such as Coal, diesel oil, and electricity saving [33], fossil energy saving[13], and coal-fired power[41]. For instance, Chen and Geng [13] proposed (four) strategies for energy saving and emission reduction (ESER) scenario while usinf fossil energy for 30 countries i.e., 26 OECD (Organization for Economic Cooperation and Development) countries and Brazil, Russia, India, and China. The result which is based on the computation of non-radial Malmquist index (NMI) reveal that fossil energy saving approach has the potential of mitigating CO_2 emissions with an underestimated performance in most countries. Importantly, higher performance of fossil ESER is observed in most developed countries such as United Kingdom, South Korea, France, Norway, and Ireland clearly because of resources endowment, and advancement in technology and renewable energy development. On the other hand, lowest fossil ESER performance is reported against Canada, Russian, and China. By grouping the countries based on the amount of renewable energy consumption and the ESER performance, the result lacks significant evidence that amount of renewable energy utilization and the ESER performance are correlated, and there technological progress and ESER performance are not in sync.

After careful review of the past studies, investigations have been documented regrading the drivers of GHG emissions within the coffin of single and group of nations. It is clear that sevreal studies on the impact of urbanisation and natural resources on GHG emissions have been documented (see [11,24,38]. Similarly, several studies have been documented regarding the role of environmental technologies in limiting GHG emissions (See [48,29]. Similarly studies on the connected bewteen energy intensity and ecological deterioration is well documented in literature [37,40,42]. However, studies of the effect of non-renewable energy efficiency and renewable energy intensity on GHG emissions is scant in empirical literature. Specifically, no study available on the effect of non-renewable energy efficiency and renewable energy intensity on GHG emissions using both EU and USA as a comparative analysis. Given the review of these selected studies, there is a clear gap that the literature is yet provide a robust knowledge on the comparison analysis of environmental perforamance roles of non-renewable energy efficiency and renewable energy intensity. Therefore, by doing a comparative investigation for the USA and the EU, this study is providing a closer perspective on the subject and by so doing enriching the body of knowledge for the first time. Furthermore, unlike prior studies (See [48,29,40,42], that does not consider the non(linearity) attributes of series, the current investigation considers the non (linearity) of the variables by employing the Kernel-Based Regularized Least Squares (KRLS) developed by Hainmueller and Hazlett [23].

Data, model and methodology

The utilized data for the investigation covers the period 1990–2019 for each of the USA and EU (specifically the EU-27). Where necessary such as the energy efficiency and intensity indicators, computations were made by the authors. Detail information about the variables are presented in Table 1. Then all these annual frequency data are transformed into logarithmic values (denoted as ln) and converted to quarterly frequencies using the quadratic match-sum method to avoid problems with small observations.

Statistics properties

Meanwhile the raw value series plots of the cases are displayed in Fig. 1. Importantly, each of the series for the cases tends to follow similar trend over the examined period. It is crucial to comprehend brief information regarding the series of investigations prior to the main analysis. Table 2 presents EU and USA variables' statistical information. For the USA and EU, InNR is more volatile while InGHG is less volatile. As shown by the kurtosis value, all variables are platykurtic with the exemption of InNR, which is leptokurtic for USA while for EU, all the variables are platykurtic. Moreover, the skewness value shows that all the series are skewed negatively for the USA except InNREE and InET, which are skewed positively. In contrast, for the EU, all series are positively skewed with the exemption of InGHG, which is negatively skewed. Lastly, the JB pvalues show that all the series do not comply with normal distribution for the EU and USA. Thus, the Ho hypothesis of "normal distribution" is dismissed for all the variables. This knowledge regarding the characteristics of the variables affirms that using a linear approach in evaluating the connection between the variables will produce unreliable results.

Table 1
Data description.

