Ecological Informatics 75 (2023) 102121

Contents lists available at ScienceDirect

Ecological Informatics

journal homepage: www.elsevier.com/locate/ecolinf

Modeling combined role of renewable electricity output, environmental regulations, and coal consumption in ecological sustainability

Munir Ahmad[a,b,*], Elma Satrovic[c,**]

[a] College of International Economics & Trade, Ningbo University of Finance and Economics, Ningbo 315175, Zhejiang, China
[b] "Belt and Road" Bulk Commodity Research Center, Ningbo University of Finance and Economics, Ningbo 315175, Zhejiang, China
[c] Department of International Trade and Logistics, Faculty of Economics, Administrative and Social Sciences, Hasan Kalyoncu University, Gaziantep, Türkiye

ARTICLE INFO

JEL classification:
Q20
Q30
Q56
Q57
O52

Keywords:
Renewable electricity output
Stringent environmental regulations
Coal consumption
Ecological footprint
Carbon emissions
Sustainable development

ABSTRACT

The Sustainable Development Goals (SDGs) allow global economies to establish nationally determined plans to track ecological and economic sustainability at regional and international levels. While renewables are proven effective ecological sustainability tools, they might not comprehensively achieve climate change mitigation without emissions control regulations available in the combined policy toolbox, largely ignored by mainstream research. Therefore, we empirically assess the combined effect of renewable electricity output, stringent environmental regulations, and coal consumption in an attempt to acquire sustainable ecosystems via employing second-generation methodological approaches to ten selected OECD members' data during 1990–2015. We revealed long-term equilibrium among our study variables, implying that our variables maintain inherent stability. Also, the environmental Kuznets Curve notion is verified in the long term. Notably, we found that renewable energy output and stringent environmental regulations effectively mitigate ecological footprint and carbon emissions, whereas coal consumption boosts them. However, as the degree of coal consumption-driven carbon emissions promotion impact exceeded that of the emissions reduction impact of renewable energy output, simply ramping up the deployment of renewable energy solutions would be insufficient for climate change mitigation targets. Instead, a comprehensive climate policy inclusive of energy transformation and environmental regulations would be indispensable. While all the under-analysis variables unveil significant impacts merely in the long term, their respective short-term policies would be ineffective. We suggest implementing marketable and non-marketable environmental laws and deploying renewable solutions for achieving SDGs involving *climate action* and *universal access to affordable alternative energy* to guide a green and sustainable future.

1. Introduction

The scientific world and a substantial portion of the policy sphere acknowledge that human actions are causing frightening ecological disruptions — the so-called anthropogenic phenomena (AGR, 2022; Gokul et al., 2023). Many climate scientists contend that anthropogenic climatic adversities are presumably the cornerstone of changing environmental conditions since human actions at one place on the planet could even impact planet-wide frameworks capable of inducing societal, biophysical, biochemical, and biological repercussions for decades and centuries (Ahmad and Wu, 2022a; NOAA, 2022). There are numerous anthropogenic actions leading to greenhouse gas (GHG) emissions and climatic disturbances involving the increased occurrence of floods, extreme weather events, escalating sea levels, melting ice caps, and warmer seas that may immediately endanger species, ruin their habitats and inflict damage upon human populations and economies (Intergovernmental Panel on Climate Change, 2022). Nevertheless, the activities imparting the biggest impact during the last several decades are fossil fuel burning and the consequently emitted GHGs, predominantly carbon dioxide (Acuña-Alonso et al., 2022; CCDR, 2022). Therefore, fuel consumption should be the prime concern to comprehend and combat global warming, and this current study surrounds this subject.

The Paris Agreement, the United Nations Sustainable Development Goals (SDGs) and the international community aim to set ambitious

---

* Corresponding authors at: College of International Economics & Trade, Ningbo University of Finance and Economics, Ningbo 315175, Zhejiang, China.
** Corresponding author.

E-mail addresses: munirahmad@nbufe.edu.cn, munirncepu@gmail.com (M. Ahmad), elma.satrovic@hku.edu.tr (E. Satrovic).

https://doi.org/10.1016/j.ecoinf.2023.102121
Received 11 March 2023; Received in revised form 6 May 2023; Accepted 6 May 2023

targets of Net-zero emissions by 2040 and 2055 (Jabeen et al., 2023a). In this context, renewable energy transition is the central focus to mitigate environmental emissions and climate change (Ahmad et al., 2022). However, such energy transformation is not limited to changing the energy structure by increasing the share of renewables but also discarding traditional fossil fuel facilities (Davidson, 2019). Promoting renewable energy resources may advance SDG-7 by focusing on "*ensuring access to affordable, reliable, sustainable and modern energy for all*" (Jabeen et al., 2023b) while restricting consumption of fossil fuels like coal, which has been argued to be the principal culprit of carbon emissions, will aid SDG-13 involving "*taking urgent action to combat climate change and its impacts*." Despite the fact that the proportion of renewable energy resources roughly doubled between 2000 and 2017, and the proportion of solar and wind power has quadrupled, the above advances seem to substitute much. According to statistics, around 80% of the global primary energy use was provided by fossil-based energy resources in 2000. Whereas, as of 2017, this figure was 81% (BP, 2019), which does not seem to decrease drastically in the coming twenty years, given existing regulations remain in the status quo, while overall power usage keeps climbing, especially for the economies facing rapid industrialization process (Damrah et al., 2022a; Wang et al., 2022). Thus, since the introduction and deployment of renewables alone would not suffice, policies restricting the fossil-based energy demand would be needed for comprehensive energy transformation to combat climate change.

Given the foregoing argumentation, we cannot completely rely on market mechanisms to provide an efficient and market-clearing response to the adverse ecological effects since those mechanisms have resulted in environmental inefficiencies. Hence, to preserve a healthy and renewable ecological system, the function of stringent environmental regulations is becoming increasingly crucial. Several governments of developed countries have started widely embracing regulatory instruments, such as the enforcement of environmental taxation in transport and power sectors (Jabeen et al., 2021; Yirong, 2022), along with efforts to stimulate the development and utilization of sustainable power (Li et al., 2022). Modern literature has been attempting to determine if the strictness of environmental laws improves ecological sustainability, where the stringent environmental regulations can be characterized as the "implied or visible price of ecologically detrimental conduct (OECD, 2017)." For instance, levying taxation on energy- and carbon-intensive items shall drive individuals and businesses to transform to the usage and manufacturing of eco-friendly goods and services (Mao et al., 2023; Tchorzewska et al., 2022). From another viewpoint, ecological governance has been argued to significantly contribute to ecological systems by influencing land use and land cover conditions (Zhu et al., 2022). Therefore, the consideration of stringent environmental regulations would encapsulate the effect of environmental laws on ecological sustainability as well as contribute to the profitability of firms by inducing them to innovate for competitiveness in the global marketplace.

