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The moderating role of environmental-related innovation and technologies in growth-energy utilization nexus in highest-performing eco-innovation economies

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ABSTRACT

In pursuance of SDG 7, 8 and 12, unearthing the substantive role of environmental-related innovations and technologies in mitigating the undesirable effects of fossil fuel dependence and natural resources consumption on the environment in selected highest performing eco-innovation economies unveils cutting edge policy options to aspiring eco-innovation economies. Considering the selected panel of leading eco-innovation economies (Austria, Denmark, Finland, France, Germany, Netherland, Spain, and Sweden), this study examines the contribution of oil utilization, environmental-related technologies-innovations, and the moderating role of environmental-related technologies-innovations in energy-economic output nexus over the period 1990–2020. By employing the recently developed method of moments quantile regression approach alongside long-run estimator and Granger causality approaches as robustness, we found that oil utilization and environmental technologies spur economic growth in the countries while environmental innovations hinder output. Yet, environmental technologies further moderate the positive effect of oil utilization on economic prosperity but the disservice effect of environmental-related technological innovation is further exemplified when such innovation is applied to the oil consumption network. Moreover, while a one-way Granger causality evidence is established from environmental technologies to economic output, there is statistical evidence of a bi-directional causal relationship from oil utilization and environmental-related technological innovation to economic output. The policy relevance of this study further unearths the importance of the valuation of cost-effectiveness and energy efficiency of economic inputs such as technology-related inputs, especially during the design and manufacturing process.

1. Introduction

Without a doubt, there are enormous studies in the literature that affirms the nexus of economic development, energy use, and environmental degradation. Given that economic growth is engineered by increased energy consumption which in turn spurs environmental degradation, deliberate effort is now increasingly been dedicated to the avenues to maintain growth while minimizing environmental damage. This account is responsible for the increasing deployment of technologies and innovations in the energy system especially through research and development (R&D). For instance, Fethi and Rahuma (2019) argued that eco-innovation (through R&D) exerts a long-term and significantly negative effect on environmental degradation in the top 20 refined oil-exporting nations. Ding et al. (2021) concluded that eco-innovations through the use of cost-saving technologies and eco-friendly technologies aid countries' agenda for the reduction of greenhouse gas emissions among the G-7 countries. With such approach, at least for the long-run benefit, countries seeking economic growth may have to endure a short-term environmental consequence until the turning point is attained vis-à-vis the reality of the environmental Kuznets curve (EKC)

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hypothesis. For instance, Akadiri et al. (2021) employed the case of tourism island states (TIS) and posit that globalization and tourism-induced economic growth EKC hypothesis is valid for the TIS. It means that economic developments brought about by growth in the tourism industry in the TIS states resulted in environmental degradation in the meantime the environmental hazard is minimized with economic growth the long-run.

The Organization for Economic Cooperation and Development (OECD) countries are considered the most industrialized and developed countries, contributing largely to the world GDP but have the highest energy consumption share while promoting clean energy. According to British Petroleum (2019), oil consumption remains the largest fragment of the global total energy consumption (TEC) with OECD countries' TEC increasing to 5569 Mtoe with a 1.5 % annual growth rate in 2018. OECD countries are also positioned among the top-spenders on eco-innovative investments and occupy several spots among the top-ranked countries with high eco-innovation index. Given the high energy consumption index of the OECD countries and the high investment in eco-innovations in the region, investigating the real impact of eco-innovation investments on the nexus of economic development, oil/energy consumption and environmental degradations represents a gap in the literature with huge potential for policy directions towards the attainment of the global carbon-neutral environment.

Against this backdrop, this study aims to investigate the role of eco-innovation (technology use and innovation) in reducing the environmental degradation effect (oil consumption) of economic growth (Real GDP) in the Top 10 countries with high eco-innovation index. The contributions of this study to knowledge repository and policymaking are clearly outlined. Firstly, deviating from the focus of most studies in investigating linkages between economic growth and environmental degradation, rather the current study breaks new ground by introducing the interaction effect of eco-innovation into the discussion. After a thorough literature search, only Fethi and Rahuma (2019) and Dong, et al. (2021) introduce eco-innovation in their analysis while a multitude of studies focuses on implementation of EKC hypothesis. Secondly, the current study is unique from the contribution of Fethi and Rahuma (2019) who focused on R&D assuming investments in clean technologies as eco-innovation and also our study offers a unique contextual contribution that differentiates it from Dong et al.'s (2021) study and equally validates the relevance of the eco-innovation argument in the OECD context; (c) our current study empirically validates the impact of varying degrees of eco-innovation as precursory to the level of carbon emission reduction potentials of renewable energy consumption and economic growth. Specifically, with increasing investment in eco-innovation, policymakers can effectively lower the emission of GHG while also increasing their oil consumption.

Following the expectation from this study, there is a logical arrangement of the other sections of the study such that related studies are discussed under the heading 'literature review' in Section 2. The employed empirical methods and results are presented in Sections 3 and 4 respectively while the summary of the study alongside relevant policy dimension is outlined in Section 5.

2. Literature review

In this part of the study, a plethora of studies, both on the nexus of oil consumption and economic output and for the role of technology and innovation in the dynamics of economic output are presented.