Variable	Sign	Measurement	Source
Environmental Degradation	GHG	Greenhouse gas emissions (tonnes per capita)	OWD [31]
Non-Renewable Energy Efficiency	NREE	$\frac{GDP}{NREU}$($/kWh) where GDP is gross domestic product PPP (constant 2017 international $ per capita) and NREU is non-renewable energy usage (kWh per capita)	OWD [31]
Renewable Energy Intensity	REI	$\frac{REU}{GDP}$(kWh/$) where REU is renewable energy usage (kWh per capita)	OWD [31]
Environmental Technologies	ET	Patents in environment-related technologies (% of total)	OECD [30]
Natural Resources	NR	Total natural resources rents (% of GDP)	WDI [45]
Urbanization	UR	Urban population (% of total population)	WDI [45]

Model and empirical method

Environmental impact of human activities was initially conceived and presented through an econometric-based model named 'Stochastic Impacts by Regression on Population, Affluence and Technology'[21], Dietz & Rosa, 1997; [47]. Following these earlier studies, environmental impacts have been expanded to several other aspects including energy efficiency or intensity, and socioeconomic aspects such as institution quality, environmentally responsible behaviour, and environmental-related innovations e.t.c. [5,14,10,7,2]. Given that our variable selection accounts for affluence, population, and technology, the model adopted for this investigation is presented as

$$lnGHG = f(lnNREE, lnREI, lnET, lnNR, lnUR) \tag{1}$$

Given the model in equation (1), the empirical method follows the flowchart depicted in Fig. 2. To begin with, the as a prerequisite, relevant tests including stationarity and (non)linearity are conducted to provide the necessary direction for the coefficient estimation. Following the non-normality (see JB in Table 2) results, the Kernel-Based Regularized Least Squares (KRLS) developed by Hainmueller and Hazlett [23] method is found appropriate for this study. The step-by-step illustration and representation of KRLS is not provided here because of limit space, however, this information is well-documented in Hainmueller and Hazlett [23].

Empirical results

In order to support JB results, we also perform 3 unit root and nonlinearity tests. These results are first considered before going ahead with the KRLS estimation.

Stationarity tests

First the study used two conventional unit root tests (16) (ADF and PP) to evaluate the series stationarity characters (see Table 3). For the USA, all series are non-stationary at level as presented by the ADF results, while for the PP results, only InUR is stationary at level. Similarly,

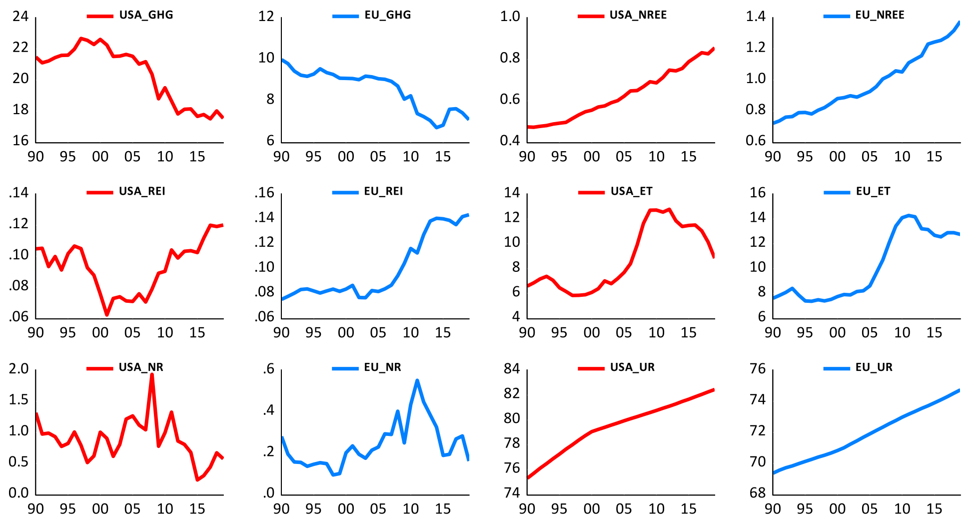

Fig. 1. Visualization of series trend.

Table 2
Summary statistics.