Against this backdrop, we attempt to answer the following critical research queries: does combined consideration of renewable energy and stringent environmental regulations successfully achieve ecological sustainability goals? Whether the favorable influence of renewable energy exceed or lag behind the adverse ecological effects of coal consumption? Do strict environmental regulations and renewable energy consumption harness eco-friendly outcomes in the long- and short-term perspective? Table 1 documents a summary of selected works on the ecological impacts of renewable energy, stringent environmental regulations, and coal use. The mainstream literature can be classified under the following three headings:

Table 1
Summary of selected works on the ecological nexus of renewable energy, environmental regulations, and coal consumption.

Author (s)	Sample (period)	Methods	Dependent variable	Findings (impacts of determinants)
(Niu et al., 2023)	China (1970-2019)	GLM, DLS	Carbon emissions	Energy transition (−), external trade balance (−), urbanization (+), natural resources (−), renewable energy use (+)
(Javed et al., 2023)	Italy (1994–2018)	DARDL	Ecological footprint	Green technology (−), renewable energy (−), environmental taxation (−), trade openness (+)
(Caglar and Yavuz, 2023)	22 EU (1995–2018)	CSC-ARDL	Load capacity factor	Environmental expenditures (/), renewable energy (−), natural resource rents (−), trade openness (+)
(Hassan et al., 2023)	OECD (1990–2019)	CSC-ARDL, AMGT	Ecological footprint	Economic complexity (+), nuclear energy use (−), globalization (−), economic growth (+)
(Chang et al., 2023)	15 RCEP (1990–2018)	CSC-ARDL	Ecological footprint	Renewable energy use (−), militarization (+), economic growth (+)
(Liao et al., 2023)	10 OECD (1990–2019)	MMQRA	Ecological footprint	Industrialization (+), foreign direct investment (+), renewable energy use (−)
(Meng and Yu, 2023)	China	SDM	Thermal production	Carbon taxation (−), quota ratio (−), emissions reduction intensity (−)
(Xie et al., 2023)	China	MMQRA	Carbon emissions	Imports (+), environmental regulations (−), green innovation (−)
(Dogan et al., 2023)	25 EU (1995–2019)	DLS, FM-LS	Renewable energy	Environmental taxation (−), economic growth (+), oil price (+)
(Liu et al., 2023a)	G7 (2000−2020)	CSC-ARDL	Renewable energy use	Stringent environmental regulations (+), financial development (+), green investment (+)
(Zhou et al., 2023)	Chinese firms (2004–2016)	PSM, DID	Environmental innovation	Environmental stringency (+), foreign direct investment (−)
(Liu et al., 2023b)	BRICST (1990–2020)	MMQRA	Carbon emissions	Environmental policy strictness (−), renewable energy (−), technology innovation (−)
(Li and Haneklaus, 2022b)	India (1990–2020)	ARDL	Carbon emissions	Coal use (+), clean power (−), urbanization (−), trade openness (+)
(Gyamfi et al., 2021)	E7 (1990–2016)	PQET	Carbon emissions	Coal consumption (+), economic growth (+), renewable energy (−)
(Jiang and Sun, 2023)	30 Chinese provinces (2000–2019)	CSECM	Carbon emissions	Industrial structure (/), coal consumption (+)
(Li and Haneklaus, 2022c)	China (1992–2020)	ARDL	Carbon emissions	Green energy utilization (−), coal consumption (+), trade (+)
(Kartal et al., 2023)	France (1970-2021)	DARDL	Carbon emissions	Coal use (+), renewable energy use (/), nuclear energy use (−)
(Li and Haneklaus, 2021)	China (1990–2020)	ARDL	Carbon emissions	Fossil fuel utilization (+), economic growth (−), renewable energy use (−)

Notes: + and - denote the positive and negative impacts of independent variables on dependent variables, while / indicates the insignificant relationships. **Countries:** EU: European Union, OECD: Organisation for Economic Co-operation and Development, RCEP: Regional Comprehensive Economic Cooperation, G7: Group of seven, BRICST: Brazil, Russia, India, China, South Africa, and Turkey, E7: emerging industrialized seven. **Methods:** GLM: generalized linear model, DLS: dynamic least squares, DARDL: dynamic autoregressive distributed lags, CSC-ARDL: cross-section corrected ARDL, AMGT: augmented mean group technique, MMQRA: method of moments quantile regression analysis, SDM: system dynamics model, FM-LS: fully modified least squares, PSM: propensity score matching, DID: difference-in-difference, PQET: panel quantile estimation technique, CSECM: cross-section augmented error correction method.

1.1. Renewable energy – Ecological sustainability nexus

According to the *first heading*, several scholars have explored the nexus between renewable energy and ecological sustainability to find mixed empirical outcomes. In this regard, Edziah et al. (2022) corroborated the influence of renewable energy use and imported technologies on the CO_2 of Sub-Saharan African economies by utilizing the mean group estimation approach (MGEA) on data from 1995 through 2017. The authors confirmed emission reduction in response to both variables. Using data from South Asia over the 1990–2017 period, Dogan et al. (2022) analyzed the contributions of renewable energy and unemployment on carbon emissions and disclosed a positive influence of both variables on environmental quality. Using the bounds testing approach on data from Saudi Arabia from 1980 through 2017, Abid et al. (2022) delved into and revealed the environmentally favorable effects of renewable energy use and human capital indicators. Adekoya et al. (2022) inspected the relationship between renewable power utilization and ecological systems by employing an augmented mean group technique (AMGT) on data from 14 of the net-oil importing/exporting countries. The authors concluded with the environmental quality effects of renewable power for the selected sample. Usman and Makhdum (2021) used a fully modified ordinary least squares (FM-LS) technique on panel data of BRICS and Turkish economies over the 1990–2018 period to analyze and find negative contributions of renewable energy and agricultural value-added to ecological footprint. In their study, Depren et al. (2022) conducted a bibliometric analysis of published academic sources from 1980 through 2021. The authors revealed a significant number of studies investigating and expressing the contributions of renewable energy to environmental deterioration worldwide.

