Journal of Petroleum Exploration and Production Technology (2022) 12:2967–2980
https://doi.org/10.1007/s13202-022-01478-1

ORIGINAL PAPER-: EXPLORATION ENGINEERING

Energy efficiency and Jevons' paradox in OECD countries: policy implications leading toward sustainable development

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Received: 12 January 2022 / Accepted: 1 March 2022 / Published online: 11 April 2022

Abstract

Energy consumption is defined as one of the main determinants of environmental degradation. Therefore, this issue becomes one of the main points of debate to achieve sustainable development. This research examines how a set of economic factors determine the energy consumption in Organization for Economic Cooperation and Development countries, for which second-generation econometric methods have been used that control cross-sectional dependence issues. Therefore, the results, using nonlinear methods, suggest the presence of Jevons' paradox in these countries. However, under the Jevons' paradox scenario, technological innovation becomes a factor that mitigates energy demand. Contrary to the foreign direct investment that contributes significantly to the increase in energy consumption, from the results found, some policy implications are derived in the framework of achieving sustainable development.

Keywords Energy efficiency · Jevons' paradox · Technological innovation · Nonlinear analysis · Sustainable development · Environmental policy

Introduction

The degradation of the environment and the achievement of environmental sustainability are elements that lead to more effective consumption and production patterns worldwide (Sarkodie et al. 2020). The main problem is generated due to the current design of the global economic structure of industries, which are based on high energy intensity (Chen et al. 2018; Khan et al. 2022c). Whole economic activities demand energy, which is closely related to the emission of greenhouse gases since most of the global energy consumed comes from fossil energy sources (Dyrstad et al. 2019; Janjua 2021). This situation gives rise to climate change, which alters ecosystems and leads to environmental problems such as increased temperatures, electrical storms, floods, and droughts (Janjua et al. 2021; Arendt et al. 2021; Khan et al. 2021c). Therefore, energy consumption (ENC) has taken on relevant interest and has become a topic of debate by public policy and scholars worldwide.

Despite that, environmental problems will continue to arise without a correct definition of energy policy instruments to counteract the ENC at a global level. These will

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threaten compliance with the Sustainable Development Goals (SGD) planned for the year 2030, related to the conservation of the environment, especially with the achievement of SGD7, which is aimed at changing consumption and production patterns to guarantee sustainable development from a perspective of responsibility (Bradley 2021; Khan et al. 2021d, e, f, g; Sajid 2020). However, correctly defined energy policy instruments would notably reduce the ENC and, therefore, provide sustainable solutions that mitigate environmental degradation according to various aspects (Adebayo et al. 2021; Vargas-Hernández and López-Lemus 2021; Jones and Wynn 2021).

In the first place, the decrease in ENC leads to mitigating global warming and the consequences on the planet, which guarantees an improvement in the quality of life of its inhabitants (Sarpong et al. 2020). In addition, it helps to reduce the overexploitation of natural resources used for power generation, mainly the energy that comes from fossil fuels. Second, the effective reduction of the ENC contributes to designing more efficient production processes, which makes the productive transformation a less expensive and energy-efficient process (Yu et al. 2021, 2022; Liu et al. 2021). This, in turn, sets the path to facilitate the implementation of circular economy practices (Su and Urban 2021). Third, the decrease in ENC contributes to guaranteeing the long-term energy security of an economy and decreases the dependence on importing energy from neighboring external regions (Anwar 2016). Consequently, it contributes to the country's competitiveness and improves its trade balance (Bildirici and Kayıkçı 2021).

Nevertheless, within the framework of the definition of an effective energy policy, the ENC becomes a goal, which must lead to sustainable development (Khan et al. 2021a; Brodny and Tutak 2021; Sajid et al. 2020). Therefore, the arduous task of policymakers is to identify the instruments that manage to determine the ENC to design effective strategies to achieve the objective mentioned above (Gunnarsdóttir et al. 2021; Khan et al. 2021b; Sajid et al. 2019a, b). Following the above, several academic investigations have determined what factors determine the ENC. In this sense, energy efficiency (EEF), technological innovation (TEC), economic activity (GDP), foreign direct investment (FDI), and urbanization (URB) have been identified. These factors play a transcendental role in energy saving globally.

In the case of EEF, which uses less volume of energy in productive activities, it has been considered an important determinant to mitigate the growth of ENC (Cheng et al. 2022). However, Jevon's paradox may arise due to the desire to decrease ENC (Jevons 1866). This paradox affirms that EEF can reduce energy costs, leading to lower costs and increasing the ENC. Therefore, stimulating the EEF can become an incentive to increase the ENC (Brookes 1979). In addition, to the EEF, the TEC is a vital factor to stimulate the savings of the ENC since its incidence contributes to the increase in the efficiency of the production factors (Xie et al. 2021; Schipper and Silvius 2021; Gbadegesin and Olayide 2021). In turn, GDP is a primary variable considered in the behavior of ENC since all human activities demand energy; therefore, it becomes a fundamental factor in this analysis (Wang and Chen 2018; Ponce et al. 2020). Likewise, FDI attracts investment from foreign companies, resulting in an economic spillover effect, which translates into higher energy demand (Nejati and Bahmani 2020; Khan et al. 2021h, i). The rise of the URB leads to a greater concentration of individuals in urban areas of cities, which represents a greater demand for housing, goods, among others, generating a greater need for energy (Liu et al. 2017).