	Mean	Std. Dev.	Skew.	Kurt.	JB	Prob.
Panel A: USA						
lnGHG	0.752	0.023	−0.505	1.618	14.646***	0.000
lnNREE	−0.120	0.048	0.109	1.696	8.742**	0.013
lnREI	−0.597	0.045	−0.433	2.102	7.790**	0.020
lnET	0.533	0.070	0.232	1.442	13.211***	0.001
lnNR	−0.053	0.108	−0.896	4.330	24.925***	0.000
lnUR	1.094	0.006	−0.529	2.239	8.483**	0.014
Panel B: EU						
lnGHG	0.535	0.029	−0.695	2.028	14.389***	0.001
lnNREE	−0.009	0.048	0.283	1.832	8.426**	0.015
lnREI	−0.583	0.059	0.653	1.699	16.980***	0.000
lnET	0.571	0.064	0.266	1.281	16.196***	0.000
lnNR	−0.377	0.108	0.135	2.532	1.458	0.482
lnUR	1.069	0.006	0.118	1.702	8.705**	0.013

Note: ***, **, and * symbolize non-normality at the 1%, 5%, and 10% confidence levels, respectively. JB is the Jarque & Bera [27] normality test.

for the EU nations, all the series are non-stationary at a level as shown by both PP and ADF, respectively. As stated by Korkut Pata et al., [32] and Shahbaz et al., [39], assuming stationary while neglecting break (s) in series will produce false results as most time series variables are subject to structural break (s). Thus, using ZA which can capture a single break and stationarity character in a series, will give a better picture of the series' stationarity characters. The results of the ZA (see Table 3) uncover that at level, all the series are non-stationary with the exemption of InUR, which is stationary with a break date of 2000Q3 for the USA, while for the EU, InET and InUR are stationary with break dates of 2005Q2 and 1992Q3 respectively.

(Non)linearity analysis

In the next step, we used the Broock-Dechert-Scheinkman i.e., BDS [12] test to evaluate the series' (non)linearity features in USA and EU. Following the findings of the BDS test (see Table 4), the null hypothesis—according to which it is assumed that the data are normally distributed for all variables—is not supported by any substantive evidence for the EU and the USA. These results affirm the JB results of non (normality) in series. The non-normality, non-stationary, and non-linearity of our data series reveal that the KRLS method is suitable for this study.

The KRLS result

This section presents the results of the connection bewteen non-renewable energy efficiency, renewable energy ıntensity, environmental technologies, natural resources, and GHGS emissions in the USA and EU using the KRLS method introduced by Hainmueller and Hazlett [23]. A machine learning algorithm with econometric characteristics is

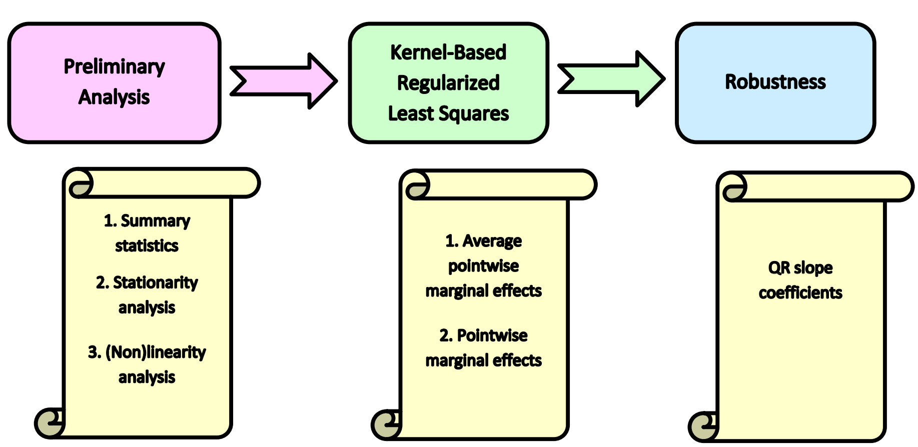

Fig. 2. The flowchart of the empirical analyses.

Table 3
Unit root test results.

