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Introducing a new measure of energy transition: Green quality of energy mix and its impact on CO_2 emissions

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ABSTRACT

This paper introduces a novel measure of the energy transition, i.e., the green quality of energy mix (*GREENQ*) across the Organisation for Economic Co-operation and Development (OECD) countries. Then, the paper examines the impact of the *GREENQ* on CO_2 emissions in the panel dataset of 36 OECD countries from 1970 to 2021. The explanatory variables include per capita income, institutional quality and technology. Long-run panel data estimations indicate that per capita income, institutional quality and technology increase CO_2 emissions. The novel evidence is that the *GREENQ* is negatively related to the level of CO_2 emissions. These findings are robust to employ different panel data estimation techniques. Potential policy implications are also discussed.

1. Introduction

Climate change is a significant threat to human life and the economic order in the world. The main reason for climate change is global warming. The global average temperature is estimated to be around 3–5 °C higher by 2100 compared to the early 2010s (Burke et al., 2015). The primary source of global warming is burning fossil fuels such as coal, crude oil (petroleum), and natural gas, leading to higher carbon dioxide (CO_2) emissions (Nordhaus, 2019). Therefore, businesses, people and policymakers must spend money and time to significantly curb CO_2 emissions. Otherwise, ongoing accumulations of CO_2 emissions around the globe will result in global warming with an outcome of climate change. Understanding the determinants of CO_2 emissions is vital for businesses, people and policymakers to decrease their levels.

What drives CO_2 emissions around the globe? Possible answers to this question are complex, and the answer changes from one country to another. Investigating the level of CO_2 emissions across the countries is essential because each country has different cultural, economic, political and social dynamics regarding environmental degradation and environmental policies (Ajmi et al., 2015; Apergis et al., 2018; Disli et al., 2016; Friedl and Getzner, 2003; Gozgor, 2017; Khan et al., 2021; Sadorsky, 2009). Therefore, panel data studies focusing on cross-country dynamics can be a good candidate to explain the determinants of CO_2 emissions across countries (Zhang et al., 2017).

One factor in determining CO_2 emissions is economic development, generally measured by per capita income in the empirical literature. Typically, the countries with higher per capita incomes are considered economically developed. The World Bank (2023a) also defines these countries as high-income countries with $13,205 or more per capita Gross National Income (GNI) in the fiscal year of 2023. According to the Environmental Kuznets Curve (EKC), proposed by Grossman and Krueger (1991 and 1995), there is a significant relationship between CO_2 emissions and per capita income. In the early stages of economic development, CO_2 emissions increase in a developing economy as the economy grows. However, once the country reaches a certain level[1] of income per capita, economic development decreases CO_2 emissions (Copeland and Taylor, 2004; Dinda, 2004). In short, the EKC hypothesis suggests an inverted U-shaped impact of per capita income on per capita CO_2 emissions, but the evidence is mixed (Dogan et al., 2020; Sarkodie and Strezov, 2019). Following the EKC hypothesis and previous papers,

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[1] This level is arguable, but many papers assume it is the threshold to pass the high-income level (e.g., Apergis et al., 2018).

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we control per capita gross domestic product (GDP) to capture the role of economic development in CO_2 emissions.

Another factor to drive CO_2 emissions is institutional quality. Institutional quality decreases corruption and promotes the efficient management of public resources (Hussain and Dogan, 2021; Khan and Rana, 2021). This decreases the costs of investments in new facilities with green production (Hassan et al., 2020). Besides, efficient management procedures of institutions and solid rule of law practices can also increase firms' sensitivity to follow the rules related to CO_2 emission limitations (Muhammad and Long, 2021). Hence, solid institutions can help to decrease environmental degradation and promote environmental sustainability (Lau et al., 2014). In this paper, we use the index of *POLITY2* proposed by Marshall and Gurr (2020) to measure institutional quality across OECD countries.

The technology level is another important parameter to affect CO_2 emissions. New technologies can increase energy efficiency by reducing fossil fuel-related consumption (Churchill et al., 2019; Sun et al., 2019). Technology also increases production efficiency, thus promoting environmental quality (Chen and Lee, 2020; Khan et al., 2022; Obobisa et al., 2022). Therefore, in this paper, we consider the role of technology by using the de facto informational globalisation (*GLB*) index of Gygli et al. (2019).