According to the United Nations (UN 2020), despite the efforts made in the investment of EEF and TEC, the ENC of the OECD countries will continue at an increasing rate. This fact makes it a matter of debate under the orbit of compliance with SDG7. Therefore, the research's objective is to determine how some economic factors affect the performance of ENC in the countries of the OECD. In this context, knowing what factors determine the ENC is necessary considering the sustainability of the economy and the environment. Therefore, second-generation econometric techniques are used from 1990 to 2020. Therefore, this study becomes a vital input contributing to the debate on energy demand, according to the following: (i) It contributes to understanding how EEF and TEC contribute to energy use efficiency in OECD countries. (ii) Second-generation econometric techniques have been used that control for cross-sectional dependence issues. (iii) Nonlinear methods, called quantile regression panels, are used to examine the behavior of ENC, which contributes to examining the presence of Jevon's paradox in OECD countries.

Finally, following the introduction, the article is structured as follows. The literature review is described in "Literature review" Section. Next, the methodological approach is described in "Data and methodology" Section. Then, "Discussion of results" Section contemplates the analysis and discussion of results. In the final section, the conclusions and policy implications are described.

Literature review

The theoretical framework that examines the behavior of the EEF has mentioned that the efforts to improve the EEF in order to decrease the ENC can become a phenomenon (Khan et al. 2021j, k; Bentzen 2004). Because the EEF is oriented to improve the factors' productivity and, therefore, to the effective reduction of energy, energy savings may be lower than expected, called the rebound effect (Saunders 1992). The rebound effect is introduced and raised in the scientific literature by Jevons (1866), known in the academic field as Jevon's paradox. Jevons (1866) supports his postulate that, in the UK, the EEF of a steam engine should lead to the saving of coal. Surprisingly, the opposite occurs; in other words, EEF increases fuel consumption. This phenomenon is because the EEF allows improving the productivity of the factors, therefore, to lower the cost of ENC, which leads to a decrease in the price of energy and is more affordable, unleashing an incentive to consume more energy (Alcott 2005). Later, studies by Brookes (1979) and Khazzoom (1980) reached similar results, which supported the existence of Jevon's paradox in the ENC.

Consequently, as mentioned in the previous paragraphs, this section examines the empirical evidence studies concerning the ENC, highlighting the explanatory factors that this study will use in the econometric evaluation. A great deal of empirical research has been carried out to examine the environmental and economic benefits of EEF over ENC. However, there is no definite consensus on this relationship. Some studies, such as that of Cheng et al. (2022), examine the role of EEF on ENC. The study's analysis reveals that ENC can be reduced with a high component of EEF and TEC, as opposed to using ventilation systems without these components. The outcomes show that EEF and TEC lead to improve energy savings up to 13.7%. Similarly, Han et al. (2022) analyze the effect of the improvement of the EEF on the ENC in buildings using Data Envelopment Analysis (DEA). The results indicate that an increase of 1% of the improvement in the EEF contributes to the energy efficiency of 1.042%.

In contrast, Wang et al. (2021) examine how EEF policies lead consumers to condition their NCD behavior. The study uses econometric strategies based on a survey that measures the purchase intention of consumers in China. The results of the study find mixed behaviors. When the price of the product is low, consumers choose products with high ENC. While when the price of the product is medium to high, consumers will choose products with high EEF and low ENC; however, the demand for these goods decreases, which shows the Jevons paradox. Similarly, in China, Liu et al. (2018) examine how technological progress contributes to EEF and subsequently to ENC savings. The authors argue their study in the growth model of Solow (1956) and the Jevons paradox (Alcott 2005); they use econometric techniques to examine the ENC in the transport sector from 1981 to 2015. The study results show that China has suffered an average rebound effect of 68%; in other words, the EEF increases the ENC, evidencing Jevon's paradox.

In this same trend, Adha et al. (2021) examine the determinants of energy demand in the Indonesian provinces from 2002 to 2018. For this, they use a dynamic two-stage data panel. The authors' findings indicate that increasing EPS reduces the ENC by 0.13% and 1.45% in the short and long term, respectively. However, there is a counterproductive rebound effect; that is, the increase in EEF leads to an increase in ENC, evidencing the existence of Jevon's paradox in the provinces with high EEF. On the other hand, Adua et al. (2021) carried out a study to evaluate the effects of EEF and ENC policies based on the theory of ecological modernization. They use econometric techniques with fixed panel data for 50 US states. The primary outcomes reveal that EEF policies have failed to achieve ENC's defined savings goals.

Next, other empirical studies examine the benefits of ENC derived from ECT processes. In this alignment is the study by Abidin et al. (2021), who examine the role of TEC on ENC in the automotive sector through the simulation cycle. The authors find that the implementation of hybrid technology in vehicles leads to ENC savings. In this same sector, de Salvo Junior et al. (2021) examine how environmental technologies reduce ENC in light vehicles in Brazil, for which they examine the environmental regulation program on the ENC. The results show that environmental technologies lead to the promotion of environmental quality through the reduction of ENC. In 27 member countries of the European Union, Xie et al. (2021) and Khan et al. (2022b) evaluate the incidence of various technological changes on the total productivity of green factors. The study is carried out using nonlinear econometric techniques. The findings reveal that TEC processes lead to ENC savings in determining consumption range.

Similarly, Al Khafaf et al. (2022) examine the energy demand behavior of Australian households. Thus, they use data from 5000 energy consumers with photovoltaic systems, energy storage systems, and users without any energy system. The results show that users implementing ECT decrease the ENC compared to individuals without an energy storage system or a photovoltaic system. Churchill et al. (2021) examine how energy technology research and development (R&D) spending affects the ENC in 18 OECD countries during 1980–2014. The results shown by the authors are heterogeneous and positive, ranging from R&D to ENC. Likewise, the findings highlight that R&D has a positive association with nonrenewable ENC in a specific range of years, showing an increasing trend, whereas R&D has a decreasing association with renewable ENC, that is, R&D is negatively associated with renewable ENC in the long term. In the same group of countries, Yao et al. (2019) examine how human capital and TEC are associated with ENC during 1965–2014. The findings reveal that TEC plays a decisive role in factor productivity, which leads to a decrease in ENC.