On the contrary, Raghutla et al. (2022) applied a panel quantile estimation technique (PQET) to data from N-11 economies from 1990 through 2018 to investigate the influence of renewable energy on environmental sustainability. The authors claimed that renewable energy utilization degraded the environmental quality of sampled countries. Then, using MMQRA, Satrovic and Adedoyin (2023) analyzed the data from Southeastern European countries over the 1997–2018 period to investigate the influence of energy transition on CO_2 and revealed an adverse effect of the same. Eventually, Li and Haneklaus (2022a) investigated the influence of green energy use, international trade, and urbanization on carbon emissions for G7 economies from 1979 through, 2019 by employing an ARDL modeling setup. The authors unfolded that international trade promoted those emissions, while urbanization and green energy use mitigated them. Nonetheless, their study did not capture the impacts of coal and stringent environmental regulations. Moreover, they only considered carbon emissions, which is one of the building blocks of ecological footprint consumption. Besides, they did not plug in their variables in a benchmark theoretical framework, which is inevitably critical to make the incorporation of estimated outcomes logical.

1.2. Stringent environmental regulations – Ecological sustainability nexus

Under the second heading, a bunch of researchers studied the influence of strict environmental laws and regulations on different ecological quality indicators. For example, Afshan et al. (2022) used a method of moments quantile regression analysis (MMQRA) to data from 27 OECD countries to investigate the effects of stringent environmental laws and energy shifts on ecological quality. The authors observed ecological sustainability improvement effects in response to both variables. Yirong (2022) applied an asymmetric ARDL strategy to examine and uncover that strictness in environmental policies promotes environmental sustainability by curbing the carbon emissions in the USA, China, Russia, Japan, and India over the 1990–2019 period. Employing the cross-section corrected ARDL (CSC-ARDL) on OECD members' data from 2001 through 2018, Li et al. (2022) analyzed and discovered the ecological improvement influence of environment-related technologies and environmental regulations. In the same vein, Luo and Mabrouk (2022) utilized the CSC-ARDL technique to empirically investigate the contributions of ecological rules' strictness and ecological innovation on ecological quality and found that both variables introduced the mitigation of ecological footprint consumption in the resource-abundant nations. Studying the case of Asia, Chien et al. (2021) assessed and disclosed an ecologically friendly influence of eco-innovation and environmental regulations by applying the CSC-ARDL method to data from 1990 through 2017. Contrastingly, Hassan et al. (2022) inspected and found an adverse ecological impact of strict environmental regulations in the OECD region over the 1990–2020 period.

1.3. Coal consumption – Ecological sustainability nexus

The third heading of mainstream literature analyzed the linkage between coal consumption and diversified ecological indicators and found ecological degradation effects. For example, Ali et al. (2022) utilized a nonlinear ARDL approach to investigate the role of coal consumption on Asia's carbon emissions during, 1970–2017. The authors unambiguously found carbon emissions acceleration effects of coal utilization in the sample countries. Applying threshold regression analysis, Adekoya et al. (2023) studied the influence of coal consumption on global giant coal consumers' environmental, economic, and health sectors over the 2000–2018 period. They observed that coal intensity reduction was expected to lead to low environmental emissions but would slow down the economic performance of the sampled countries. Jia et al. (2023) employed a logarithm-based mean divisia index approach (LMDIA) on Chinese data from 2012 through 2017 to examine and find the harmful environmental and health impacts of coal consumption. Jonek-Kowalska (2022) explored and revealed the various paths of achieving rapid carbon neutrality in the European Union (EU) countries, with the most preferential one involving cutting coal consumption. In their work, Ma et al. (2022) used stochastic impacts by regression on population, affluence, and technology (STIRPAT) benchmark framework to analyze Chinese data from 2000 through 2019. The authors observed that energy footprint was a critical contributor to provincial-level ecological footprints. Qi et al. (2022) made use of the multisource remote sensing data to test the correlation between coal mining and land use and land cover in the Datong River region of China over the 2000–2019 period. Their empirics showed a significant upsurge in road and mining space, changing the region's land use and land cover. Applying an input-output analytical strategy, Guo et al. (2012) examined and found significant contributions of coal consumption to Beijing's CO_2 in 2007. Finally, making use of China's data from 1998 to 2017, Jia et al. (2022) inspected the role of coal reduction and emissions trading regulations on the mitigation of coal consumption. The authors declared that the policies on relocating coal over-reliant industries were found to be favorable regulations in curtailing coal consumption and environmental emissions across China.

1.4. Research gaps, objectives, and contributions

Though reflective progress has been observed in the mainstream literature exploring the ecological impacts of renewable energy, environmental regulations, and coal consumption, some critical aspects with practical and theoretical cruciality have not been taken into account by previous studies. Firstly, none of the past studies has been noted to analyze the combined consideration of renewable electricity output, stringent environmental regulations, and coal consumption integrated into the same modeling framework. The previous scholars incorporated the role of the variables mentioned above in ecological sustainability on a piecemeal basis. The combined integration of the said variables is of supreme importance in that the stringency of environmental regulations alone cannot yield optimal results without promoting renewable energy and vice versa. Furthermore, the coal reduction strategies could be pragmatically essential for ecological sustainability goals, in addition to placing stringent environmental regulations and increasing the renewable resources' proportion among the energy structure of an economy. These arguments make this literature void critical enough to attract the attention of scholars, practitioners, policymakers, and governmental authorities. Secondly, the existing studies primarily failed to dig deeper into the theoretical mechanisms linking renewable electricity output, stringent environmental regulations, and coal consumption with ecological sustainability. From theoretical frontiers, this research gap is extremely vital and imperative to fill since, without a theoretical foundation, merely ad-hoc conduction of empirical analyses would yield spurious results, misguiding the policy design complemented with incomplete theoretical foundations.

To fill the above-stated critical knowledge gaps, we intend to empirically analyze the combined role of renewable electricity output, stringent environmental regulations, and coal consumption in determining the ecological quality of ten selected OECD member countries during 1990–2015. As covariates, linear and quadratic terms of per capita real GDP are also included. We put forward cutting-edge contributions: First, we consider the combined inclusion of renewable electricity output, stringent environmental regulations, and coal consumption within the same framework. This is crucial since the integration of renewable energy promotion and coal consumption mitigation policies could be considered the forefront driving forces of environmental sustainability objectives of sustainable development, as they complement and strengthen the fulfillment of SDGs 7 and 13, respectively. While coal consumption can be facilitated only under stringent environmental regulations, including such regulatory factors in a combined framework would provide insightful findings. Second, unlike previous scholars, we establish theoretical foundations of relating our choice variables with ecological sustainability by augmenting the seminal theoretical setup by Grossman and Krueger (1991). Finally, we employ modern econometric analysis strategies capable of handling the potential presence of heterogeneous slopes and cross-sectional dependency concerns. This empirical analysis will enhance our understanding regarding the efficacy of environmental regulations, renewable energy policies, and curtailment of fossil fuels to achieve ecological sustainability for climate change mitigation.

The remaining study is organized as follows: Section 2 establishes the theoretical linkages of independent variables with ecological sustainability and develops hypotheses. Section 3 explains data, variables, and methodological frameworks. Section 4 interprets the econometric outcomes. Section 5 discusses the key outcomes. Section 6 deals with conclusion points, policy suggestions, and future research directions.