The final aspect that drives CO_2 emissions is energy consumption based on the energy mix. A country typically consumes different energy sources, such as coal, crude oil (petroleum), hydroelectricity, natural gas, nuclear, and renewable energy. According to the previous papers, fossil fuel consumption, such as coal, crude oil (petroleum), and natural gas, increases CO_2 emissions in an open economy (Abas et al., 2015; Smith et al., 2021). On the other hand, the consumption of hydroelectricity, renewable energy, and nuclear energy sources are labelled as clean or green energy with (almost) zero CO_2 emissions (Ji and Zhang, 2019; Oh et al., 2010).

Previous papers examining energy consumption's impact on CO2 emissions have been straightforward, using energy consumption data from specific sources and several regression techniques. Given this juncture, this paper's main objective is to re-examine the determinants of CO2 emissions. For this purpose, we focus on the panel data of 36 OECD countries annually from 1970 to 2021. We specifically focus on the role of the energy consumption mix on CO2 emissions in the OECD economies.

Unlike previous papers, this paper introduces a novel measure of the green quality of energy mix (*GREENQ*). Our measure, the *GREENQ*, is based on calculating CO_2 emissions from electricity generation using different energy sources. Using annual data, we create the *GREENQ* measure in 36 OECD countries from 1970 to 2021. The United States (U. S.) Energy Information Administration (EIA) publishes CO_2 emissions estimates related to electricity generation in the country (U.S. EIA, 2021). Using the U.S. EIA (2021) data, we calculate how much CO_2 emissions are produced per kilowatt-hour of electricity generation in the U.S. with different energy sources. Then, we use these calculations to measure the green quality of the energy mix and to analyse how much CO_2 emissions are produced from a country's energy consumption mix.

The novelty of this paper is that it introduces a new measure of the green quality of energy mix (*GREENQ*) across 36 OECD countries from 1970 to 2021. Then, we analyse the impact of the *GREENQ* on CO_2 emissions by utilising various panel data estimation techniques. The empirical models also include the per capita income, institutional quality and technology indicators following previous empirical papers. According to the results from panel data estimation techniques, per capita income, institutional quality and technology all increase CO_2 emissions in the OECD countries. However, *GREENQ* is negatively related to the level of CO_2 emissions. Therefore, we show that the transition of the energy consumption mix from fossil fuels (coal, natural gas and petroleum) to clean energy sources (hydroelectricity, nuclear and renewable energy) significantly suppresses CO_2 emissions in the OECD countries. We suggest that energy transition is a valuable policy tool to tackle the negative consequences of climate change in the OECD economies.

The rest of the paper is organised as follows. Section 2 reviews the previous literature on the drivers of CO_2 emissions, especially in the OECD countries. Section 3 introduces the Green Quality of energy mix measure and explains the data, theoretical model and econometric methodology. Section 4 discusses the empirical findings. Section 5 concludes.

2. Literature review

Environmental degradation is usually measured by CO_2 emissions or CO_2 efficiency in the empirical literature. Therefore, various papers have examined the determinants of CO_2 emissions in developing and developed economies. Some of these papers used the energy transition as the leading driving factor of environmental degradation.

The impact of the energy transition on CO_2 emissions can be attributed to two main effects, namely the "substitution effect" and the "technology base effect". The substitution effect suggests that the increase of renewable energy sources replaces fossil-energy sources, which increases energy efficiency and thus decreases CO_2 emissions (Zhang et al., 2018). Regarding the validity of the substitution effect, Shafiei and Salim (2014) demonstrated that non-renewable energy leads to an increase in CO_2 emissions and renewable energy consumption reduces CO_2 emissions in the panel dataset of 29 OECD countries from 1980 to 2011. Bilgili et al. (2016) found that renewable energy consumption was negatively associated with the level of CO_2 emissions in the panel dataset of 17 OECD countries from 1977 to 2010. Dogan and Seker (2016) also observed that renewable energy deployment decreased CO_2 emissions in the panel dataset of 23 developed and developing countries from 1985 to 2011. Dong et al. (2020) examined the impact of renewable energy consumption on CO_2 emissions in a panel of 120 countries from 1995 to 2015. The study found a negative impact of renewable energy on CO_2 emissions, valid in low- and middle-income countries and high-income economies.