2.1. Energy consumption and economic growth

Previous empirical studies on energy use-economic growth nexus have indicated that there are four different forms of causality between these two variables. The first implies that no causality exists between oil consumption and economic growth. Specifically, Fatai et al. (2004) explored the causal relationship between economic growth and various disaggregated energy data (oil, electricity, natural gas, and coal) in New Zealand, Australia, and four other Asian economies using data between 1960 and 1990. The authors employed Granger causality tests, the TY approach, and the ARDL approach to testing these relationships and found no Granger causality between the two variables in any direction for New Zealand. Similarly, (Shaari et al., 2013) reached the same conclusion in the context of Malaysia. The authors, using data spanning between 1980 and 2010, also tested the relationship between economic growth and various disaggregated energy data using Co-integration and Granger causality.

Second, Alam and Paramati (2015); Behmiri and Manso (2013); Choi and Yoo (2016); Saboori et al. (2017); Sen and Uzunoz (2017) found bidirectional causality between oil consumption and economic growth. That is both variables can affect Granger cause each other simultaneously. Alam and Paramati (2015), using data between 1980 and 2012 in 18 developing countries, employed Vector Error Correction Model to determine the relationship between economic growth, oil consumption, industrialization, trade openness, and carbon emissions. Their empirical findings revealed a bidirectional relationship between oil consumption and economic growth. Choi and Yoo (2016) also explored the nexus between economic growth, oil consumption, and GDP per capita in the case of Brazil. Using co-integration, the Error Correction Model, and granger causality, the authors confirmed the bidirectional relationships between the two constructs. Using the Autoregressive distributed lag (ARDL), fully modified Ordinary Least Square (FMOLS), Canonical Cointegrating Regression (CCR), and asymmetric causality, Sen and Uzunoz's (2017) study confirmed bidirectional causality in the case of Turkey.

Behmiri and Manso (2013), using data from 1985 to 2011 of 23 Sub-Saharan countries investigated the relationship between oil price, oil consumption, and GDP per capita. The authors categorized the selected countries into oil-exporting and oil-importing regions. Using panel cointegration, FMOLS, and panel granger causality, they discovered a bidirectional relationship between oil consumption in oil-importing regions in the short-run and in both regions in the long run; however, they found a unidirectional causality from oil consumption to economic growth in the oil-exporting region in the short-run. Saboori et al. (2017), in their study, investigated the relationship between urbanization, trade openness, economic growth, carbon emissions, and oil consumption in Japan, China, and South Korea. Data used spanned between 1980 and 2013 and authors used Generalized Impulse Response functions (GIRF), Granger causality, Johansen cointegration test, and variance decompositions and found that there is bidirectional causality between oil consumption and economic growth in Japan but unidirectional in the case of China and South Korea.

Third, the unidirectional causality running from oil consumption to economic growth suggests that a rise in oil consumption positively affects economic growth, and when there is a shortage in oil supply, it negatively affects economic growth via transportation and production. Some recent studies (Adekoya, 2021; Fuinhas et al., 2015; Lahiani et al., 2019; Rasool et al., 2018; Waleed et al., 2018; Ziramba, 2015) have affirmed this causality. This unidirectional relationship running from oil consumption to economic growth has been confirmed in studies of single countries such as India (Rasool et al., 2018), Pakistan (Waleed et al., 2018), the United States of America (Lahiani et al., 2019), and South Africa (Ziramba, 2015). For aggregate countries, Adekoya (2021) examined the relationship between oil consumption, economic growth, Gross Fixed Capital Formation, and Labor Force for 10 resource-rich and 6 resource-poor countries. Findings reveal a positive relationship between oil consumption to economic growth in the short-run but negative in the long-run for resource-rich countries and an insignificant relationship on both long- and short-run for resource-poor countries.

Last is the unidirectional causality from economic growth to oil consumption, which indicates that oil consumption is increased by economic growth. The reason for this perspective is that when the income of the people increases, it is expected that they consume more oil.

Likewise, oil use for production and transportation increases concurrently as economic growth increases (Alam and Paramati, 2015), and several studies (Aqeel and Butt, 2001; Yang, 2000) the direction of causality. Aqeel and Butt (2001) in their study of Pakistan used cointegration and Hsiao's Granger causality test to investigate and found that economic growth leads to an increase in oil consumption. Similarly, using the Engle-Granger causality test, Yang (2000) affirmed this direction of causality in the case of Taiwan using data from 1954 to 1997. A summarized result of other related studies is presented in Table 1.

We, therefore, hypothesize that for the selected countries in this study,

Hypothesis 1. There is a positive and bidirectional relationship between oil consumption and economic growth.

≠, →, and ↔ denotes no causality, unidirectional causality, and bidirectional causality respectively.

2.2. *Eco-innovation and economic output*

The concept of eco-innovation has been studied under different contexts with varying definitions. Kemp and Pearson (2007), in their project "Measuring Eco-Innovation (MEI), defined eco-innovation as "the production, assimilation or exploitation of a product, production process, service or management or business method that is novel to the organization (developing or adopting it) and which results, throughout its life cycle, in a reduction of environmental risk, pollution and other negative impacts of resources use (including energy use) compared to relevant alternatives". Based on Kemp and Pearson's (2007) study, Horbach et al. (2012) defined eco-innovation as "product, process, marketing, and organizational innovations, leading to a noticeable reduction in environmental burdens. Positive environmental effects can be explicit goals or side-effects of innovations". Eco-innovation, according to Eco-Innovation Observatory (EIO) (2021) is "any innovation that reduces the use of natural resources and decreases the release of harmful substances across the whole life-cycle."