Another determining factor is GDP. This issue is demonstrated by the study by Shahbaz et al. (2021) developed for China. The authors use econometric cointegration techniques with Augmented Auto-regressive Distributive lag

(ARDL) from 1971 to 2018. The outcomes of the long-term study indicate that human capital decreases in global ENC and from fossil fuels and increases the ENC of renewable sources. Furthermore, GDP is positively associated with global ENC and renewable ENC, while it negatively affects ENC from fossil fuels. Similarly, Cui et al. (2021) examine the association between GDP, TEC, employment, FDI, and industrial ENC in the provinces of China. They employ a geographic regression approach during the 1999–2014 period in five-year intervals. The results show a clear positive association between GDP and ENC; meanwhile, employment, TEC, and FDI decrease industrial ENC in the period examined. Similarly, Wang and Chen (2018) evaluate the role of GDP and other factors on energy demand in 30 provinces of China. The result finds that GDP, URB, and level of education are positively associated with ENC.

On the other hand, Li and Leung (2021) examine the long-term cointegration between fossil fuels and GDP with the renewable ENC in seven European countries to evaluate the energy transition. The results show a long-term equilibrium relationship and show that GDP leads to increased renewable ENC, which shows the concern to move toward sustainable development. Similarly, the rise in fossil fuel prices (natural gas and coal) encourages clean energy consumption. In addition, Odhiambo (2021) examines the causal relationship between trade openness, GDP, and energy consumption in Asian countries between 1990 and 2019. The results show that GDP is the primary driver of ENC; however, exports are a determinant of ENC, in contrast to imports that do not represent statistical significance on ENC.

Consequently, as mentioned in the previous paragraph, trade relations between countries determine the behavior of the ENC. This fact is shown by the case of Fan and Hao (2020), who use a series of econometric techniques, especially cointegration and impulse response functions, to examine the role of FDI on the ENC. The research results show a long-term equilibrium relationship in the provinces of China during 2000–2015. In the short term, FDI does not affect ENC, in contrast to the long term, in which the decrease in FDI is negatively associated with ENC. Li et al. (2020) examine the role of the Chinese FDI in world economies and its penetration into the energy sector in Asia and Latin America. The results indicate that the Chinese FDI is a crucial determinant for the energy sector's growth; mainly, the FDI drives the increase of the ENC of coal and gas. Zhao et al. (2020) examine how energy security improves in China due to the country's oil deficit. The revealing results show that a 1% increase in Chinese FDI in a host country leads to a 1.2% increase in the probability of obtaining imported energy from that country. However, the authors find mixed effects when the country is developed or developing.

On the other hand, Nejati and Bahmani (2020) establish that the inflow of capital, a product of the FDI, generates productivity spillovers in the Iranian economy. The authors find that the Iranian economy has benefited from the inflow of FDI capital, which has improved the country's productivity. Consequently, FDI has boosted the growth of primary sectors, such as oil exploitation; that is, FDI has created the propitious scenario to increase the ENC. At the level of a global study, Khan et al. (2021b, c, f, g, l) examine the short- and long-term determinants of energy demand. They employ panel data econometric techniques in 69 that have "Belt and Road Initiative (BRI)" from 2000 to 2014. The results show that GDP, FDI, and TEC are negatively associated with the renewable ENC. In contrast, the total ENC has a positive relationship with TEC, FDI, and GDP. In a complementary way, the Jiang and Martek (2021) and Khan et al. (2022a) study reveals that the FDI in the energy sector can be affected by external factors, such as the legal system and political risk.

One of the factors affecting the ENC is the URB, as affirmed by the following empirical studies. Shahbaz et al. (2017) examine the long-term relationship between TEC, GDP, URB, and ENC in Pakistan during 1972–2011. The findings reveal that URB is positively associated with the increase in ENC due to the concentration population and the greater demand for services. Likewise, TEC, GDP, and the transportation sector sharpen the demand for ENC and its subsequent impact on the environment.

Wang et al. (2019) spatially examine the role of the URB on carbon emissions, a product of ENC, in regions of China according to various types of the economic sector. They use a spatial econometric model in 2000, 2005, 2010, and 2015, showing that the URB is positively associated with GDP, showing heterogeneous relationships according to the economic sector. Yu et al. (2020) examine the determinants of energy demand in 108 Chinese cities located in the economic sector of the Yangtze River. The research uses spatial and heterogeneous econometric models to verify how the URB affects the ENC. The results indicate that the demographic URB increases the ENC between 49 and 66%, while the soil URB increases the ENC between 68 and 91%. Using the Stochastic Impacts by Regression on Population, Affluence and Technology (STIRPAT) econometric model, Liu et al. (2017) examine the URB's spatial spills on ENC, considering direct and indirect effects. The findings reveal that a 1% increase in one region represents a 0.14% increase in ENC in neighboring regions. Likewise, Keho (2016) examines the effect of URB on ENC in various countries of Sub-Saharan Africa with individual cointegration tests of time series during 1970–2011. The results indicate that URB and GDP maintain a positive relationship with ENC, which differs across the countries examined.