On the other hand, the "technology base effect" suggests that renewable energy increases environmental degradation (measured by the level of CO_2 emissions in general). This impact is because renewable energy instalments require significant initial capital investments, high-skilled workers (human capital) and complicated technology, which need environmental space and technical support (Kim and Park, 2016; Olabi and Abdelkareem, 2022; Yao et al., 2019). Mainly, electricity generation via renewable energy sources sometimes requires fossil energy sources as a backup to meet the peak demand. Due to a lack of energy storage technology, renewable energy supply may be intermittent (Bellocchi et al., 2018). This issue can limit the effectiveness of the substitution effect, where renewable energy is expected to replace fossil fuels and reduce CO_2 emissions. The technology base effect can be more effective than the substitution effect in some countries (Bai et al., 2020). For instance, Yurtkuran (2021) observed that renewable energy production increases CO_2 emissions in Turkey from 1970 to 2017, implying that the technology base effect is more prominent in Turkey for the period concerned.

Meanwhile, several papers have found mixed or heterogeneous effects of renewable energy on CO_2 emissions via the technology channel. For instance, Cheng et al. (2021) used the panel dataset of 35 OECD countries from 1996 to 2015. They found that technological innovation decreases CO_2 emissions, but the impact is heterogeneous across different panel quantile regressions. Ullah et al. (2021) obtained similar heterogeneous effects of renewable energy on CO_2 emissions from 1990 to 2018 in Pakistan. Dong et al. (2022) also found the heterogeneous effects of renewable energy demand on carbon emission efficiency in the panel dataset of 32 developed economies from 2000 to 2018. According to Tzeremes et al. (2023), there is (reverse) causality from CO_2 emissions to energy transition in Brazil, China and India, Russia and South Africa from 2000 to 2017.

As we can see from the literature review, there can be positive, adverse, insignificant or heterogeneous effects of the energy transition on environmental degradation. Unlike previous studies, this paper introduces a measure of the energy transition called the *GREENQ*. Then, we analyse the impact of the *GREENQ* on CO_2 emissions in the panel dataset of 36 OECD countries from 1970 to 2021. We observe that the *GREENQ* reduces CO_2 emissions. We suggest that energy transition is a valuable policy tool to tackle the negative consequences of climate change in the case of the OECD economies.

3. Data, model, and methodology

3.1. Measuring green quality (GREENQ) of energy mix

We introduce the *GREENQ,* based on CO_2 emissions estimates related to electricity generation in the United States. For this purpose, we use the U.S. EIA (2021) data and calculate how much CO_2 emissions are produced per kilowatt-hour of electricity generation in the United States with different energy sources. These data show that per kilowatt-hour of electricity generation with coal, petroleum, and natural gas produce 1.0121, 0.9513, and 0.4107 units of CO_2 emissions, respectively. Other energy sources may have other problems in electricity generation, but they generate zero CO_2 emissions (U.S. EIA, 2021). The data show that coal consumption produces 2.46-fold (1.0121/0.4107) more CO_2 emissions than natural gas consumption.[2] Meanwhile, coal consumption produces 1.06-fold (1.0121/0.9513) more CO_2 emissions than petroleum consumption.[3]

Thus, we analyse how much CO_2 emissions are produced from a country's energy consumption mix. Then, we use these coefficients to calculate the green quality of the energy mix (*GREENQ*) by introducing the following formula in Eq. (1):

$$GREENQ = \frac{1}{\frac{x_{1i,t}}{X_{i,t}}*1.0121 + \frac{x_{2i,t}}{X_{i,t}}*0.9513 + \frac{x_{3i,t}}{X_{i,t}}*0.4107} \tag{1}$$

In Eq. (1), $X_{i,\,t}$ is the total primary energy consumption; $x_{1i,\,t}$, $x_{2i,\,t}$, and $x_{3i,\,t}$ are the energy consumption from different energy sources (i.e., coal, petroleum, and natural gas, respectively). i represents the country, and t indicates the time in the panel dataset.