Despite these several definitions, they all include the environmental element and indicate two major outcomes: resource efficiency and fewer adverse environmental effects which suggests sustainability. According to Triple Bottom Line theorists, sustainability covers three aspects: economical, environmental, and social, and according to Ahmed et al. (2020), sustainability cannot be achieved without integrating innovation across all aspects. Several researchers (Peng and Liu, 2016; Tamayo-Orbegozo et al., 2017; Xavier et al., 2017) have considered eco-innovation to be a panacea to address the continuous adverse effect on the environment. With different empirical methods, eco-innovation has been reported by different studies to be a solution for different countries like G-7 nations (Ahmad et al., 2021; Ding et al., 2021; Khan et al., 2020), EU countries (Andabaka et al., 2019), USA (Van Song et al., 2021), OECD countries (Li et al., 2020)(Su et al., 2021), etc. as shown in Table 2. Aldieri et al. (2021) exposed a profound policy option through

Table 1
Summary of related studies on oil (energy) consumption and economic growth.

Reference	Period	Countries	Variables	Method	Findings
Fatai et al. (2004)	1960–1999	Thailand, The Philippines, Indonesia, India, Australia, and New Zealand	TFEC, CC, GC, ELEC, OC, and GDP	Granger causality tests, the TY approach and ARDL	*OC* ≠ *GDP* in New Zealand
Shaari et al. (2013)	1980–2010	Malaysia	GDP, ELEC, OC, GC, and CC	Co-integration, Granger causality	*OC* ≠ *GDP*
Alam and Paramati (2015)	1980–2012	18 developing countries	GDP, OC, FD, I, TO, and CO_2	VECM	*OC* ↔ *GDP*
Behmiri and Manso (2013)	1985–2011	23 Sub-Saharan African countries	OC, P and GDP per capita	Panel co-integration, panel FMOLS, Panel Granger causality	*OC* ↔ *GDP* in the oil-importing region in the short-run *OC* ↔ *GDP* in both regions in the long-run *OC* → *GDP* in the oil-exporting region in the short-run
Choi and Yoo (2016)	1965–2010	Brazil	OC, GDP, GDP per capita	Co-integration, ECM, and Granger Causality	*OC* ↔ *GDP*
Saboori et al. (2017)	1980–2013	South Korea, China, and Japan	URB, TO, GDP, CO2, and OC	GIRF, Granger causality, Johansen cointegration test, and variance decompositions	*OC* ↔ *GDP* for Japan but *OC* → *GDP* for China and South Korea
Sen and Uzunoz (2017)	1965–2013	Turkey	GDP and OC	ARDL, FMOLS, CCR, and asymmetric causality	*OC* ↔ *GDP* in the long-run
Rasool et al. (2018)	1971–2015	India	GDP and OC	ARDL	*OC* → *GDP*
Adekoya (2021)	1990–2017	10 Resource-rich and 6 resource-poor countries	OC, GDP, GFCF, and LF	ARDL, AMG, and panel threshold regression	Resource-rich countries: *OC* → *GDP* (+) on short-run; *OC* → *GDP* (−) on long-run Resource-poor countries: *OC* → *GDP* (insignificant) on long- and short-run
Waleed et al. (2018)	1965–2015	Pakistan	OC, GDP, GDP per capita	Co-integration, ECM, and Granger Causality	*OC* → *GDP* in the long-run
Fuinhas et al. (2015)	1960–2011	OPEC	GDP, OC, OP, X, and P	Co-integration, OLS, DOLS	*OC* → *GDP* in the short-run
Lahiani et al. (2019)	1955–2016	United States of America	OC and GDP	Co-integration, Granger Causality, Quantile ARDL	*OC* → *GDP*
Ziramba, 2015)	1970–2008	South Africa	GDP, OC, and K	Co-integration and Granger causality	*OC* → *GDP*
Aqeel and Butt (2001)	1956–1996	Pakistan	GDP, OC, GC, and ELEC	Co-integration and Hsiao's Granger causality	*GDP* → *OC*
Yang (2000)	1954–1997	Taiwan	GDP, OC, GC, CC, and ELEC	Co-integration and Granger causality	*GDP* → *OC*

Note: GFCF, LF, FD, I, TO, CO_2, K, OP, X, P, TFEC, CC, GC, ELEC, VECM, GIRF, OPEC, OLS, DOLS FMOLS, CCR, and TY is Gross Fixed Capital Formation, Labor Force, Financial Development, Industrialization, Trade Openness, Carbon Emissions, Capital, Oil Production, Export, Oil Prices, Total Final Energy Consumption, Coal Consumption, Gas Consumption, Electricity Consumption, Vector Error Correction Model, Generalized Impulse Response Functions, Organization Of The Petroleum Exporting Countries, Ordinary Least Squares, Dynamic OLS, Fully Modified OLS, Canonical Cointegrating Regression, Toda and Yamamoto.

Table 2
Summary of related studies on innovation and economic growth.