Table 1 Description of variables

Variable	Description	Symbol	Data source
Energy consumption	Primary energy consumption per capita (Gigajoule)	ENC	BP (2020)
Energy efficiency	GDP per unit of energy use (constant 2017 PPP $ per kg of oil equivalent)	EEF	WDI (2020)
Technological innovation	Total patented applications (units)	TEC	WDI (2020)
Gross domestic product	Gross domestic product per capita (constant 2010 US$)	GDP	WDI (2020)
Foreign direct investment	Foreign direct investment, net inflows (BoP, current US$)	FDI	WDI (2020)
Urbanization	Urban population (persons)	URB	WDI (2020)

Table 2 Descriptive statistics

Statistic	ENC	EEF	TEC	GDP	FDI	URB
Mean	5.0173	8.1504	8.0572	10.2131	22.5927	16.0588
Median	5.0587	8.1806	7.9121	10.4201	22.7832	15.8657
Minimum	3.2806	6.4242	3.0911	8.4045	14.5092	12.3512
Maximum	6.5278	9.8317	13.3398	11.6259	27.3215	19.4226
Standard dev	.5762	.5561	2.1415	.7229	1.8851	1.5369
Kurtosis	3.5141	4.0588	2.9233	2.4293	3.4739	2.6263
Skewness	−0.3665	−0.2905	0.31216	−0.4887	−0.4156	−0.1842
Jarque–Bera	38.38***	69.72***	17.24***	59.04***	38.73***	13.16**
Correlation	–	0.9779***	0.1606***	0.7788***	0.2260***	−0.2311***

*** and ** show significance level at 1% and 5%, respectively

Data and methodology

Data

This research examines the long-term causal link between ENC and EEF, TEC, GDP, FDI, URB in 37 OECD countries from 1990 to 2020. The countries used in this research are detailed in Table 9, chosen according to the availability of information. For this reason, Costa Rica is excluded from the analysis. The variables are annualized series taken from official World Bank databases (WDI 2020) and BP Statistical Review of World Energy (BP 2020). Energy efficiency (EFF) is used as a dependent variable (ENC) and energy efficiency (EFF) as independent variables, followed by the square of energy efficiency (EFF2) to verify the Jevons paradox.

Additionally, it is used as explanatory variables to technological innovation, gross domestic product per capita, foreign direct investment, and urbanization, represented by their acronyms, TEC, GDP, FDI, and URB, respectively. Table 1 shows the detail of the variables used in the model, in which their description, symbol, and the name of the database from which they come are evidenced. The variables are expressed in natural logarithms (ln) to standardize the unit of measurement and analysis.

Table 3 VIF Statistic

Variables	EEF	TEC	GDP	FDI	URB
VIF	2.34***	1.78***	1.45***	1.98***	2.56***
1/VIF	0.43	0.56	0.69	0.51	0.39

***Representa los valores de VIF menores a 5

Next, Table 2 shows the main descriptive statistics of the variables used in the econometric estimation and the correlation matrix at 1% significance. The variables present skewness values, and the Kurtosis test describes the concentrated distribution of the variables. Likewise, the Jarque–Bera statistic suggests that the variables do not have a normal distribution of their observations, which becomes an argument for using regressions at different points of the distribution of the dependent variable, called ENC (Koenker and Bassett 1978).

Subsequently, the variance inflation factor (VIF) test is applied, which is used to evaluate the possible existence of multicollinearity in the data panel among the variables examined (Belsley et al. 1980). The VIF results are described in Table 3, below five, which guarantees that the econometric estimates do not encounter multicollinearity problems (Ndubizu and Wallace 2003).

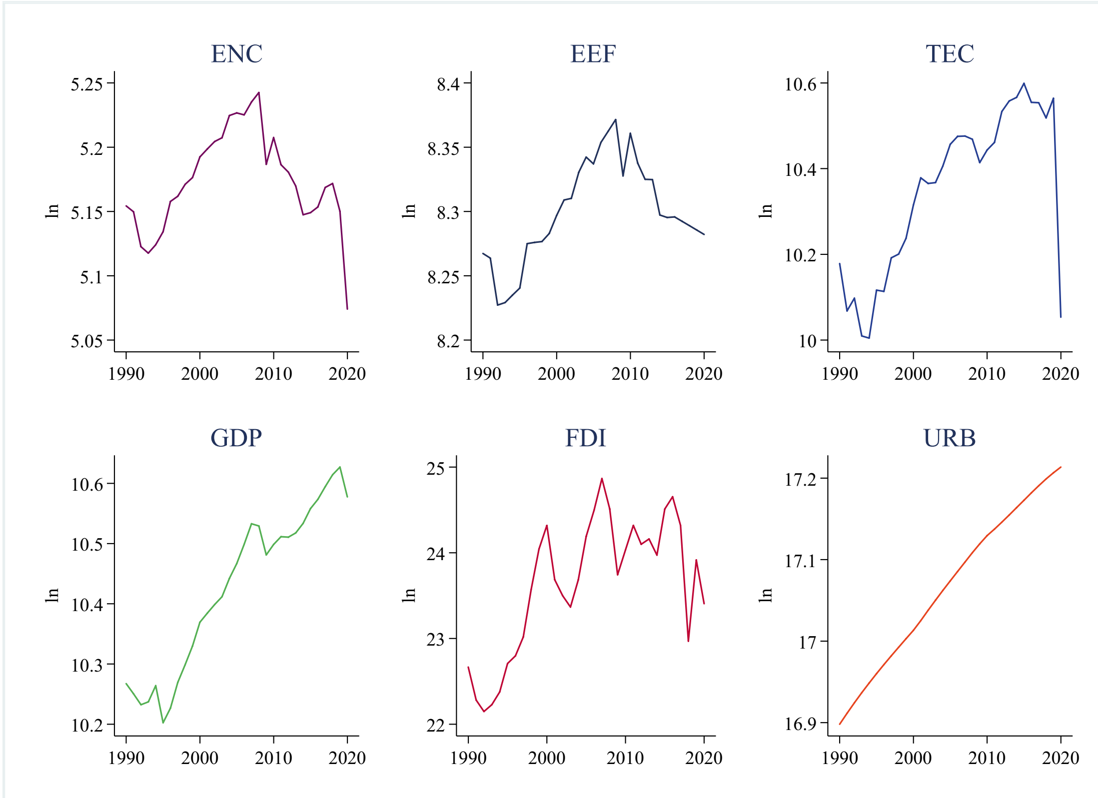

Fig. 1 The trend of the model variables

To finish this section, Fig. 1 represents the trend of the variables used in the model, represented in their natural logarithm.