Panel A: USA				
Variables	ADF	PP	ZA	Break time
lnGHG	0.388	0.765	−3.428	2007Q4
lnNREE	1.059	1.565	−4.038	2004Q3
lnREI	−1.335	−0.867	−3.693	1997Q4
lnET	−1.793	−1.152	−1.628	2003Q4
lnNR	−1.654	−2.441	−3.263	2011Q4
lnUR	−1.209	−6.686***	−11.899***	2000Q3
Panel B: EU				
lnGHG	−0.468	−0.555	−3.142	2008Q2
lnNREE	1.502	1.422	−2.182	1994Q4
lnREI	−0.397	−0.029	−4.051	2007Q4
lnET	−1.261	−0.723	−5.490***	2005Q2
lnNR	−1.849	−1.899	−2.690	2014Q1
lnUR	2.126	2.013	−5.329**	1992Q3
Confidence levels	Critical values			
1%	−3.491	−3.486	−5.340	
5%	−2.888	−2.886	−4.800	
10%	−2.581	−2.580	−4.580	

Note: ***, **, and * indicate stationarity at the 1%, 5%, and 10% confidence levels, respectively. ADF symbolizes the Augmented [16], PP the Phillips-Perron (1988), and ZA the [49] unit root tests.

Table 4
Evidence of (non)linarity by BDS test.

Panel A: USA					
	Dimension				
Variables	2	3	4	5	6
lnGHG	0.189***	0.314***	0.396***	0.451***	0.490***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
lnNREE	0.202***	0.341***	0.438***	0.507***	0.556***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
lnREI	0.180***	0.300***	0.379***	0.429***	0.461***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
lnET	0.198***	0.336***	0.428***	0.488***	0.524***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
lnNR	0.159***	0.259***	0.321***	0.355***	0.369***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
lnUR	0.208***	0.354***	0.456***	0.529***	0.581***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Panel B: EU					
lnGHG	0.189***	0.313***	0.396***	0.450***	0.485***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
lnNREE	0.200***	0.337***	0.434***	0.502***	0.551***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
lnREI	0.199***	0.334***	0.425***	0.486***	0.529***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
lnET	0.196***	0.331***	0.421***	0.480***	0.518***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
lnNR	0.164***	0.271***	0.337***	0.375***	0.394***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
lnUR	0.205***	0.348***	0.448***	0.520***	0.571***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)

Note: This table shows BDS statistics. ***, **, and * represent non-linearity at the 1%, 5%, and 10% confidence levels, respectively.

used in this method. In contrast to conventional econometric techniques, the KRLS approach produces mean marginal effects and pointwise derivatives, does hypothesis testing, and produces consistent and trustworthy estimates. Similarly, when it comes to problems with misspecification bias over statistical assessment, the KRLS technique surpasses current machine learning methods. Furthermore, in classification and regression complexity with uncertain functional forms, the KRLS technique offers comprehensible and flexible parameters. It establishes the functional structure of the data series under discussion and safeguards analysts against specification bias. According to Hainmueller & Hazlett [23], the KRLS technique is also useful for assessment that entails understanding the process of data generating, model-driven causal evaluation, prediction, and missing data imputation.

Table 5 summarizes the findings of the KRLS assessment. For the USA and EU, the R^2 are 0.994 and 0.977, respectively, which shows that 99% (USA) and 97% (EU) of the regressors (non-renewable energy efficiency, renewable, energy ıntensity, environmental technologies, natural resources) can explain the changes in GHGs emissions.

The KRLS average marginal results show that a 1% increase in NREE, REI, and ET decreases GHGs emissions in the USA by 0.142%, 0.049%, and 0.058%, respectively, while a 1% increase in NR and UR increases GHGs emissions by 0.026% and 0.195%. Likewise, for the EU, a 1% increase in NREE, REI, and ET decreased GHGs emissions in the USA by 00.349%, 0.215, and 0.103%, respectively, while a 1% increase in NR and UR increased GHGs emissions by 0.019% and 1.756%. Fig. 3 presents the KRLS average pointwise marginal effects for the EU and the USA.