3.2. Data

This paper uses the unbalanced panel data in 36 OECD countries from 1970 to 2021.[4] The sample selection is based on data availability of the OECD countries and the years. The frequency of the data is annual.[5]

The dependent variable is the CO_2 emissions per capita (metric tons) in the natural logarithmic form (*LNCO2PC*), and the related data are downloaded from British Petroleum (BP) (2022).

We also use three control variables. The income effect is captured by the GDP per capita (current $ prices) in the natural logarithmic form (*LNGDPC*), and the data are downloaded from the World Bank (2023b). Institutional quality is measured by the index of *POLITY2*, published by Marshall and Gurr (2020). *POLITY2 is* an index from −10 to +10, which shows the autocracy and democracy levels of a country. A higher level of *POLITY2* shows a higher institutional quality. In addition, we use the index of de facto information globalisation in the natural logarithmic (*LNGLB*) form to measure technology.[6] *LNGLB* is an index from 0 to 100, and a higher level of the related index indicates higher technology. The related data were obtained from Gygli et al. (2019).

Finally, as the primary variable of interest, we consider the index of green quality of energy mix (*GREENQ*). The data come from our calculation based on the energy consumption series in British Petroleum (BP), 2022. A higher level of GREENQ represents greener energy consumption.

3.3. Theoretical model

Sustainable economic development calls for using green energy sources to fuel the economy. The prime independent variable we have taken in modelling CO_2 emissions is the green quality of energy mix (*GREENQ*) to trace the effectiveness of the greening quotient of the energy used in economic activities. Renewable energy mixes contain fewer or no hydrocarbons. In natural scientific theory, hydrocarbons are the source of atmospheric pollution. Therefore, a rise in the green quality energy mix is supposed to emit less polluting gases like CO_2 emissions. In this line, our study hypothesises that using a green-quality energy mix to a greater degree will benefit environmental quality management by reducing CO_2 emissions.

The other variable we have included in the model is the log per capita GDP (*LNGDPC*). *LNGDPC* represents the economic growth achieved through the exploitation of natural resources. Since the introduction of the industrial revolution, historically, excessive and blind use of natural resources has caused severe damage to the environment. This issue is because economic expansion requires the growth of economic activities (production and consumption of goods and services) involving environmental costs in terms of pollution and toxic emissions. Therefore, economic growth is expected to increase CO_2 emissions. This proposition is consistent with and derived from Esso and Keho's (2016) and Li et al. (2019) findings.

The variable *POLITY2* in our model captures the institutional quality of a particular country. Higher institutional quality is characterised by formulating well-designed and necessary policies and adequately implementing them. Countries with higher institutional quality are expected to strictly implement environmental and energy policies, considering environmental vulnerability. This will encourage ecologically viable economic activities and reduce environmental pollution. Therefore, maintaining high institutional quality is expected to reduce CO_2 emissions, as Ibrahim and Law (2016) show.

The model assesses the impact of technological environmental degradation in the domestic country via the de facto informational globalisation (*LNGLB*) variable. Globalisation fosters competition among international firms and countries. To survive in a highly competitive global market, firms often resort to productions with a comparative advantage rather than an environmental advantage, keeping aside the environmental costs of the productions. This, in turn, increases environmental pollution, including CO_2 emissions (Le and Ozturk, 2020).

From the above discussion, the following theoretical model can be built.

$$LNCO2PC = f\left(\underset{(-)}{GREENQ}, \underset{(+)}{LNGDPC}, \underset{(-)}{POLITY2}, \underset{(-)}{LNGLB}\right) \tag{2}$$

The econometric form of Eq. (2) is presented below.

$$\begin{aligned} LNCO2PC_{it} = {} & \alpha_{it} + \beta_1 GREENQ_{i,t} + \beta_2 LNGDPC_{i,t} + \beta_3 POLITY2_{i,t} \\ & + \beta_4 LNGLB_{i,t} + \varepsilon_{i,t} \end{aligned} \tag{3}$$

[2] In other words, coal consumption produces 146% more CO_2 emissions than natural gas consumption.

[3] Simply put, coal consumption produces 6% more CO_2 emissions than petroleum consumption.