Econometric strategy

According to Breusch and Pagan (1980), in the long-term models, the possible interdependence between the study variables must be controlled, established due to the economic and social interaction present in the countries examined. This interaction between countries occurs due to globalization, political relations, economic agreements, commercial exchange, among others, which causes the political decisions of one country to have repercussions on the rest and vice versa (Surugiu and Surugiu 2015). Consequently, to ensure the efficiency and robustness of the long-term estimators, the cross-sectional dependence (CD) test developed by Pesaran (2015) is applied.

According to the findings of the CD test, the second-generation unit root test is used to test the stationarity of the variables used in the model. Consequently, the second-generation cross-sectional augmented Im, Pesaran, and Shin (CIPS) and the cross-sectional augmented Dickey-Fuller (CADF) tests were applied in this study. These tests were included in the scientific research by Pesaran (2007) and offer the advantage of controlling the presence of CD (Safi et al. 2020).

Subsequently, once the presence of DC and the order of integration of the study variables have been verified, the long-term cointegration between the model variables is examined using second-generation tests. Therefore, the Westerlund (2007) error correction mechanism (ECM) approach is applied, a second-generation cointegration method that controls for DC and heterogeneity drawbacks, the same one that uses four various statistical tests, two for panel statistics $\left(P_t, P_\alpha\right)$, and two for group statistics (G_t, G_α). In this context, the four statistics to examine are written below:

$$G_t = \frac{1}{N}\sum_{i-1}^{N}\frac{\alpha_i'}{\mathrm{SE}_{\left(\delta_i'\right)}} \quad (1)$$

$$G_\alpha = \frac{1}{N}\sum_{i=1}^{N}\frac{T\alpha_i'}{\alpha_i'(1)} \quad (2)$$

$$P_t = \frac{\alpha'}{\mathrm{SE}_{\alpha'}} \tag{3}$$

$$P_\alpha = T\alpha' \tag{4}$$

The term α' represents the ECM, calculated by including the value of P_α within Eq. (4), representing the adjustment speed toward equilibrium in the long term. Subsequently, after checking the long-term equilibrium relationship between the model variables, the next step is to examine the long-term elasticities.

In general, the distribution of the variables does not follow an asymmetric distribution so that ordinary least squares estimators can find biased and inefficient values (Khan et al. 2020). Additionally, Sánchez-Silva et al. (2016) affirm that in practice and reality, the data of the economic variables have different distribution patterns. Therefore, using approaches that focus on the average of the explained variable can lead to erroneous statistical inferences (Malumfashi et al. 2020). In the same way, the statistics detailed in Table 1 (Kurtosis, Skewness, and Jarque–Bera) suggest that the distribution of the variables has an asymmetric distribution. Consequently, the econometric model to be estimated is described as follows:

$$\begin{aligned} \ln \mathrm{ENC} = \theta_{it} + \beta_1 \ln \mathrm{EFF}_{it} + \beta_2 \ln \mathrm{EFF2}_{it} + \beta_3 \ln \mathrm{TEC}_{it} \\ + \beta_4 \ln \mathrm{GDP}_{it} + \beta_5 \ln \mathrm{FDI}_{it} + \beta_6 \ln \mathrm{URB}_{it} + \mu_{it} \end{aligned} \tag{5}$$

ENC represents energy consumption, EFF denotes energy efficiency, EFF2 represents the square of the EFF, TEC represents technological innovation, GDP represents economic growth, FDI means foreign direct investment, and URB denotes urbanization. The term μ represents the error term of the equation. The expression ln represents the natural logarithm of the model variables. Furthermore, the sub-indices i and t are the countries $i = 1, 2, 3, \dots, N$ in the examined period $t = 1990, 1991, 1992, \dots, T$, respectively.

As a consequence of the above, the present study uses the panel quantile regression (PQR) method. The PQR approach was introduced in the scientific field by Koenker and Bassett (1978), which is an approach that offers vast advantages compared to ordinary least squares estimates (Akram et al. 2021). Among the multiple advantages offered by PQR results, the following stand out: (i) PQR delegitimizes the existence of a moment function (Zhu et al. 2016); (ii) PQR offers efficient and unbiased coefficients in the presence of nonuniformly distributed values and heavy-tailed distributions (Chen et al. 2018); (iii) PQR allows us to examine the unobserved heterogeneity between the cross sections and examines parameters at various points of the conditional median of the explained variable (Sherwood and Wang 2016). The standard form of standard PQR can be defined as follows:

$$\mathrm{Quant}_\varphi\left(y_i|x_i\right) = x\beta_\varphi + \varepsilon_\varphi, 0b\varphi b1 \tag{6}$$

where y expresses the dependent variable, x represents a vector containing the explanatory variables, ε is the error term at the distribution point at φ th in the explained variable. Consequently, PQR is used to evaluate the association between explanatory variables and ENC. The following equation defines this relationship:

$$\begin{aligned} Q_\tau\left(\ln \mathrm{ENC}_{it}\right) =& \theta_\tau + \beta_{1\tau} \ln \mathrm{EFF}_{it} + \beta_{2\tau} \ln \mathrm{EFF2}_{it} + \beta_{3\tau} \ln \mathrm{TEC}_{it} \\ &+ \beta_{4\tau} \ln \mathrm{GDP}_{it} + \beta_{5\tau} \ln \mathrm{FDI}_{it} + \beta_{6\tau} \ln \mathrm{URB}_{it} + \mu_{it} \end{aligned} \tag{7}$$

where Q_τ is the estimated parameters of the τth distributional point, and τ represents the quantile of the distribution of the explanatory variables defined in Table 1.