The current study also utilised the KRLS pointwise marginal effects graph (see Fig. 4) to evaluate the nexus between GHGs emissions and the regressors. Thus, the pointwise marginal effects of non-renewable energy efficiency, renewable, energy intensity, environmental technologies, urbanization and natural resources on GHGs emissions are plotted in Fig. 4. For the USA and EU, NREE impact GHGs emissions negatively; however, the magnitude of the negative coefficient increases up to certain points before decreasing. Regarding the effect of REI, in the USA, REI impacts GHGs emissions positively in the beginning before a negative impact is observed. However, for the EU, the negative effect of REI is dominant; although, its magnitude diminishes slightly. Besides, in the USA, ET impact GHGs emissions positively in the beginning before a negative impact is observed. However, for the EU, the negative effect of REI is dominant; though, its magnitude diminishes slightly. The effect of NR and UR on GHGs emissions is positive for both the USA and EU; although the magnitude of the coefficients varies in both countries.

Robustness

The current investigation used Quantile Regression (QR) (see Fig. 5) as a robustness check for the Kernel-Based Regularized Least Squares (KRLS) approach. The results show that for the USA and EU, the effect of NREE on GHGs emission is negative across the quantiles; thus, showing the GHGs emissions decreasing effect of NREE. These observations show that NREE boosts the quality of the ecosystem in the USA and EU. Likewise, GHGs emissions decreasing effect of REI and ET are observed across all quantiles for the USA and EU. These findings show that REI and ET enhance ecological quality in the USA and EU. Lastly, the GHGs emissions increasing effect of UR and NR is noticed in each quantile, suggesting that an increase in UR and NR contribute to decrease in ecological quality. The graphs above are quite close to the results obtained with KRLS and robust our main findings.

Discussion of findings

This section presents precise discussion and justification or argument regarding the results obtained above. In the current study, it was discovered that renewable energy intensity and environmental technologies had a negative correlation with GHG emissions in the EU and the USA. This implied in the current context that whenever there is an upsurge in the possible investment in environmental technologies and intensification of renewable energy efficiency, a reduction in GHGs emissions is realized. Similarly, non-renewable energy efficiency negatively impacts GHGs emissions in the two economies. Specifically, these desirable environmental performances of environmental-related technologies, non-renewable energy efficiency, and renewable energy intensity are more pronounced in the EU. This implies that non-renewable energy efficiency could yet play a significant role in decreasing

Table 5
KRLS average marginal effects table.

Panel A: USA							
	Avg.	Std. Er.	t-stat.	Prob.	25%	50%	75%
NREE	−0.142***	0.012	−12.089	0.000	−0.238	−0.167	0.056
REI	−0.049***	0.010	−4.917	0.000	−0.082	−0.040	−0.003
ET	−0.058***	0.008	−7.467	0.000	−0.099	−0.075	−0.033
NR	0.026***	0.003	8.098	0.000	0.003	0.031	0.046
UR	0.195***	0.063	3.083	0.000	−0.279	0.122	0.627
Diagnostics							
R^2	0.994	Lambda	0.078	Sigma	5	Looloss	0.026
Panel B: EU							
	Avg.	Std. Er.	t-stat.	Prob.	25%	50%	75%
NREE	−0.349***	0.037	−9.531	0.000	−0.375	−0.305	−0.242
REI	−0.215***	0.030	−7.075	0.000	−0.384	−0.148	−0.090
ET	−0.103***	0.026	−3.888	0.000	−0.146	−0.088	−0.041
NR	0.019***	0.007	2.661	0.000	−0.019	0.036	0.051
UR	1.756***	0.279	6.291	0.000	0.507	0.766	2.461
Diagnostics							
R^2	0.977	Lambda	0.110	Sigma	5	Looloss	0.109

Note: ***, **, and * demonstrate significance at the 1%, 5%, and 10% confidence levels, respectively. 25%, 50%, and 75% represent quartiles of marginal effects.

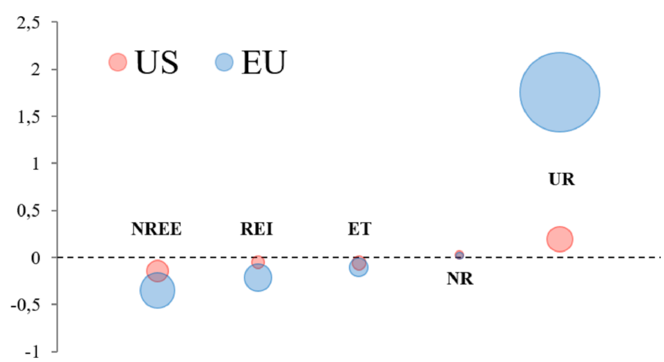

Fig. 3. KRLS average pointwise marginal effects.