[4] Among the OECD countries in early 2023, Costa Rica and Iceland are excluded as there are no data for these countries.

[5] Since we use unbalanced panel data in the estimation, missing values in the variables are assumed to be the same as the last year's value.

[6] This index includes high technology exports, international patents, and used internet bandwidth. For details, refer to Gygli et al. (2019).

LNCO2PC, GREENQ, LNGDPC, POLITY2, and *LNGLB,* are the CO_2 emissions, green quality energy mix index, per capita income, institutional quality, and technology. In Eq. (3), i represents the cross-section (country) subscript, and t is the time (year) subscript. α is the intercept term and β_1, β_2, β_3, *and* β_4 are the individual coefficients of the independent variables. ε_{it} is the error term, assuming the constant influence of other determinants embodied in the error term on the dependent variable.

3.4. Econometric methodology

This study empirically tests the hypothesis built in the previous section in Eq. (3). The econometric operation starts with the cross-section dependence tests of the model. The three tests employed are Breusch and Pagan's (1980) Lagrange Multiplier (LM), Pesaran's (2004 and 2021) Scaled LM and Pesaran's (2004 and 2021) Cross-sectional Dependence (CD) tests. These tests help direct the use of appropriate econometric techniques in subsequent empirical analyses. In the presence of cross-sectional dependence in the model, we use the Cross-sectionally Augmented Dickey-Fuller (CADF) panel unit root test proposed by Pesaran (2007). The CADF test considers the t-test for stationarity in heterogeneous panels, considering both cross-sectional and time dimensions in line with Im et al.'s (2003) panel unit root test. The null hypothesis of the CADF test is the non-stationarity of the variable. The test statistic for the CADF unit root test can be written as follows:

$$\Delta y_{i,t} = \alpha_i + \beta_i y_{i,t-1} + \delta_i \overline{y}_{t-1} + \sum\nolimits_{j=0}^{\rho} \theta_{ij} \Delta \overline{y}_{t-j} + \sum_{j=1}^{\rho} \mu_{ij} \Delta y_{i,t-j} + \varepsilon_{it} \tag{4}$$

y_t is mean at time t of all considered countries. After obtaining the integrating property of the variables, it is required to test whether the model's variables are cointegrated. For this purpose, we use cointegration tests developed by Kao (1999), Pedroni (1999), and Westerlund (2008).

To obtain the long-run coefficients, we use the panel Generalised Methods of Moments (GMM) type system dynamic panel data estimation proposed by Arellano and Bover (1995) and Blundell and Bond (1998). This model is also known as the Arellano-Bover/Blundell-Bond system estimator. It is an extension of Arellano and Bond's (1991) GMM technique that captures significant autoregressive parameters and a relatively large ratio of the variance of the panel-level effects to the variance of idiosyncratic error terms. In addition, this model can include predetermined or endogenous regressors and moving-average serial correlation in the residuals. Therefore, we also employ the Feasible Generalised Least Squares (FGLS) method developed by Hansen (2007). We also utilise the Panel Corrected Standard Errors (PCSE) technique, proposed by Bailey and Katz (2011) and Reed and Webb (2010). The FGLS and the PCSE methods give reliable results in cross-section dependency in the model. Hence, these models provide robustness to the results obtained from the system GMM panel data estimations.

4. Empirical findings

4.1. Preliminary tests

Table 1 provides the summary statistics for the variables used to estimate the model specified in Eqs. (2) and (3). The mean and the median of the variables are positive, i.e. greater than zero for all the variables. However, for all variables except the green quality of the energy mix, including environmental degradation, the medians are more significant than their means. All other variables are negatively skewed except the green quality of the energy mix. In other words, only for the green quality of the energy mix future expected values would be greater than the calculated mean. Therefore, it can be concluded that the environmental quality can improve in the 36 OECD countries considered in this study. The skewness for institutional quality measured by *POLITY2* is the highest and negative, indicating that institutional quality in these countries is expected to decrease more than environmental degradation, globalisation, and economic development.

Table 1
Summary statistics.