Reference	Period	Countries	Variables	Method	Findings
Ahmad et al. (2021)	1980–2016	G7 nations	EF, TG, GDP, FG, EG, URB, and EI	CS-ARDL and Granger causality	*EI → EF*
Andabaka et al. (2019)	2010–2016	28 EU countries	EI, GDP, QI, and RRMW	Arellano-Bover/Blundell Bond – system GMM	*GDP positively affects EI*
Van Song et al. (2021)	1990–2015	USA	GDP, PPPI, EI, CO_2, PM2.5	QARDL	EI reduces CO_2
Li et al. (2020)	1990–2017	OECD countries	REC, EI, EP, HC, and EPR	CS-ARDL, Durbin Hausman cointegration test, and AMG	EI increases REC at both short- and long-run
Tao et al. (2021)	1995–2018	E-7 economies	CE, EI, ET, and GDP	CS-ARDL, AMG, and CCEMG	EI reduces CE
Wang et al. (2020)	1990–2017	G-7 countries	CO_2, ED, EI, and REC	CS-ARDL, cointegration, and AMG	EI reduces CO_2
Fethi and Rahuma (2019)	2007–2016	20 Refined oil-exporting countries	CO_2, GDP, EC, EI	Cointegrating test, and panel causality	EI reduces CO_2
Chien et al. (2021)	1990–2017	Top Asian countries	CO_2, PM2.5, REC, NREN, EI, and ERT	CS-ARDL, AMG, CCEMG, and cointegration	Long-run association between EI and CO_2
Khan et al. (2020)	1995–2017	G-7 countries	EI, HC, EP, FD, RD, TEC, NREN, REC	Cointegration and AMG	The negative association of EI with TEC and NREN
Ding et al. (2021)	1990–2018	G-7 countries	CO_2, E, I, EI, GDP, REC, ENP	Cointegration, CS-ARDL, AMG, and causality test	EI mitigates CO_2
Su et al. (2021)	1990–2018	7 OECD countries	FiD, GDP, REC, NREN, PRI, RER&D, EI	CS-ARDL, CCEMG	EI reduces NREN
Sun et al. (2021)	1995–2018	Turkey	CO_2, EF, TOR, EI, and GDP	QARDL	EI reduces CO_2 and EF
Huang et al. (2021)	1990–2017	OECD	TEC, EI, GDP, EP, HC, and TO	AMG and CS-ARDL	EI reduce TEC

Note: EF, TG, FG, EG, URB, EI, QI, RRMW, PPI, PM2.5, REC, EP, HC, EPR, E7, CE, ET, ED, NREN, E, I, ENP, CS-ARDL, AMG, CCEMG, FiD, PRI, RER&D, TOR: Ecological Footprint, Trade Globalization, Financial Globalization, Economic Globalization, Urbanization, Eco-Innovation, Quality of Institution, Recycling Rate of Municipality Waste, Public-Private Partnership Investment, particle matter 2.5, renewable energy consumption, energy price, human capital, energy productivity, emerging seven, Consumption-based in CO_2, Environmental Taxes, Export Diversification, Non-Renewable Energy, Export, Import, Energy Productivity, Cross-sectional augment ARDL, Augmented Mean Group, Common Correlated Effects Mean Group, Fiscal Decentralization, Political Risk Index, Research and Development on renewable energy, Tourism.

which negative externalities of production process on the environment is reduced through a well-bred competition structure and individual firm's productivity is higher through its innovation activities.

Eco-innovation embodies the introduction of technologies to environmental management or green product design, recycling, pollution prevention, and energy-saving (Cai and Li, 2018). Additionally, eco-innovation focuses on advancing economic growth while mitigating negative effects on the environment (González-Ruiz et al., 2018). All eco-innovation measurement instruments have been based on four categories originally determined by Acs and Audretsch (1993). These are input measures (innovation, research, and development (R&D) personnel, R&D expenditure); direct output measures (increase in sales of new products or several innovations); indirect impact measures (productivity and changes in resource efficiency), and intermediate output measures (scientific articles and patent). A summarized result of other related studies is presented in Table 2. Other relevant studies emphasising the moderating role of eco-innovation in the energy consumption-economic output nexus; Jahanger et al. (2022) depending on PMG-ARDL econometric technique found that technological innovation exerted a moderating effect to reduce the negative environmental consequences associated with natural resource consumption. Likewise, Balsalobre-Lorente et al. (2021a, b) advocated that adoption of environmental restrictions and implementation of clean technologies reduces energy intensity and fossil-fuels dependence in BRICS countries.

In this research, direct and intermediate output measures (environmental-related technologies in relation to the percentage of all technologies and percentage of inventions worldwide) are used and we propose that:

Hypothesis 2. Eco-innovation moderates the relationship between oil consumption and economic growth.

3. Material and empirical tests

The dataset employed for this study is that of the ten (excluding Italy and Luxembourg because of data limitation) leading eco-innovation countries that include Austria, Denmark, Finland, France, Germany, Netherland, Spain, and Sweden over the period 1990–2018. In Table 3, there is documentation of other information about the dataset.

Standard deviation close to zero depicts that data points are close to the mean and in Table 4. Thus, we can easily decipher that the reported standard deviation statistic for ERTTec and ERTInno (4.240 and 3.976 respectively) signifies closeness to the mean. However, a preponderance of low values may necessitate standard deviation is greater than the mean in the case of ERTInno. On the other hand, standard deviation statistics reported for Gdp and Oil are high, signifying the preponderance of high values in the dataset. GDP has the highest observation in the dataset followed by Oil whereas ERTInno has the lowest observation in the dataset.

3.1. Empirical model

While the early work of Schumpeter and Nichol (1934) as documented in similar studies (Arrow, 2015; Schumpeter and Backhaus,

Table 3
Description of dataset.