2. Modeling theoretical linkages and hypotheses formulation

We build on the seminal framework by Grossman and Krueger (1991), who pioneered in identifying the linkages between environment and economy via offering the following parsimonious framework in Eq. 1:

$$LED_{it} = \alpha + \beta_1 LRGPC_{it} + \beta_2 LRGPC^2{}_{it} + \varepsilon_{it} \tag{1}$$

Where L is the natural logarithmic operator, LED is a natural log of ecological degradation (ED), measured by two proxies: the ecological footprint (ECFP) and carbon dioxide emissions (CDE). After that, LRGPC and LRGPC^2 refer to the natural log of per capita real GDP (RGPC) and per capita real GDP squared (RGPC^2). Finally, $i = 1, 2, \ldots 10$; $t = 1, 2, \ldots 26$, and ε_{it} refers to the residual term. The parameter α indicates the drift of the model while β_s are the coefficients of independent variables. In light of Eq. 1, Grossman and Krueger (1991) hypothesized that anthropogenic activities by economic agents (households and firms) deteriorate the ecological systems up to a certain level (i.e., $\beta_1 = \frac{\partial LED_{i,t}}{\partial LRGPC_{i,t}} > 0$), after which ecological quality starts improving in response to an increase in those activities (i.e., $\beta_2 = \frac{\partial LED_{i,t}}{\partial LRGPC^2{}_{i,t}} < 0$). After the inception of this environment-economy debate, economic scholars and energy-environmental scientists have studied the modeling setup in Eq. 1 to integrate diversified factors (Damrah et al., 2022b; Dinda, 2004). Following this convention, we augment Eq. 1 for renewable electricity output (REO), stringent environmental regulations (EPSI), and coal consumption (COAL) to investigate the combined effects of those variables on ecological sustainability.

According to our *first augmentation*, the REO is embedded in the ecological degradation model as a factor of ED to quantify and capture the environmental sustainability effects of renewable electricity output. Theoretically, the link between renewable electricity output and ecological footprint consumption is intricate. On one side, a rise in the amount of investment in renewable energies might result in an expansion of economic activity, a boost in power usage, as well as an elevation in carbon footprint (Ahmad and Wu, 2022b; Oluoch et al., 2021). Furthermore, boosting such investment endeavors might cut GHG emissions by encouraging the transition of the energy layout, leading to less intensive power utilization (Liu et al., 2022; Zhang et al., 2022). It demonstrates that the magnitude of resources invested in renewables induces a direct as well as an indirect influencing mechanism on ecological sustainability. From another perspective, a suitable investment layout may support the restructuring of industrial design, improve the generation capacity of societal goods and services, and allow further opportunities for the growth of investment ventures from the long-run perspective (Broska, 2021; Hao et al., 2023). It suggests that the pattern of investments in renewable energy development may influence the magnitude of such investments, consequently influencing the ecological systems via energy mix, industrial prosperity, and energy efficiency (Shimbar and Ebrahimi, 2020; Wu et al., 2024). Such investments in renewable energy sources and the consumption of those sources might have diversified ecological quality consequences. Based on these viewpoints, we formulate the following association:

Hypothesis 1. Renewable electricity output is expected to either improve or deteriorate ecological quality (i.e., $\frac{\partial LED_{i,t}}{\partial LREO_{i,t}} < 0 \textit{ or } > 0$).

As a *second augmentation*, we introduce EPSI as a determinant of ED. From one standpoint, seizing the contributions of stringent environmental regulations conveys the effectiveness of ecological standards in reducing carbon emissions. From another aspect, it might enable economies to realize the EKC's tipping point relatively faster, probably in the early stages of industrial prosperity. These reasons sufficiently demonstrate the significance of incorporating EPSI in the model. The stringent environmental regulations may surge the cost of utilizing environmentally inefficient energy sources and technologies, thereby inducing industries to transition to environmentally friendly solutions such as renewable and energy-efficient technologies for energy conservation and ecological protection (Afshan et al., 2022). Moreover, strict environmental laws might compel high-polluting businesses to shift their capital to low-environmental standard countries, the so-called capital outflow, driving down domestic ecological pollution (Ahmad and Satrovic, 2023). Given these arguments, we hypothesize the following relationship between EPSI and ED:

Hypothesis 2. Stringent environmental regulations are likely to foster ecological sustainability (i.e., $\frac{\partial LED_{i,t}}{\partial LEPSI_{i,t}} < 0$).

Our *third augmentation* of the ecological degradation model involved the inclusion of COAL to the baseline Eq. 1. While the power sector generally influences ecological systems, coal usage is primarily responsible for climatic adversities. The combined oxidation and burning of coal and carbon produces CO_2, a GHG that traps heat in the atmosphere and acts as a layer in the atmospheric environment, causing planet earth's temperatures to rise beyond the desirable levels persistently. Globally, coal contributes to the power sector as a dominant energy source. Considering its functionality, steam is produced as a result of the burning of coal, powering turbine generators to produce electric power. Since coal products produce high-demand products, their use has become inevitable. For instance, the coking form of coal is principally utilized in the steel industry. Further, approximately 70% of steel production globally is derived from charcoal, a black carbon residue from coal. Unlike other fossil-based energy sources, burning coal involves far more CO_2 per unit of latent heat. Eventually, the coal's ignition process creates black carbon, which contributes to the amplification of the global warming phenomenon. In light of the arguments mentioned earlier, we formulate the following hypothesis:

Hypothesis 3. Coal consumption is expected to impart a detrimental influence on ecological sustainability (i.e., $\frac{\partial LED_{i,t}}{\partial LCOAL_{i,t}} > 0$).

Given the above theoretical contributions, we augment Eq. 1 by incorporating EPSI, COAL, and REO, yielding Eq. 2:

$$LED_{it} = \alpha + \beta_1 LRGPC_{it} + \beta_2 LRGPC^2{}_{it} + \beta_3 LEPSI_{it} + \beta_4 LCOAL_{it} + \beta_5 LREO_{it} + \varepsilon_{it} \tag{2}$$

To account for the ecological degradation effects of EPSI, COAL, and REO, along with the EKC phenomenon, we adapt two model specifications based on two alternative proxies: ECFP and CDE. These models are specified as Eqs. 3 and 4 as follows:

$$\textbf{\textit{Model}}\ \mathbf{1}: LECFP_{it} = \alpha + \beta_1 LRGPC_{it} + \beta_2 LRGPC^2{}_{it} + \beta_3 LEPSI_{it} + \beta_4 LCOAL_{it} + \beta_5 LREO_{it} + \varepsilon_{it} \tag{3}$$

$$\textbf{\textit{Model}}\ \mathbf{2}: LCDE_{it} = \alpha + \beta_1 LRGPC_{it} + \beta_2 LRGPC^2{}_{it} + \beta_3 LEPSI_{it} + \beta_4 LCOAL_{it} + \beta_5 LREO_{it} + \varepsilon_{it} \tag{4}$$

We estimate both models using FM-LS and PM-ARDL estimation strategies, robust to cross-section dependency and slope heterogeneity issues.