ecological deterioration in both countries. As noticed from the results, improving non-renewable energy efficiency demonstrates a larger GHG emission reduction that intensifying renewable energy usage in both economies. Thus, policymakers in the USA and EU could further explore all opportunities by carefully take into account the role of non-renewable energy efficiency. Of course, using renewable energy and clean technologies instead of non-renewable energy in economic sectors might be a crucial instrument for implementing policies to slow down ecological deterioration. Given that the deployment of clean energy sources and clean technologies are expected to reduce GHGs emissions. Juxtaposing these findings with the literature, we found that Li and Lin [33] and Chen and Geng [13] also established that fossil liquid and solid fuels (especially gasoline, coal and diesel oil) exhibit some varying levels of efficiency in term of emission reduction. Specifically, Chen and Geng [13] note that fossil fuel significantly shows energy saving and emission reduction performance especially among developed countries. On the account of environmental related technologies and renewable energy, the result in this investigation aligns with Ibrahim et al. [28] but contradicts finding on renewable energy in Alola et al. [6].

Additionally, in the examined economies, urbanization positively impacts GHG emissions. In this investigation, we discovered that a significant increase in GHG emissions arising from a percent intensification of urbanization and the impact is reasonably larger in the EU. This result aligns with the studies of Faisal et al., [19], Asongu et al. [8], and Ahmad et al. [3] which documents that increase in GHG emissions is caused by an upsurge in urbanisation. Although significant gains in urbanization indicate a nation's quick economic progress, this is accompanied by rising GHGs emissions. For instance, there will be issues with providing sewage, drainage services and sanitation when the rural population migrates to urban areas i.e., increasing pressure on urban infrastructure facilities. Similar to how it forces cities to grow unevenly, urbanization arguably raises the pollution levels in the environment. Unexpected urbanization is a critical issue in the USA and EU, even if it results from economic expansion. First, the growing urban population alters the agricultural and manufacturing industries, raising energy consumption and, as a result, pollution levels. Secondly, when cities get more populated, it suggests increased in mobility with a resulting surge in transportation usage and emissions levels. In order to decrease the risk of ecological deterioration, policymakers in the USA and EU should continue to encourage sustainable and green urbanization. Moreover, these countries should further scale up the influence of renewables in the urban areas, such as through the use of solar lighting and ethanol in motor vehicles, among other things.

The effect of natural resource on GHGs emissions is positive and significant in the USA and EU, which indicates that an upsurge in natural resources damage the environment. Our finding aligns with the studies of Adebayo [1], Onifade et al., [35], Aladejare [4], Danish et al., [15] and Hassan et al., [22] who reported positive association between natural resources and ecological deterioration. Our discovery, which has a significant and favorable coefficient, implies that although the USA and EU have abundant natural resources, these are yet to be sustainably utilized without compromising on the quality of their environments. This is a reflection of resource curse hypothesis which claims that when a nation has plentiful resources, it might tumble into the resource curse hole given the caliber of environment and institutions already presented in the nation. As a result, these economies are expected to explore more stringent resource efficiency measures to avert potential socioeconomic situations such as a slow economic progress and deterioration of the environment arising from misuse of natural resources. Thus, it can be inferred that the poor management of resource rent by the USA and EU countries still has an adverse impact on ecological quality.

Conclusion and policy recommendations

Although significant progress has been recorded in coordinating measures toward tackling climate change since the implementation of the Paris Agreement by the United Nations Framework Convention on Climate Change (UNFCCC), improving energy efficiency is one of the specified solution to achieve net zero emission by 2050. By considering the cases of the USA and EU, this environmental performances of improving non-renewable energy efficiency and intensifying renewable energy utilization are compared over the 1990–2019. Moreover, the