Variables	Description	Sources
Oil Consumption (coded as Oil)	Oil consumption in Million tonnes	British Petroleum (2021)
Economic Growth (coded as GDP)	GDP (constant 2015 US$)	World Development Indicators (2021)
Environmental-related technologies (coded as ERTec)	Environmental-related technologies (% of all technologies)	OECD Statistics
Environmental-related technological innovations (coded as ERTInno)	Environmental-related technologies (% of all inventions worldwide)	OECD Statistics
Environmental-related technology with international collaboration (coded as ERTIntC)	Environmental-related technologies with international collaboration	OECD Statistics

Note: OECD Statistics is The Organization of Economic Cooperation and Development (OECD Statistics, 2021).

Table 4
Summary statistics of the dataset.

Variables	Mean	Std. dev.	Min	Max	Observation
Gdp	1.112e+12	1.07e+12	1.50e+12	3.92e+12	232
Oil	45.228	40.038	7.4	137.3	232
ERTTec	10.838	4.240	4.05	23.37	232
ERTInno	2.511	3.976	0.12	18.51	232

Source: Authors' computations.

2003) was an attempt to modify the economic theory along with the perception of change as against the traditional equilibrium, the perception was sooner corroborated. For the aggregate growth of the economy, as later revealed in the studies of Romer (1990) and Lucas Jr (1993), knowledge is largely recognized as a central factor of economic growth. Following this observation, the current study examines the dynamics of economic growth in the eco-innovation economies such that the research model (see Fig. 1) illustrates the role of both oil energy consumption. Technological innovations, and to an extent the moderating role of innovation in the nexus of oil consumption and economic growth.

Thus, by using oil consumption, environmental-related technologies, and environment technological innovations as the explanatory variables, three distinct models are implied accordingly for the study.

$$GDP = f\ (Oil, ERTTec, ERTInno) \tag{1}$$

$$GDP = f\ (Oil, OilTec) \tag{2}$$

$$GDP = f\ (Oil, OilInno) \tag{3}$$

where OilTec is oil*ERTTec (interaction of oil and ERTec) and OilInno is Oil*ERTInno (interaction of oil and ERTInno). While the GDP and oil are transformed to logarithmic values, the raw values of ERTec and ERTInno are employed since they are in percentages.

3.1.1. *Pre-tests: unit root and cointegration*

There is an extant need to ascertain the order of integration of every variable of interest and following, by examining the cointegrating relationships of the three models in the preceding methodological section. The author adopted the Pesaran (2007) unit root-test which is built on the assumption of cross-sectional dependence (CsD). The results as contained in Table 5 shows that all variables (GDP, Oil, ERTTec, and ERTInno) are all stationary after the first difference depicting that all variables are integrated of order one I (1).

Table 5
Pesaran panel unit root with CsD.

Variables	Levels		First difference	
	T	$\mathcal{T}$	T	$\mathcal{T}$
Gdp	−3.686*	−2.171***	−3.582*	−3.805*
Oil	−3.638*	−1.817	−5.883*	−5.762*
ERTTec	−2.964**	−2.477**	−5.642*	−5.541*
ERTInno	−2.879***	−2.278***	−4.418*	−4.458*

Note: **, ***, and $\mathcal{T}$ represent 5 % statistically significant level, 10 % statistically significant level, and the 'without trend value'. CS is cross-sectional dependence.

By affirming the existence of cross-sectional dependence, the author takes solace in the error-correction-based tests and adopts the residual-based tests as a sort of robustness check or to shore up the accuracy of result extracted from the error-correction based tests (Westerlund & Edgerton, 2007) cointegration approach. Therefore, for the three model specifications [1] to [3], we employ the cointegration bootstrapping option that enables the author to rely on the reported robust *p*-values as shown in Table 6 in order to proceed with the estimation technique. Evidence from Kao cointegration result output provides econometric wit to reject the null hypothesis of no cointegration in the three model specifications, On the other hand, evidence from the Westerlund cointegration result output also rejects the null hypothesis of no

Table 6
Panel cointegration with CsD.

	G_t	G_a	P_t	P_a
Gdp = *f* (Oil, ERTTec, ERTInno)	−3.182	−12.843***	−7.782	−15.067**
	(0.100)	(0.050)	(0.170)	(0.020)
Gdp = *f* (Oil, OilTec)	−3.273**	−16.983**	−8.748**	−16.946**
	(0.040)	(0.020)	(0.030)	(0.020)
Gdp = *f* (Oil, OilInno)	−3.369**	−17.135**	0.7.768	(0.160)
	(0.030)	(0.020)	(0.160)	(0.120)
	Westerlund cointegration		Kao cointegration	
	Statistic	P-value	Statistic	P-value
Gdp = *f* (Oil, ERTTec, ERTInno)	−1.330	0.090***	−2.255	0.012**
Gdp = *f* (Oil, OilTec)	−3.27	0.05**	−2.777	0.003**
Gdp = *f* (Oil, OilInno)	−1.676	0.047**	−1.554	0.065***

Note: **, ***, and () represents 5 % statistically significant level, 10 % statistically significant level, and robust p-value. The Kao cointegration adopt the Augmented Dickey-Fuller t-test by using the Newey-West lag selection (2), and kernel is Bartlett. CS is cross-sectional dependence.