3. Data and methods

This section explains compilations, calculations, and definitions of our under-analysis data and empirical methods employed to examine those data for long-term policy insights.

3.1. Data

In order to analyze the relationship between stringent environmental regulations and ecological degradation, this study makes use of the annual frequency-based longitudinal data from 1990 through 2015 for ten OECD member countries (i.e., Australia, Canada, France, Germany, Italy, Japan, Korea, Rep., Turkey, the United Kingdom, and the United States). The ten OECD member countries and the time period are selected based on the availability of data for 25 years and beyond. In fact, the analysis period is limited to 26 observations, as data on stringent environmental regulations index are only available for the period 1990–2015 for the selected ten OECD member countries. The data of interest are gathered from various sources. The ecological footprint was obtained from the GFN (2019), whereas the stringent environmental regulations index was collected from the OECD (2017). Furthermore, data on GDP per capita, CO_2 emissions (metric tons per capita) and renewable electricity output (% of total electricity output) were gathered from the WB (2021). Data on coal consumption were collected from the BP (2021). In Table 2, information about the inspected variables is presented.

The descriptive statistics by OECD member country of all the sampled variables are presented in Table 3. The rank of United States is among the OECD members having the greatest average ecological footprint per capita (9.58), followed by Canada (8.53), with Japan and Turkey having the least average ecological footprint per capita for the period 1990–2015. Turning to CO_2, the United States shows the greatest average values, followed by Australia. Moreover, Turkey and France have the lowest average per capita CO_2. For per capita real GDP, maximum average values are reported for Australia (45,608.18) followed by the United States (44,582.00), whereas the minimum average values are reported for Korea, Rep. (17,355.62) and Turkey (9306.71).

Table 2
Variables' description.

Variable code	Description	Source
ECFP	Ecological footprint of consumption (global hectare – gha per capita)	(GFN, 2019)
CDE	Carbon dioxide emissions (metric tons per capita)	(WB, 2021)
RGPC	Per capita GDP (constant 2010 US$)	(WB, 2021)
RGPC^2	Per capita GDP squared (constant 2010 US$)	(WB, 2021); authors' calculations
EPSI	OECD's stringent environmental regulations index	(OECD, 2017)
COAL	Coal consumption (million tonnes of oil equivalent)	(BP, 2021)
REO	Renewable electricity output (% of total electricity output)	(WB, 2021)

Concerning stringent environmental regulations, Germany has the highest average stringent environmental regulations index of 2.43, followed by France (2.08). Turkey (1.03) and Australia (1.60) have the least average stringent environmental regulations index. Based on the data for the whole panel, it can be concluded that the United States has the highest average coal consumption, million tonnes of oil equivalent, followed by Japan, whereas France and Italy have the least average coal consumption. Turning to renewable energy, Canada has the highest average renewable electricity output (% of total electricity output) followed by Turkey, whereas Korea, Rep. and the United Kingdom have the least average renewable electricity output (% of total electricity output) in our sample. The time series trends of all variables for individual countries can be seen in Fig. 1.

Notably, Germany has shown the highest average stringent environmental regulations index, yet, we observed it to be among the highest coal consumer countries too. Nevertheless, looking at Germany's overall data trends during 1990–2015 (see Fig. 1), while the stringent environmental regulations index consistently crawled up, the carbon emissions and coal consumption revealed slightly declining trends, which are perhaps attributable to the strict environmental regulations and renewable energy transition efforts. Despite this, Germany remains among the top coal-based electric power producers globally, generating around 35% of electricity from coal resources (i.e., hard and lignite coal) (Oei et al., 2020). In this context, coal was reported to contribute about 70% of total carbon emissions from the electric power industry as of, 2019. In addition, the famous climate policy-motivated tool, the European Emissions Trading System (EUTS), was criticized for rather impeding coal consumption mitigation pathways (DIW Berlin, 2019). Against this backdrop, Germany has recorded stagnant GHG emissions levels even after shutting down the country's hard natural coal mining operation in 2018 (Oei, 2018). This is perhaps because the nation's coal production cut was insufficient to mitigate those emissions and put the country on the path to achieving the climate policy goals. Most recently, in the wake of the Russia-Ukraine war, Germany has seen a notable resurgence in coal consumption in the electric power generation sector due to the high oil and natural gas prices induced by their supply distribution from Russia (Adolfsen et al., 2022). This scenario might bring about significant delays in achieving Germany's coal phasing-out targets.

In Table 4, as per the correlation matrix, ecological footprint established positive correlations with (i) per capita real GDP; (ii) coal consumption, and (iii) renewable electricity output, while the negative correlation between ecological footprint and stringent environmental regulations index is not statistically significant. Similar conclusions can

Table 3
Summary statistics.