Statistic	*LNCO2PC*	*GREENQ*	*LNGDPC*	*POLITY2*	*LNGLB*
Mean	2.010	1.595	9.537	8.727	4.201
Median	2.058	1.414	9.708	10.00	4.262
Maximum	3.784	4.482	11.818	10.00	4.585
Minimum	0.119	1.015	5.632	−9.000	3.405
Std. dev.	0.643	0.559	1.110	3.427	0.250
Skewness	−0.569	2.324	−0.643	−3.667	−0.815
Kurtosis	3.408	9.577	3.056	16.128	3.183
Observations	1650	1650	1650	1650	1650
Data source	The BP (2022)	The BP (2022)	The World Bank (2023b)	Marshall and Gurr (2020)	Gygli et al. (2019)

The kurtosis values for all the variables are more than three. In other words, the variables follow the leptokurtic series, which is lower than normal distributions. Table 1 further shows a considerable difference between the minimum and the maximum values for all the variables, as indicated by the standard deviations. This suggests variations among the observations of each variable, making them suitable for regression analysis without introducing any issues related to outliers.

Table 2 presents the correlation matrix of the variables. All the independent variables are significantly correlated with the dependent variable. The green quality of the energy mix is negatively correlated with environmental degradation, meaning the two variables move in opposite directions. All other explanatory variables positively correlate with environmental degradation, with statistically significant correlation coefficients.

The primary requirement for conducting core econometric operations is testing for cross-sectional dependency. Table 3 presents the results of the cross-sectional dependence tests conducted on the model. All three tests have the same null hypothesis of cross-sectional independence, indicating the model's absence of cross-sectional dependence. However, all three tests reject the null hypothesis at a 1% significance level and conclude that the environmental degradation model has the issue of cross-sectional dependency. Cross-sectional dependence is a common issue in panel data analysis. This result suggests that there may be some unobserved factors common to all 36 OECD countries included in our study that are not considered in our analysis. The common factors related to our study are the innovation in the energy field, the global recession in 2008, geopolitical tensions, the trade war and the Covid-19 pandemic.

After confirming the presence of cross-sectional dependence, it is imperative to use the second generation unit root test, the CADF test for unit root. The CADF unit root test results are presented in Table 4. The t-test statistics for the CADF unit root test are presented for variables with "constant" and "constant and trend". The results also give the statistics at both levels and the first difference. For every combination of difference and trend, the test's null hypothesis is unit root or non-stationarity. Based on the test statistics and their corresponding significance levels, it can be concluded that all variables, except for economic growth, are integrated in order of one, i.e., I(1). This implies that environmental

Table 2
Correlation matrix.

Indicator	LNCO2PC	GREENQ	LNGDPC	POLITY2	LNGLB
LNCO2	1				
GREENQ	−0.141***	1			
LNGPDC	0.539***	0.345***	1		
POLITY2	0.471***	0.177***	0.504***	1	
LNGOB	0.425***	0.292***	0.662***	0.312***	1

Note: *** $p < 0.01$.

Table 3
Cross-sectional dependence tests.

LNCO2PC = (*GREENQ, LNGDPC, POLITY2, LNGLB*)	
Test	Statistic
Breusch-Pagan LM	16,836.1***
Pesaran Scaled LM	456.55***
Pesaran CD Test	115.91***

Note: *** $p < 0.01$.

degradation, green quality of energy mix, institutional quality, and globalisation are stationary at their first differences.

After obtaining the mixed order of integration among the variables, three sets of cointegration are employed to confirm the long-run associations among the variables. The cointegration test results are presented in Table 5. All three tests have the same null hypothesis of no cointegration among the variables.

Table 5 shows that the null hypothesis of no cointegration is rejected for all three tests, confirming the cointegration in the model. This result provides evidence of a significant long-run relationship between environmental degradation and the variables of green quality of the energy mix, economic development, institutional quality, and technology.

4.2. Baseline results for green quality of energy mix

The presence of the long-run associations of environmental degradation with green quality of energy mix, economic development, institutional quality, and technology calls for obtaining long-run coefficients of these associations. We have done so by estimating the environmental degradation model with the GMM-type system dynamic panel data method. The results of the estimation are presented in Table 6.

The results show a negative impact of green quality of energy mix on environmental degradation, indicating that an increase in green quality energy mix reduces environmental degradation. This finding is consistent with our hypothesis made in Eqs. (2) and (3).