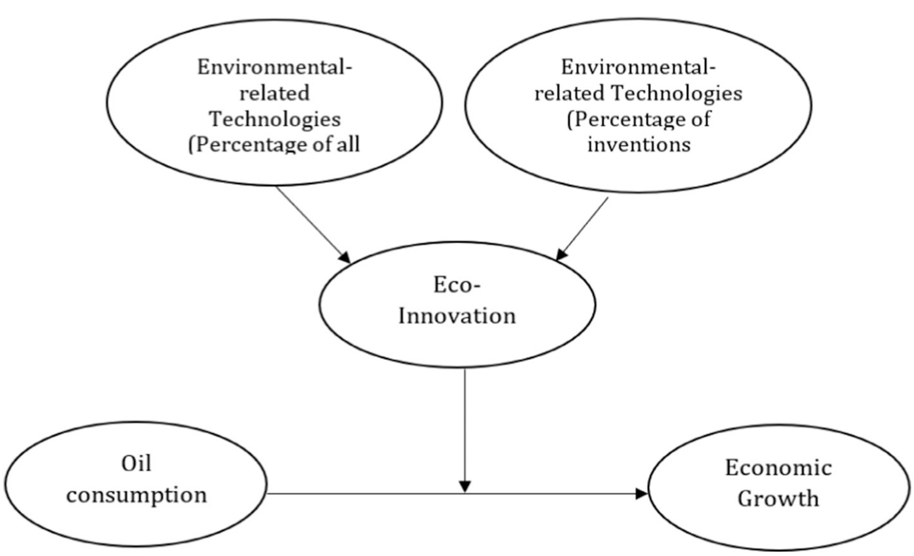

Fig. 1. Research model.

cointegration in all the model specifications. Thus, available evidence from Table 6, from both cointegration approaches reaffirms the existence of cointegration among the variables in [1] to [3] model specifications.

4. Empirical analysis and discussion

Alongside the main empirical analysis method employed for this study i.e. the Method of Moment Quantile Regression by Machado and Silva (2019), we also employ the fully-modified ordinary least square (FMOLS) and dynamic ordinary least square (DOLS) by Kao and Chiang (2001) which are found to be robust against endogeneity bias and serial correlation. Additionally, we employ the newly improved Granger causality approach by Xiao et al. (2021) to provide more robustness to the result.

4.1. The MMQR approach

For the MMQR approach, first, we present the panel expression of the location-scale variant model of conditional quantile for the first model (Eq. (1)) as

$$QGDP_{i,t}\left(\tau|X_{i,t}\right) = \propto_0 + \propto_{oil}OIL_{i,t} + \propto_{erttec}ERTTEC_{i,t} + \propto_{ertinno}ERTINNO_{i,t} + \mathcal{E}_{i,t} \quad (4)$$

so that $QGDP_{i,\ t}$ is the τ^{th} conditional quantile function while the set of explanatory variables (ERTTEC and ERTINNO) is denoted by X_{it}.

Again, the above expression i.e. Eq. (4) is also reparametrized as.

$$QGDP_{i,t}\left(\tau|X_{i,t}\right) = \left(\propto_i + \theta_i q(\tau)\right) + X'_{i,t}\beta + Z'_{i,t}\gamma q(\tau) \quad (5)$$

such that $\alpha_i(\tau) \equiv \alpha_i + \theta_i q(\tau)$ represent the scalar parameter that shows the quantile-τ fixed effect for each country i. Additionally, $Z_l = Z_l(X)$,where $Z$is the k-vector of identified differentiable components of X with l element and $l = 1, \ldots, k$. As against the least-squares fixed effects, the country-specific effects in this approach are not the intercept shifts but are rather parameters that are time-independent. Moreover, their heterogeneous impacts could vary across the quantiles of the conditional distribution of the dependent variable.

Proceeding from Eq. (5) above, Machado and Silva (2019) imply that the conditional quantile which is estimated based on the MMQR approach offer solution to the following optimization problem:

$$min_q \sum_i \sum_t \rho_\tau\left(\widehat{R}_{it} - \left(\widehat{\delta}_i + Z'_{it}\widehat{\gamma}\right)q\right) \quad (6)$$

such that the check function as defined by $\rho_\tau(\mu) = \mu(\tau - 1(\mu \le 0) + (\mu > O)$.

Considering that three models are specified for this study, the aforementioned step-by-step MMQR approach for model 1 is repeated for the second and third models. Consequently, the results for model 1 (see Table 7) and models 2 and 3 (see Table 8) are presented accordingly.

4.1.1. The robustness estimates

Furthermore, as robustness, the DOLS and FMOLS approaches as detailed in the studies of Phillips and Hansen (1990) and Pedroni (1999) provide long-run elasticities for variables in the implied model specifications (1) to (3). Additionally, the newly modified Granger causality approach of Xiao et al. (2021) offers a more relevant analysis. However, the step-by-step procedures of the methods are not provided here because of space limitations.

4.2. Discussion of results

First, we begin with the main estimation result from the MMQR approach. As earlier stated, the model specifications (1) to (3) were subjected to the MMQR empirical analysis. The favorable influence of oil consumption on economic growth as seen in developing economies and some developed economies are debunked evident from the outcomes of MMQR in Table 7. As expected, the effect of fossil fuel consumption on economic growth reduces from 0.752 to 0.328 across the quantile. This is common evidence in many empirical studies, where economic prosperity is seen to be largely reliant on conventional energy utilization such as oil, coal, and natural gas (Adedoyin and Zakari, 2020; Kose et al., 2020). However, we observe a declining dependence on fossil fuels to engineer growth and development in the panel of the selected eco-innovation economies, thus translating to a proven record of transitioning to cleaner forms of energy for residential and industrial use.