Variable	Measure	Australia	Canada	France	Germany	Italy	Japan	Korea, Rep.	Turkey	United Kingdom	United States	Total
ECFP	Mean	8.01	8.53	5.33	5.54	5.26	5.11	5.16	2.90	5.60	9.58	6.10
	St dev	0.76	0.45	0.29	0.45	0.42	0.35	0.68	0.32	0.47	0.77	1.96
	Max	9.19	9.50	5.77	6.90	5.83	5.63	5.95	3.39	6.19	10.48	10.48
	Min	6.40	7.76	4.70	4.94	4.39	4.46	3.74	2.33	4.59	8.15	2.33
CDE	Mean	16.98	16.00	5.77	10.14	7.17	9.28	9.57	3.48	8.55	18.65	10.56
	St dev	1.10	0.75	0.51	0.79	0.76	0.31	1.77	0.63	1.04	1.55	4.88
	Max	18.50	17.37	6.50	12.03	8.19	9.89	11.96	4.48	9.93	20.47	20.47
	Min	15.32	14.73	4.59	8.97	5.39	8.60	5.81	2.58	6.15	15.54	2.58
RGPC	Mean	45,608.18	42,280.57	37,973.72	38,653.28	34,866.60	42,749.18	17,355.62	9306.71	36,192.72	44,582.00	34,956.86
	St dev	6827.17	5556.20	3409.20	3878.85	2291.79	2565.38	5532.81	2174.17	4833.05	5357.12	12,303.92
	Max	55,079.90	50,427.90	41,793.50	45,208.10	38,272.20	47,102.60	26,063.70	13,924.10	42,121.70	52,236.10	55,079.90
	Min	35,033.40	35,108.50	32,524.00	32,430.30	30,871.30	38,092.70	8495.58	6708.88	28,214.50	35,542.10	6708.88
EPSI	Mean	1.60	1.76	2.08	2.43	1.99	1.81	1.85	1.03	1.86	1.65	1.81
	St dev	1.12	1.31	1.15	0.56	0.74	0.72	1.16	0.64	1.13	0.81	1.01
	Max	4.07	3.85	3.70	3.14	3.28	3.50	3.52	2.21	3.83	3.17	4.07
	Min	0.46	0.38	0.71	1.21	0.96	1.13	0.50	0.21	0.81	0.58	0.21
COAL	Mean	48.25	26.76	13.43	88.13	13.58	100.41	51.30	24.04	40.68	491.28	89.79
	St dev	6.20	3.82	2.82	12.67	1.90	16.20	21.54	7.00	10.59	45.89	138.09
	Max	58.23	31.92	20.21	131.53	16.67	121.65	85.40	36.50	65.06	545.74	545.74
	Min	38.21	19.65	8.59	71.74	10.67	76.12	23.57	15.80	23.07	372.23	8.59
REO	Mean	9.66	61.22	13.54	10.97	22.31	10.24	1.73	30.32	5.68	10.16	17.59
	St dev	1.83	1.50	1.93	7.94	7.60	1.84	1.04	8.47	5.89	1.64	17.20
	Max	14.91	63.30	17.06	29.23	43.39	15.98	6.04	46.18	24.84	13.23	63.30
	Min	7.50	58.03	9.86	3.17	15.48	7.99	0.99	17.35	1.63	6.78	0.99

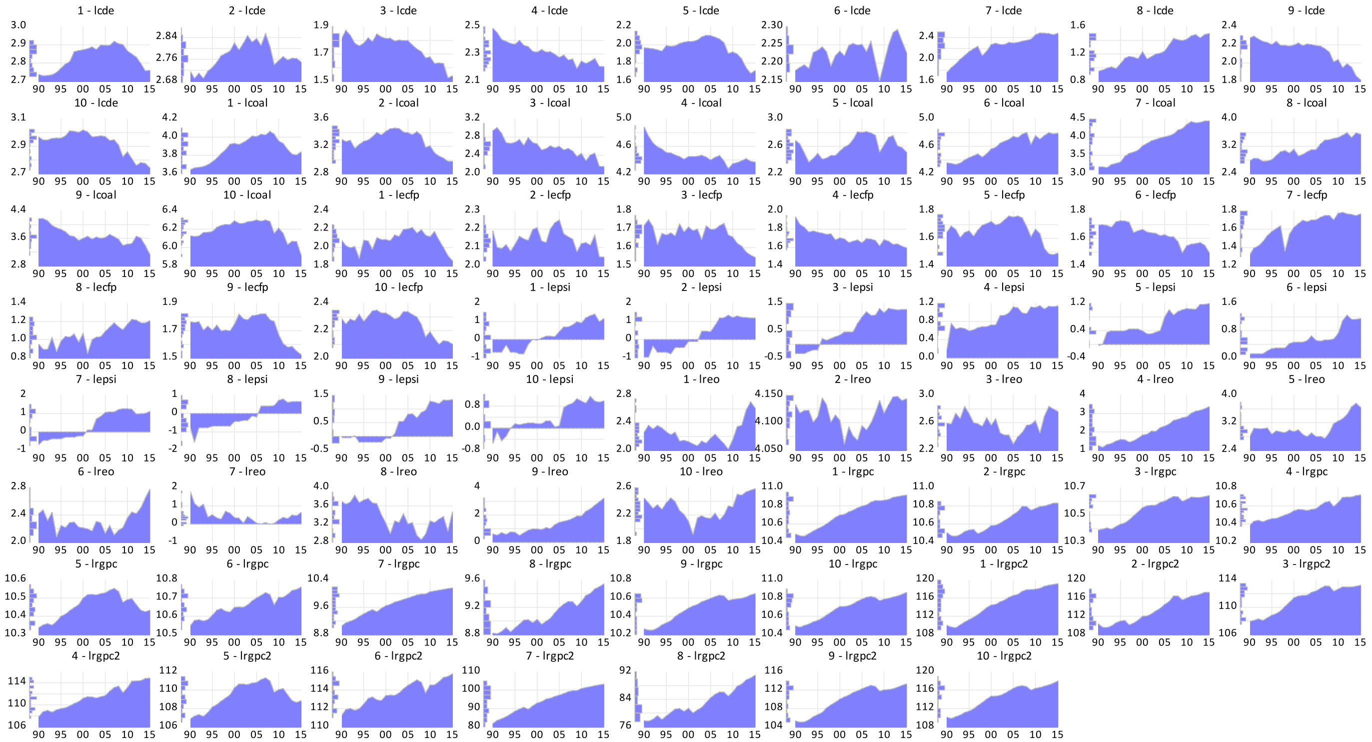

Fig. 1. Trends of final estimation variables across selected 10 OECD members.
Note: 1 = Australia, 2 = Canada, 3 = France, 4 = Germany, 5 = Italy, 6 = Japan, 7 = South Korea, 8 = Turkey, 9 = United Kingdom, 10 = United States.
(Source: Authors' estimations)

be drawn for carbon dioxide emissions. However, we report a positive but insignificant association between renewable electricity output and CO_2. Moreover, the per capita real GDP is positively correlated to stringent environmental regulations index and coal consumption, while the correlation coefficient between per capita real GDP and renewable energy is not statistically significant. The stringent environmental regulations index is negatively correlated to coal consumption and renewable energy, but these coefficients are not significant. Moreover, coal consumption is negatively correlated with renewable energy. Besides, in Fig. 2, the graphical correlations among the study variables found correlations consistent with those of Table 4.

3.2. *Methods*

The OECD is committed to coordinating policies to help member countries mitigate environmental challenges. Considering the higher

Table 4
Correlation matrix.

Variables	ECFP	CDE	RGPC	EPSI	COAL	REO
ECFP	1					
CDE	0.950***	1				
RGPC	0.658***	0.604***	1			
EPSI	−0.006	−0.006	0.429***	1		
COAL	0.593***	0.591***	0.308***	−0.024	1	
REO	0.129**	0.080	0.019	−0.017	−0.227***	1

Note: **$p < 0.05$ and ***$p < 0.10$ denote 5 and 10% levels of significance, respectively.

degree of economic and environmental integration of OECD member countries and their commitment towards better lives, one major issue that is likely to arise in the observed sample is the interdependence between individual countries of interest. Herein, our paper analyzed the cross-section dependency (CSDP) using Breusch and Pagan's (1980) Lagrange multiplier (LM) test, Pesaran's (2004) scaled-LM test and Pesaran's (2015) CSDP test.