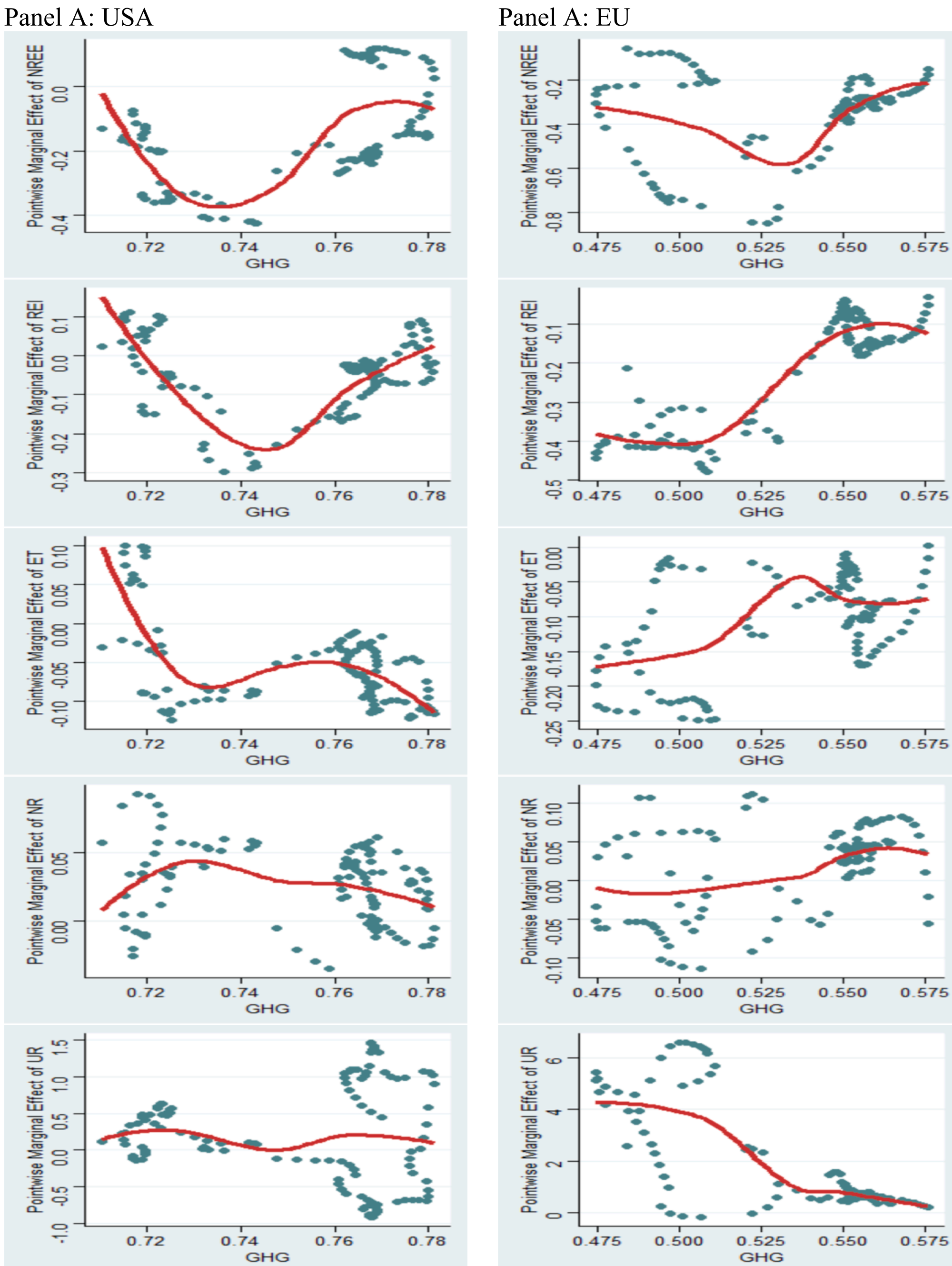

Fig. 4. KRLS pointwise marginal effects graphs.

roles of other factors such as environmental-related technologies, natural resource rent, and urbanization were also examined and compared. Given the non-normality of these variables, the empirical KRLS approach was considered suitable and robustness estimation was performed using a quantile regression approach.