Startling evidence is seen regarding the nexus of environmental-related technological innovations and economic output. The amount of innovations relating to technologies capable of ameliorating environmental challenges is not yet at the threshold to foster economic growth because the impact of ERTInno on economic growth is (although small) largely negative and statistically significant across the quantile. On the other hand, countries in our sample with the highest

Table 7
Results of Machado and Silva (2019) MMQR.

Variables										
	Location Parameters	Scale Parameters	Quantiles							
Model 1			0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
Oil	0.541**	−0.138	0.752*	0.689*	0.640*	0.581*	0.517*	0.479*	0.442*	0.384*	0.328**
	(0.040)	(0.103)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.001)	(0.014)
ERTInno	−0.008	−0.001**	−0.006**	−0.007*	−0.007*	−0.008*	−0.008*	−0.009*	−0.009*	−0.009*	−0.010*
	(0.128)	(0.019)	(0.017)	(0.001)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
ERTTec	0.014*	−0.002*	0.017*	0.016*	0.016*	0.015*	0.014*	0.014*	0.013*	0.012*	0.012*
	(0.000)	(0.008)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Robustness											
Oil	0.317	−0.088	0.469**	0.424**	0.372*	0.319*	0.290*	0.266*	0.246*	0.225**	0.191
	(0.330)	(0.417)	(0.014)	(0.005)	(0.001)	(0.000)	(0.000)	(0.001)	(0.005)	(0.024)	(0.117)
ERTInno	−0.012	0.002	−0.016*	−0.015*	−0.014*	−0.012**	−0.012*	−0.011*	−0.011*	−0.010*	−0.010*
	(0.113)	(0.546)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
ERTIntC	0.013*	−0.000	0.013*	0.013*	0.013*	0.013*	0.013*	0.013*	0.013*	0.013*	0.013*
	(0.002)	(0.876)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)

Note: * and ** indicate significance at the 1 % and 5 % statistically significant levels respectively. The values in the parentheses are the standard error of the estimated parameters.

Table 8
Results of Machado and Silva (2019) MMQR.

Variables	Location parameters	Scale parameters	Quantiles								
			0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
Model 2											
Oil	0.376	−0.073	0.503*	0.463*	0.424*	0.390*	0.362*	0.332*	0.318*	0.295*	0.273**
	(0.134)	(0.417)	(0.002)	(0.005)	(0.001)	(0.000)	(0.000)	(0.000)	(0.000)	(0.002)	(0.015)
OilTec	0.012*	−0.001	0.013*	0.013*	0.012*	0.012**	0.012*	0.012*	0.012*	0.011*	0.011*
	(0.000)	(0.446)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Model 3											
Oil	−0.101	−0.269***	0.379	0.240	0.120	−0.074	−0.192	−0.286**	−0.331*	−0.373*	−0.427*
	(0.820)	(0.081)	(0.201)	(0.313)	(0.550)	(0.621)	(0.119)	(0.016)	(0.007)	(0.005)	(0.004)
OilInno	−0.007	0.002	−0.011*	−0.010*	−0.010*	−0.008*	−0.007*	−0.006*	−0.006*	−0.005*	−0.005*
	(0.120)	(0.184)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)

Note: * and ** indicate significance at the 1 % and 5 % statistically significant levels respectively. The values in the parentheses are the standard error of the estimated parameters.

environmental technology innovations carry a greater environmental and social cost which prohibits growth as funds are diverted towards improving environmental quality and settling legal disputes which is prevalent in a country like Germany.

As opposed to inventions, adoption and deployment of existing environmental technologies (ERTTec) in these eco-innovation economies increases economic growth more significantly in lower quantiles as opposed to higher quantiles with decreasing effects from 0.017 to 0.012. The inference from the ERTInno and ERTTec impacts offer more economic and environmental intuition that suggests that a proportion of innovations are a disservice to the economy while it is more appropriate to conclude that there is technological-led growth evidence. Moreover, the robustness check conducted for the model specification (1) is provided in the lower part of Table 7. The outcomes in the case of oil consumption corroborate with the initial result presented, reiterating the effect is more significant at lower quantiles and reduces as the quantile increases up to the eight quantiles but insignificant in the ninth quantile. ERTTec was indifferent and maintained its positive sign and significance at 5 %. ERTInno turned out to be a distinctive reversal to the result initially presented in the main MMQR estimation positing a significant effect at lower quantiles as opposed to higher quantiles recorded in the main MMQR estimation.

As for the innovative models (2) and (3), the results are presented in Table 8. Attending to outcomes from the MMQR estimation for model specification [2], the proportion of growth influenced by fossil fuel consumption in the selected eco-innovation economies is visibly higher in the early and transitional stages of development which also reduces overtime. The weakening in the positive impact of oil consumption over time could be due to the reduction in the dependence on fossil fuels to gauge local demand for energy and transiting to renewable forms of energy. Specifically, the positive effect of oil consumption is more significant and decreases from 0.503 to 0.273 to the 90th quantile. The interaction term OilTTec indeed contributes to economic growth and the coefficients across all quantiles are not necessarily different in terms of magnitude but were reported significant at 1 % and 5 %. Oil consumption in Model specification [3] was positive but insignificant at 1 % and 5 % from 10th quantile to median quantile, after the median quantile, a balance was found in the 60th quantile to the 90th quantile. Furthermore, the interaction term OilInno hinders economic growth in selected eco-innovation economies in the lower quantiles but the effect decreases from the median quantile to the 90th quantile. Thus, this evidence suffices that environmental technologies moderate the positive effect of oil consumption on economic growth while the moderating role of environmental innovation is undesirable to the economy.