Two of the most popular unit root tests, namely Im et al. (2003) cross-sectionally adjusted (CAGIPS) test and the cross-sectionally adjusted Dickey and Fuller (CAGDF) testing approach of Pesaran (2007) are used to unearth the stationary of the inspected variables. The CAGDF test can be formulated as below (Eq. 5):

$$\Delta y_{it} = \alpha_i + \beta_i y_{it-1} + \gamma_i f_t + \varepsilon_{it} \tag{5}$$

where $v_{it} = \gamma_i f_t + \varepsilon_{it}$, with common factor denoted by f_t and country-specific errors by ε_{it}, $\alpha_i = (1 - \delta_i)\mu_i$, $\beta_i = -(1 - \delta_i)$ and $\Delta y_{it} = y_{it} - y_{it-1}$. These tests are designed to test the null hypothesis of a unit root for a series in a panel ($H_0 : \beta_i = 0$) against the alternative ($H_1 : \beta_i < 0$ for $i = 1, 2, \dots, N$, $\beta_i = 0$ for $i = N_1 + 1, N_1 + 2, \dots, N$). The CAGIPS test statistics

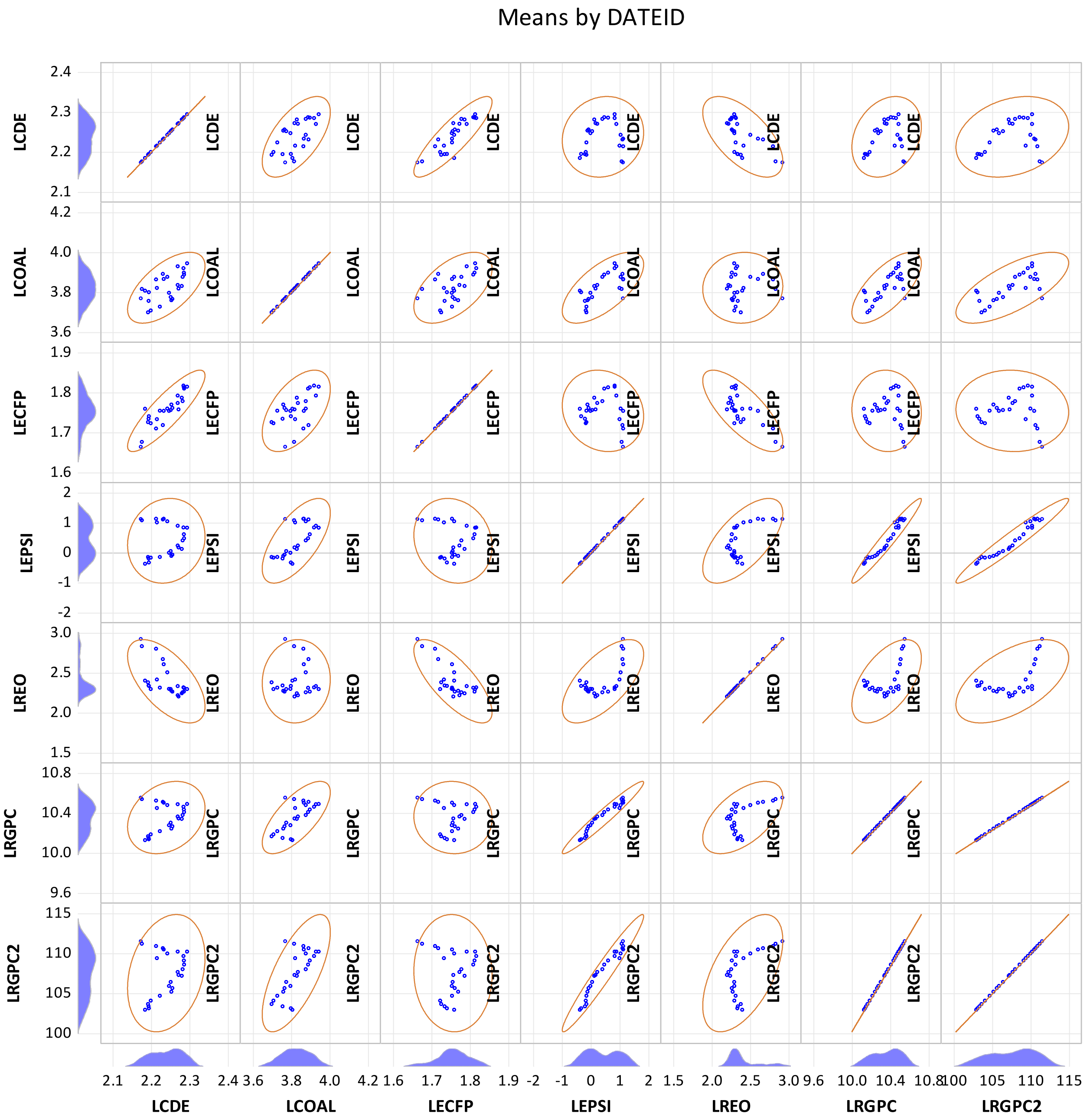

Fig. 2. Graphical correlations among the under-analysis variables via scatter chart.
(Source: Authors' calculations)

can be expressed as follows – Eq. 6:

$$CAGIPS = \frac{1}{N}\sum_{i=1}^{N} CADF_i \tag{6}$$

The critical values for comparison with calculated values by Eq. 6 are acquired from Pesaran (2007).

The slopes across the individual cross-sectional units need to be heterogeneous to use the second-generation cointegration approach. Hence, we made use of Pesaran and Yamagata's (2008) slope heterogeneity approach, which is an upgraded version of Swamy's (1970) technique. The statistics for large and small panels, respectively, are given as:

$$D\_tilde = \sqrt{N}\left(N^{-1}\widetilde{SY} - e\Big/2e\right) \sim {\chi^2}_e \tag{7}$$

$$D\_tilde_{adj} = \sqrt{N}\left(N^{-1}\widetilde{SY} - e\Big/v(T,e)\right) \sim N(0,1) \tag{8}$$

where SY is indicative of Swamy's ingredient, e is the depiction of the explanatory variables, N shows the number of countries, and $v(T,e)$ is the standardized formulation of the residuals. The null hypothesis of slope homogeneity is tested against the alternative of heterogeneous slopes.