The finding is, as expected, in line with the discussions in the previous section. With the growing need for climate action from all possible corners, the energy sector has a vital role in mitigating the effects of climate change and preserving the natural environment. Our results show that a greener energy mix positively affects the environment by reducing carbon dioxide emissions. Primarily, the results can be attributed to the fact that green energies are less pollution-intensive due to their low hydrocarbon contents. Energy fuels the economy, and although all OECD countries have enjoyed a certain level of economic development, they need to sustain this progress to ensure a high quality of life for their citizens. They need to use a judicious mix of energy with minimal environmental costs without hampering the necessary economic operations involved in production and consumption. Green energy serves the dual interests of environmental protection and sustainable economic development.

4.3. Baseline results for control variables and implications

The results obtained in our study support the hypothesis that economic development is detrimental to the natural environment. The negative impact of economic development on the quality of the natural environment is manifold. Most economic activities involve negative externalities. Economic activities also often require excessive use of natural resources. Exploiting natural resources beyond the environment's assimilative capacity causes an imbalance in the ecosystem. This imbalance, in turn, threatens the very existence of life. Excessive resource extraction to meet the economic demand of the growing population is resulting in substantial environmental costs. Apart from the initial extraction of resources, the economic expansion also results in pollution during the successive production and consumption phases of goods and services, further damaging the environment. Unchecked demand for comforts and consumerism has historically been facilitated by blind economic growth since the first industrial revolution. This unregulated use of resources and pollution-intensive production methods damage the natural environment through carbon dioxide emissions driven by economic growth.

According to the results reported in Table 6, institutional quality increases carbon dioxide emissions. This finding contradicts our hypothesis that higher institutional quality will help protect the natural environment through properly implementing environmental policies. Such findings can be attributed to the lack or insufficient attention from the policymakers in the OECD countries given to promulgating and implementing policies concerning protecting the natural environment.

Table 5
Panel cointegration tests.

Kao (1999)	
Modified Dickey-Fuller t	−1.325*
Dickey-Fuller t	−2.048**
Augmented Dickey-Fuller t	−0.154
Unadjusted Modified Dickey-Fuller t	−2.157**
Unadjusted Dickey-Fuller t	−2.528***
Pedroni (1999)	
Modified Phillips-Perron t	−0.957
Phillips-Perron t	−3.559***
Augmented Dickey-Fuller t	−2.779***
Westerlund (2008)	
Variance Ratio	−3.068***

Note: *** $p < 0.01$, ** $p < 0.05$, and * $p < 0.1$.

Table 6
Panel data estimations for long-run relationship.

Methodology	System GMM (SGMM)	Feasible Generalised Least Squares (FGLS)	Panel-corrected Standard Error (PCSE)
GREENQ	−0.072***	−0.407***	−0.442***
LNGDPC	0.003	0.121***	0.241***
POLITY2	0.014**	0.060***	0.051***
LNGLB	0.041***	0.0234***	0.454***

Notes: The dependent variable is LNCO2PC. *** $p < 0.01$ and ** $p < 0.05$.

Table 4
CADF panel unit toot tests.

Variable	Constant		Constant and trend		Integrating property
	Level	First difference	Level	First difference	
LNCO2PC	0.641	−18.941***	−1.373	−17.562***	I(1)
GREENQ	−0.108	−17.597***	0.100	−17.364***	I(1)
LNGDPC	−3.199***	–	−1.354*	–	I(0)
POLITY2	2.166**	−14.241***	−0.768	−13.960***	I(1)
LNGLB	3.368	−15.650***	−0.803	−12.967***	I(1)

Notes: *** $p < 0.01$, ** $p < 0.05$ and and *$p < 0.1$. The panel unit root test of Im et al. (2003) is used only for the POLITY2 variable due to some missing observations.

Although these countries have higher institutional quality, the benefits of this have not been fully translated to ecologically viable policies, such as setting emissions standards for greenhouse gases.