4.2.1. *Discussion of robustness results*

Treating the FMOLS and DOLS estimation results which are largely unanimous, we can see that conventional oil consumption which constitutes traditional fossil fuels contributes positively to economic growth in selected countries in the model specification (1) and (2). On the other hand, conventional oil consumption is not significant in model specification [3] i.e. when the moderating role of ERTInno is considered. Similar to the MMQR results, ERTTec is significant and positively signed in the model specification (1) positing that environmental-related technologies contribute positively to sustainable economic growth in selected eco-innovation economies. The result is in tandem with the reality of increasing rate of technology adoption in dealing with sustainability challenges and transitioning to cleaner forms of energy in the selected countries. (see Ulucak and Khan, 2020 in the case of BRICS economies). In the opposite direction, ERTInno is negatively signed and significant at a 5 % level in model specification [1] positing that an increase in inventions of environmental-related technologies reduces economic growth in the selected countries. A declining trend in the share of environmental-related patents in the total number of patents applications worldwide and exhaustion of technological opportunities in energy generation, distribution, transmission, and transport may limit the rate of inventions (see Urbaniec et al., 2021). Moreover, the results here for the moderating roles of environmental technologies and environmental innovation are in tandem with the MMQR results, thus providing a significant sense of robustness (Table 9).

Furthermore, the novel Granger non-causality test proposed by Xiao et al. (2021) is estimated and result is presented in Table 10. Here, the null hypothesis remains that no causal relationship between variables whereas the alternate hypothesis points to the existence of causal relationship between selected variables. The results portray a two-way causation running between GDP and Oil that is statistically significant.

Table 9
Additional long-run estimates.

Variables	FMOLS			DOLS		
Oil	0.569 (0.000) *	0.390 (0.006) *	0.072 (0.311)	0.447 (0.024) **	0.427 (0.009) *	0.145 (0.232)
ERTTec	−0.0150 (0.000) *			0.012 (0.000)*		
ERTInno	−0.007 (0.045) **			−0.009 (0.013) **		
OilTec		0.012 (0.000) *			0.012 (0.000) *	
OilInno			0.105 (0.000) *			−0.105 (0.000) *

Note: * and ** are 1 % and 5 % statistically significant level respectively.

Table 10
Panel Granger non-causality test.

Relationship	Coefficient	S.E (*P*-value)
Gdp does not granger cause Oil	−0.484	0.127 (0.000) *
Oil does not granger cause Gdp	−0.080	0.046 (0.078) ***
Gdp does not granger cause ERTInno	−3.955	1.795 (0.028) **
ERTInno does not granger cause Gdp	−0.002	0.001 (0.037) **
Gdp does not granger cause ERTTec	−7.556	12.779(0.554)
ERTTec does not granger cause Gdp	−0.0005	0.0001(0.007) *

Note: *, **and ***represents 1 %, 5 %, and 10 % statistically significant level respectively.

Additionally, the second scenario portrays the existence of feedback causal effect between ERTInno and GDP. The reported *p*-values are significant at 5 % level positing the existence of a bidirectional causal relationship between ERTInno and GDP. The third scenario portrays a one-way causation only running from ERTTec to GDP significant at 5 % statistically significant level.

5. Conclusion and policy implications

This study is largely built on the endogenous growth theory which considers the importance of innovation and knowledge as the significant contributors to economic prosperity. While employing a three-model approach, the study illustrated the role of oil consumption, environmental technologies, and environmental technological innovation in the economic growth of selected eco-innovation economies over the period 1990–2018. To achieve the desired objective, the MMQR approach alongside the long-run estimators (FMOLS and DOLS) and Granger causality approaches were utilized to provide robustness evidence.

The investigation provides startling and unanimous results across the estimation techniques. Specifically, in the first model, we found that oil consumption and environmental technologies spur economic growth in the panel by a significant amount while environmental technological innovation is found to be detrimental to economic advancement. The distinction between invention and innovation seems to explain the rationale behind the disparity in the effect of environmental technologies and technological innovation in the case of eco-innovation economies. In the second model specification, both coefficients of oil consumption and the interaction term Oil*Tec (oil and environmental technologies) show a statistically significant inference, thus justifying the desirable role of environmental technologies as a moderator of the oil-leg growth. However, the coefficient of the interaction term Oil*Inno (oil and technological innovation) in the third model specification is also statistically significant but shows an undesirable impact on the economy. Given these results, and by working the inherent limitation(s), future study could utilise the same approach to explore other energy mix and as well implement the study for several cases. Indicatively, there are supposed policies relevant to the aforementioned results.

5.1. Policy recommendation

While the environmental technological innovations could be found effective at mitigating environmental degradation, economic-related demerit arising from energy inefficiency, cost ineffectiveness among other reasons could be a setback. As such, economic valuation and assessment especially from the perspective of cost-benefit analysis should be prioritized alongside the technical design of environmental technologies and technological innovation. Importantly, the policy guideline and standardization of patent registration as being globally officiated by the World Trade Organization should be harmonized with the national policies of the member countries. Moreover, given that the economic and environmental benefits associated with energy innovation and clean technological advancement, policy makers are encouraged not to limit or cut down investments in research and development.

CRediT authorship contribution statement

Taiwo Temitope LASISI: Data curation and Writing.
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Kayode Kolawole ELUWOLE: Writing.

Declaration of competing interest

The authors declare no conflict of interest.

Data availability

Data will be made available on request.

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