Discussion of results

Prior to obtaining the PQR coefficients, preliminary tests are required to ensure the quality of the long-term estimators. The tests to be carried out are (a) CD test; (b) unit root; (c) long-term cointegration. For this reason, Table 4 presents the results obtained from the Pesaran (2015) CD test. The results strongly reject the null hypothesis of independence for all the study variables. That is, there is an existence of interdependence between the variables examined.

Next, the second-generation unit root test is developed to examine the model variables' stationarity (see Table 5). In levels, the Pesaran (2007) tests show the presence of a unit root in all variables. Consequently, the first difference (Δ) of the variables is obtained, with which the CIPS and CADF tests strongly reject the hypothesis of the null of a unit root. The variables have integration order I (1); this condition allows the long-term cointegration analysis (Dogan and Inglesi-Lotz 2017).

Table 6 provides the statistics of cointegration among groups (G_t y G_t) and among panels (P_t y P_t) of the second-generation tests of Westerlund (2007), which allow rejecting

Table 4 Cross-sectional dependence test

	Variables	ENC	EEF	TEC	GDP	FDI	URB
OECD countries	Statistic	28.94***	19.65***	3.17**	110.62***	60.21***	66.31***
	p-value	0.000	0.000	0.0015	0.000	0.000	0.000

*** and ** indicate statistical significance at 1% and 5% levels, respectively

Table 5 Second-generation unit root test

Variable	CIPS		CADF	
	Level	Δ	Level	Δ
ENC	− 1.823	− 4.678***	− 1.364	− 4.567 ***
EEF	− 1.634	− 7.274***	− 0.935	− 4.689 ***
TEC	− 0.732	− 5.723***	− 1.456	− 8.885***
GDP	− 1.702	− 4.981***	− 1.638	− 7.445***
FDI	− 1.082	− 3.439***	− 0.934	− 5.672**
URB	− 3.467***	− 6.738***	− 1.753	− 7.796***

Δ represents the first differences, ***Indicates statistical significance at 1% level

the null hypothesis of no cointegration at 1% significance. In other words, the existence of long-term cointegration between the variables examined is confirmed.

Next, Table 7 reports the estimates made by PQR in various quantiles (10th–90th) of ENC.

The findings show a positive and significant relationship between EEF and ENC across all quantiles. This finding suggests that the EEF increases the ENC, which is counterproductive since the EEF is expected to decrease the ENC. However, this result takes another meaning when considering the quadratic term of EEF, which is used to validate the Jevons paradox and energy efficiency. Consequently, the term EEF2 is negatively related to ENC from the 10th to 60th quantile. In contrast, EEF2 and ENC are positively related in the 70th–90th quantiles. The findings show that energy efficiency lowers ENC in the early and middle phases. However, after crossing a certain ENC, the effect of EFF becomes the opposite. In other words, in the 70th–90th quantiles, the Jevons' paradox is fulfilled, suggesting that the EEF decreases the instantaneous ENC but subsequently increases the ENC. In this case, in the initial path of the ENC, the EEF generates the expected results to decrease the ENC. However, at higher ENC levels, the EEF has the opposite effect on ENC. The findings coincided with Adha et al. (2021) and Adua et al. (2021), who show compliance with the Jevons' paradox; regions with high EEF tend to increase ENC.

On the other hand, TEC is positively related to the ENC across all quantiles except for the first quantile, which has a negative relationship with the ENC, and the ninth quantile, which has no statistical relationship with ENC. This finding implies that TEC works in a complementary way to EFF, since modern technological processes improve the performance of the factors of the firms and generate efficiency in

Table 6 Panel cointegration tests

Test	Statistic	Value	*p*-value	Cointegration
Westerlund panel cointegration	G_t	− 6.346***	0.000	Yes
	G_α	− 8.318***	0.001	Yes
	P_t	− 11.956***	0.000	Yes
	P_α	− 4.845***	0.001	Yes

***Indicates significance at 1% level

Table 7 The results of panel quantile regression estimation

Quantiles	10th	20th	30th	40th	50th	60th	70th	80th	90th
EEF	0.6989***	0.7013***	0.7557***	0.7434***	0.7654***	0.7392***	0.7134***	0.6423***	0.6002***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
EEF2	− 0.0951***	− 0.0765***	− 0.0721***	− 0.0583***	− 0.0488***	− 0.0256***	0.0015***	0.0387***	0.0789***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
TEC	0.0053***	− 0.0018***	− 0.0098***	− 0.0115***	− 0.0116***	− 0.0063***	− 0.0029***	− 0.0019***	0.0057
	(0.002)	(0.000)	(0.001)	(0.000)	(0.001)	(0.001)	(0.000)	(0.000)	(0.372)
GDP	0.2556***	0.3199***	0.2849***	0.2999***	0.2854***	0.3261***	0.3162***	0.3768***	0.4209***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
FDI	0.0023	0.0024	0.0022	0.0021	0.0011	0.0018	0.0023***	0.0024***	0.0021**
	(0.609)	(0.313)	(0.997)	(0.423)	(0.937)	(0.734)	(0.001)	(0.004)	(0.026)
URB	0.2134***	0.4899***	0.6783***	0.9962***	1.0963***	1.4832***	1.5623***	1.9643***	2.0167***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.004)
Shape of Jevons	Inverted U-shaped	Inverted U-shaped	Inverted U-shaped	Inverted U-shaped	Inverted U-shaped	Inverted U-shaped	U-shaped	U-shaped	U-shaped

***, **, and * indicate significance at 1%, 5%, and 10% levels. Values in parentheses represent *p*-values the energy consumption. In addition, TEC allows energy loss or leakage to be reduced. However, at higher ENC levels, more outstanding TEC efforts are required to mitigate the increase in ENC. The result is explained due to the Jevons' paradox, examined above. These results are similar to the study by Churchill et al. (2021), who explain that through the TEC, the ENC can be reduced in OECD countries, therefore mitigating the impact on the environment.