Interestingly, the result shows that improving non-renewable energy efficiency perform better i.e more environmentally sustainable than intensification of renewable energy. However, environmental performance of intensive utilization of renewable energy outweighs that of environmental-related technologies. Importantly, given the three metrics (non-renewable energy efficiency, renewable energy intensity, and environmental-related technologies), the EU derives more environmental sustainability achievements than the USA. In term of natural resource rent and urbanization, both exhibit significant and positive influence on GHG emissions, suggesting that environmental quality is hampered with increase in urbanization and natural resource endowment in the USA and EU. Noticeably, increased urban development amidst movement to the urban areas across the EU poses more environmental drawback than in the USA. Although future study could explore the disaggregate sources of non-renewable and renewable energy mix, these novel comparative findings offer robust policy measures for the examined economies and more so for global perspective.

There is no doubt that series of specified policy tools are conceivable from these results. For instnace, the USA and EU must continue to implement fiscal and financial initiatives that does not only lower the cost of renewable energy technologies but that also offer improvement in the efficiency of fossil fuels usage in transportation (especially in the USA), residential, and industrial sectors. With the need to improve on renewable energy efficiency (given the evidence from the findings), policymakers in the US and EU could provide energy technology

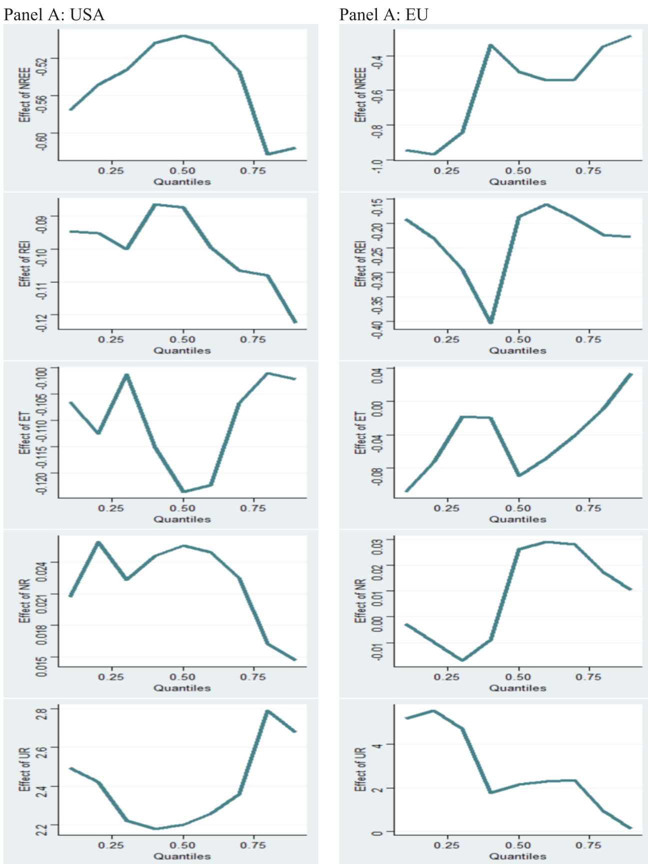

Fig. 5. Quantile regression slope coefficients for the quantiles from 0.10 to 0.90.

startups and inventors with more financial credits through low interest loans and subsidies to specifically enhance more research and development (R&D) exploits in renewable energy efficiency opportunities. Besides the above-mentioned energy-related policies, more stringent adoption of resource circularity measures such as reuse and recycling among others should potentially mitigate the adverse environmental consequence of natural resource rent. Meanwhile, providing incentives for electric vehicle usage and promoting economic activities in suburb and rural communities could effectively help in decongesting or avoid rapid urbanization in the countries, especially in the EU. Given the magnitude of the impact of the examined indicators, larger impacts are comparatively observed in the EU scenario. Thus, this posits an encouragement for the energy and environmental-related stakeholders in the EU and potentially triggering more determination to drive the region's energy efficiency policies.

CRediT authorship contribution statement

Oktay Özkan: Methodology, Conceptualization, Formal analysis. **Andrew Adewale Alola:** Writing – original draft, Investigation. **Tomiwa Sunday Adebayo:** Writing – original draft.

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.

Data availability

Data will be made available on request.

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Further reading

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