In addition to institutional quality, our findings suggest that the rise in technology is also positively associated with carbon dioxide emissions. This positive effect of technology is inconsistent with our hypothesis that technological advancements would lead to more environmentally friendly practices. Additionally, globalisation's rise leads to excessive competition among firms operating in multiple countries. Governments in these countries are also in a race to accommodate the tough competition and introduce policies to boost their international ease of business. However, these are inviting production which is not environmentally sustainable, resulting in pollution-intensive practices by businesses. As a result, rapid globalisation has been a major contributor to the degradation of the environment via carbon dioxide emissions.

4.4. Robustness checks

Table 6 also presents the results obtained from the estimations of the environmental degradation model by using the FGLS and the PCSE techniques. The results obtained from the FGLS and the PCSE techniques are consistent with those reported by the GMM-type system dynamic panel data method. Therefore, our results are robust to different estimation techniques. The results show that a 1% rise in the green quality of the energy mix reduces carbon dioxide by 0.41% in the 36 OECD countries. On the other hand, the growth of the economy in terms of real GDP per capita by 1% increases the carbon dioxide emissions by 0.12%. Similarly, a 1% higher institutional quality results in a 0.06% increase in environmental degradation. Lastly, a 1% increase in technology is responsible for a 0.023% increase in environmental degradation.

Our findings have crucial and timely policy implications for governments and policymakers in the OECD countries. This study calls for promoting green energy to achieve sustainable environmental quality, as using green energy in the energy mix reduces pollution. Governments and policymakers in the OECD countries should encourage, subsidise, and facilitate green energy production, transmission, and consumption. We also suggest reducing the carbon intensity of economic growth in the OECD countries. This can be achieved by promoting technological innovation to increase the efficiency of the natural resources used, thus reducing the environmental burden and the number of resources used to achieve long-term economic growth. New production facilities should be set up with their environmental viability in mind.

Designated institutions responsible for overseeing environmental challenges related to climate change and global warming must be empowered and given the necessary resources to carry out their responsibilities effectively. Further, the authorised stakeholders in the OECD countries must ensure transparency and accountability in the framing and implementing of environmental and energy policies. In addition, the internationalisation of the domestic market should also keep the environmental consequences on the table, and the feasibility of environmental quality should be a parameter for cross-border business and investment, alongside the comparative advantage in trade.

5. Conclusion

This study introduced a new index of green quality of energy mix in the environmental degradation model in the panel dataset of 36 OECD countries from 1970 to 2021. Furthermore, the effects of economic development, institutional quality, and technology on environmental degradation are studied in a panel data framework. Using the tests for cross-sectional dependency in the environmental degradation model, we test the integrating property of the variables and the presence of long-run associations among the variables with second-generation econometric tools. To obtain the directions and magnitudes of the relationships of environmental degradation with the explanatory variables, we use the system GMM, the FGLS, and the PCSE panel data techniques.

The crucial finding of the study is the beneficial impact of green quality of energy mix on the quality of the natural environment in the OECD economies. Our finding supports using renewable and green energy to sustain economic development while minimising environmental costs. However, economic development is found to be detrimental to environmental quality management, and developed countries cannot yet decouple economic growth and environmental pollution. They must reconcile the two to find ways to ensure sustainable economic growth that does not come at the cost of the environment. Adding to this, institutional quality is found to increase carbon dioxide emissions, contrary to expectations. Lastly, as per our results, technology also pressures the natural environment by increasing atmospheric pollution.

Overall, this paper introduced a novel measure of the green quality of the energy mix in the OECD countries and showed the negative impact of this measure on CO_2 emissions. However, our findings are limited to the OECD countries. We have opened a new avenue to empirical literature where further research is needed to explore the impact of this newly developed green quality of energy mix index measure on other regions and economies. Future studies can focus on large and growingdeveloping economies such as Brazil, Russia, South Africa, China and India within panel and time series frameworks. Future research can also use different econometric techniques to analyse the impact of our green quality of energy mix indicator on other variables of interest.

CRediT authorship contribution statement

Chi Keung Lau: Writing – original draft, Data curation. **Giray Gozgor:** Writing – original draft, Conceptualization. **Mantu Kumar Mahalik:** Supervision, Writing - original draft. **Gupteswar Patel:** Formal analysis, Investigation. **Jing Li:** Writing – original draft, Supervision.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eneco.2023.106702.

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