Next, it is indicated that GDP maintains a positive relationship with ENC across all quantiles examined. This finding is evident because ENC is the basis for the development of economic activity since all production processes demand ENC. Likewise, the magnitude of the GDP coefficients is more robust in the upper quantiles of ENC, which can be explained because creating a greater quantity of goods and services requires a greater ENC. Similar findings are reported in the study by Cui et al. (2021) and Chakraborty and Mazzanti (2021), who state that economic activity increasingly demands a greater volume of energy.

Then, the results show a positive and significant relationship between FDI and ENC in the upper quantiles of the ENC (70th–90th). The findings find evidence in favor of FDI generating higher ENC, which is associated with creating agricultural, industrial, service companies, among others, which in turn demand large amounts of ENC. Likewise, the incidence of FDI is intensive at high levels of ENC since this type of economic activity requires much ENC when the FDI has achieved high participation in the economies of the countries. These results corroborate the assertions of Khan et al. (2021a, b, c, d, e, f, g, h, i, j, k, l), authors who state that FDI and GDP contribute significantly to ENC and carbon emissions in BRI countries.

On the other hand, the URB maintains a positive and significant relationship with ENC across all quantiles. The concentration of the population in the urban part of cities and towns represents a greater demand for goods, housing, public services, among others, which in turn represents a greater demand for the ENC in cities, places where the most of the population. These results coincide with Liu et al. (2017), who affirm that the URB impacts the growth of ENC in the region itself and that of its neighboring regions.

Figure 2 graphically shows the heterogeneity of the estimated coefficients and their relationship with the ENC. The findings show the importance of examining the ENC with PQR techniques since the conditional distribution of ENC varies according to the quantiles examined. Since it

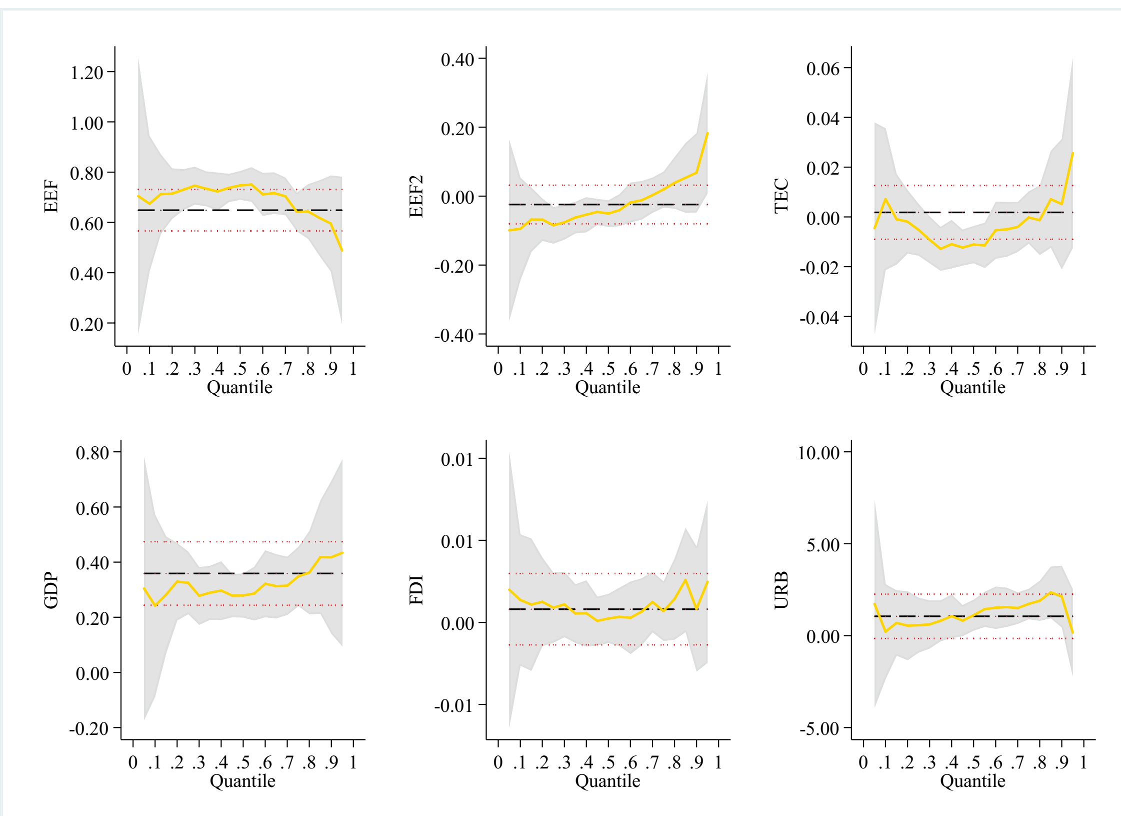

Fig. 2 Quantile distribution explanatory variables on air pollution. *Note* Yellow line represents a 95% confidence level for the quantile estimates. The gray area means the confidence interval for quantiles estimates. The black dashed line represents the corresponding OLS estimate with a 95% confidence interval represented with the red dashed line

allows to detail the behavior of ENC in several quantiles (10th–90th), this fact represents an advantage compared to conventional estimation methods that focus on the average of the variable examined and could lead to erroneous inferences about the ENC. Additionally, examining the ENC in different quantiles allows discovering the fulfillment of the Jevons paradox in the OECD countries.

On the other hand, the global results give several indications to improve the energy transition and to be able to meet the long-term sustainable development objectives, specifically oriented to the achievement of the SDG7. The EFF should be considered as a precious energy policy instrument to reduce ENC. However, EFF has a significant incidence in the initial and middle phases of ENC; on the contrary, the effect of EFF is positive at the highest levels of ENC. This situation leads policymakers to define actions for the EFF to meet the expected results of reducing the ENC at all levels of consumption, which will cause a decrease in environmental degradation, given that fossil fuels cover most of the global energy demand.

Similarly, it is evident that the TEC is a critical complementary factor in decreasing the ENC; therefore, the energy transition should be promoted through the TEC, which contributes to reducing the ENC. Furthermore, in the presence of the Jevons paradox, TEC contributes to reducing ENC at the highest levels of consumption, although not in its entirety, which suggests that more significant efforts should be made in EFF and TEC to reduce ENC at the highest levels and mitigate the negative effect on the environment.

Finally, the causal relationship between the model variables is examined using the heterogeneous panel causality test of Dumitrescu–Hurlin (2012). This test makes it possible to identify how the policy instruments affect the target policy parameter in the countries examined and vice versa. Table 8 gives indications of a unidirectional causality that goes from FDI and URB toward the ENC. Additionally, there is evidence of a bidirectional relationship between ECN, TEC, GDP, and EEF. In other words, it can be stated that any policy measure in FDI and URB has implications for ENC. Furthermore, any energy policy measure in ENC has an impact on EEF, TEC, and GDP.

Conclusion and policy relevance

Environmental conservation concerns are aimed at developing various strategies to generate sustainable development. One of these strategies is to reduce the ENC, which has a direct impact on environmental degradation. Consequently, it is an important task to know the factors that determine the ENC. For this reason, this study examines the role of the EFF, TEC, GDP, FDI, and URB on the ENC in 37 OECD countries, during 1990–2020. To fit this objective, long-term econometric cointegration techniques are used. Second-generation nonlinear econometric techniques have been used that control the problems of transversal dependence between the sections. Then, the PQR method is used to examine the elasticities between the study variables. Finally, the panel causal relationship is examined.

The results show a long-term equilibrium relationship between the variables examined. On the other hand, the Jevons' paradox is revealed in the upper ENC quantiles (Ismayilova and Silius 2021; Chen and Lei 2018). In contrast, in the low and middle quantiles, the EFF2 allows the ENC to be reduced, aiming to comply with the SDG7. Additionally, a positive association is found between ENC and GDP, FDI, URB. In contrast, TEC is negatively associated with ENC (Michel 2021; Pedroni 2004; Xu and Lin 2020). At the same time, the causality results show a unidirectional relationship that goes from FDI and URB to ENC. On the other hand, there is evidence of a bidirectional relationship between ENC and EFF, TEC, GDP, respectively.

Therefore, the following policy implications are derived from this study to comply with SDG7: (i). The results show that the Jevons paradox is fulfilled when the demand for ENC is at the highest levels; therefore, the effort to improve the EEF should be more significant. This situation is related to the fact that most of the ENC of the OECD countries comes from fossil fuels. Therefore, the industry should be encouraged to adopt EEF processes at all levels

Table 8 The results of Dumitrescu–Hurlin panel causality tests

		Independent variables					
		ENC	EEF	TEC	GDP	FDI	URB
Dependent variables	ENC	–	6.546***	8.372***	11.485***	3.852***	7.093***
	EEF	8.329***	–	–	–	–	–
	TEC	4.239***	–	–	–	–	–
	GDP	5.228***	–	–	–	–	–
	FDI	–	–	–	–	–	–
	URB	–	–	–	–	–	–

***Indicates the statistical significance at the 1% level

Table 9 OECD countries

S. No	OECD countries
1	Australia
2	Austria
3	Belgium
4	Canada
5	Chile
6	Colombia
7	Czech Republic
8	Denmark
9	Estonia
10	Finland
11	France
12	Germany
13	Greece
14	Hungary
15	Iceland
16	Ireland
17	Israel
18	Italy
19	Japan
20	Korea, Dem. People's Rep
21	Latvia
22	Lithuania
23	Luxembourg
24	Mexico
25	Netherlands
26	New Zealand
27	Norway
28	Poland
29	Portugal
30	Slovak Republic
31	Slovenia
32	Spain
33	Sweden
34	Switzerland
35	Turkey
36	UK
37	USA

of production. (ii). Likewise, the TEC does not have the expected effect on the highest consumption of ENC. The implementation of emerging technologies is suggested to improve the efficiency of resources, leading to improved production productivity and a decrease in ENC. (iii). Likewise, the FDI must be regulated at all levels of implementation in the economies. Therefore, governments must ensure that the FDI complies with environmental and energy efficiency standards, which leads to improving the ENC. (iv). The URB is a growing process and demand for various products and services in cities. Therefore, URB processes must be complemented with the improvement of EEF to mitigate the growing demand for ENC. Finally, one of the study's main limitations is the disaggregation of ENC according to the type of economic activity, which would lead to defining targeted policies to reduce ENC. Therefore, the extensions of this work could analyze energy consumption according to the diversity of economic activity.

Appendix

See Table 9.

Acknowledgements The author Ateeq Ur Rehman Irshad would like to thank Prince Sultan University for paying the APC and the support through TAS research laboratory.

Authors contribution ZY, PP, and KP conceptualized the study; ARI, AR, and PP helped in methodology; ZY and PP developed the software; ARI and AR validated the study; PP and ZY formally analyzed and curated the data; ARI and KP investigated the study; PP and KP contributed to resources; ZY, MT, and PP wrote the original draft; ARI, KP, and PP wrote the review and edited; MT and ZY visualized the study; YU, PP, and MT supervised the study; ARI, MT administrated the project; YU and ARI acquired the funding. All authors have read and agreed to the published version of the manuscript in "Journal of Petroleum Exploration and Production Technology."

Funding This research is supported by the Beijing Key Laboratory of Urban Spatial Information Engineering (No. 20210218).

Declarations

Conflict of interest The authors declare no conflict of interest.

Ethical approval The authors are fully responsible and there is no ethical issue in this manuscript.

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