For testing the long-term relationship between sampled variables and accounting easily for CSDP, our study employs the Westerlund (2007) panel cointegration tests (i.e., four tests in total). The underlying idea is to test the null hypothesis of no cointegration. Two tests evaluate the H_1 that the panel is cointegrated as a whole (G_t, G_a) while P_t and P_a analyze the existence of at least one individual that is cointegrated under the H_1. For the sake of robustness, this study employs the Kao (1999) panel cointegration test.

After determining the long-term relationship among ecological footprint, carbon emissions, linear and squared terms of per capita real GDP, renewable electricity output, stringent environmental regulations index, and coal consumption, we need to estimate the cointegration coefficients of Eqs. 3 and 4 by employing FM-LS proposed by Pedroni (2000) and PM-ARDL proposed by Pesaran et al. (1999) estimation procedures. The FM-LS can be formalized as below (Eq. 9):

$$\widehat{\beta}_{GFM} = \left[\sum_{i=1}^{N}\sum_{t=1}^{T}(x_{it}-\overline{x}_i)(x_{it}-\overline{x}_i)'\right]^{-1}\left[\sum_{i=1}^{N}\left(\sum_{t=1}^{T}(x_{it}-\overline{x}_i)\widehat{y}_{it}^{+} - T\widehat{\Delta}_{\varepsilon U}^{+}\right)\right] \tag{9}$$

where $\overline{x}_i$ refer to the country specific means; N stands for cross-sectional dimension; T denotes the time period; $\widehat{y}_{it}^{+}$ denotes the y series; $\widehat{\Delta}_{\varepsilon U}^{+}$ is the correction term. The econometric model for the PM-ARDL technique can be constructed as below (Eq. 10):

$$LED_{it} = \sum_{j=1}^{p}\theta_{ij}LED_{it-j} + \sum_{j=0}^{q}\rho_{ij}x_{it-j} + \mu_i + u_{it} \tag{10}$$

Here, ED stands for ecological degradation proxy variables; x_{it} indicates explanatory variables, ρ_{ij} is the vector of respective regression coefficients,θ_{ij} indicates the parametric estimates having lags associated with the explained variable, μ_i is the individual cross-section-based error term, and u_{it} indicates the general residuals. Short-run coefficients consider the following specification (Eq. 11):

$$\begin{aligned}\Delta LED_{it} =& \alpha_0 + \sum_{i=1}^{p}\theta_i\Delta LED_{t-i} + \sum_{j=1}^{q}\delta_j\Delta LRGPC_{t-j} + \sum_{m=1}^{q}\beta_m\Delta LRGPC2_{t-m}\\ &+ \sum_{r=1}^{q}\varphi_r\Delta LEPSI_{t-r} + \sum_{s=1}^{q}\sigma_s\Delta LCOAL_{t-s} + \sum_{v=1}^{q}\sigma_v\Delta LREO_{t-v}\\ &+ \tau ECT_{t-1} + \varepsilon_{it}\end{aligned} \tag{11}$$

where p denotes the explained variable's lags and q as regressors' lag. ECT stands for the error-correction term.

Finally, Dumitrescu and Hurlin's (2012) causal linkage detection approach is employed in this paper to analyze the causality connections between inspected variables. This test computes the Wald statistics (W_{it}) given by (Eq. 12):

$$W_{N,T}^{HNC} = \frac{1}{N}\sum_{i=1}^{N} W_{it} \tag{12}$$

where $W_{N,\ T}^{HNC}$ depicts statistics obtained with averaging each Wald statistics for cross-sections. The null hypothesis of "homogeneous non-causality" is assessed against the alternative of heterogeneous causal connections that can exist between variables for some OECD member countries.

4. Estimation results

This section reports the empirical results obtained by a series of advanced panel data econometric techniques ranging from pre-analysis to main data analysis outcomes.

4.1. Testing CSDP

When working on longitudinal data, CSDP is an important issue to consider, as it might appear in longitudinal data models in the face of the considerable financial and environmental interdependence of OECD countries. Following this discussion, in the initial stage of our analytical procedures, we conducted the CSDP tests. As per Table 5, beginning with the findings of test results, CSDP is found to exist as the null hypothesis of cross-section independence is subject to rejection in our models.

Since the considered CSDP tests reject the null hypothesis of cross-sectional independence for both models, empirical outcomes validate our preliminary insight that OECD member countries may reveal extremely close economic and environmental interdependence mainly attributable to efforts to reduce greenhouse gas emissions. The output depicted in Table 5 gives enough evidence that there is CSDP in our models.

4.2. Panel unit root and slope homogeneity test results

As pointed out by (Baltagi et al., 2016), unit root tests that assume cross-sectional independence could not work in general on panel data models with CSDP. Instead of using unit root tests that assume cross-sectional independence, we adopt tests that could control the CSDP. Table 6 presents the statistical outcomes of CAGIPS and CAGDF testing approaches. In the case of ECFP, the null hypothesis of non-stationary series without trend is accepted in the model in its levels. However, the two testing approaches suggest all of the series become unit root-free in the first-differenced form with and without trend.

The estimation outcomes for the CAGIPS and CAGDF testing approaches outline that ecological footprint per capita, per capita real GDP, per capita real GDP squared, stringent environmental regulations index, coal consumption, renewable electricity output and carbon dioxide emissions per capita contain no unit root at the first difference in

Table 5
CSDP test results.

Items	Model 1 (with LECFP)		Model 2 (with LCDE)	
Test/Variable	Statistic	Prob.	Statistic	Prob.
Breusch-Pagan LM	200.71***	0.000	217.06***	0.000
Pesaran scaled LM	15.36***	0.000	17.08***	0.000
Pesaran CD	5.45***	0.000	2.24**	0.025

Note: $^{**}p < 0.05$ and $^{***}p < 0.10$ denote 5 and 10% levels of significance, respectively. L denotes the natural logarithmic form.

Table 6
Results of slope homogeneity and CAGIPS and CAGDF approaches for stationarity testing.

Level form	LECFP	LCDE	LRGPC	LRGPC^2	LEPSI	LCOAL	LREO
CAGIPS (constant)	−2.12	−1.47	−1.58	−1.54	−3.35***	−1.16	−2.00
CAGIPS (constant & trend)	−3.37***	−2.85*	−1.91	−1.85	−3.30***	−1.95	−3.65***
CAGDF (constant) t-bar	−1.74	−1.40	−1.61	−1.60	−2.70***	−0.97	−1.49
CAGDF (constant & trend) t-bar	−2.85**	−2.94**	−1.81	−1.80	−2.72*	−1.87	−2.78*
First difference form	ΔLECFP	ΔLCDE	ΔLRGPC	ΔLRGPC^2	ΔLEPSI	ΔLCOAL	ΔLREO
CAGIPS (constant)	−5.57***	−4.96***	−3.98***	−3.94***	−5.34***	−4.41***	−5.77***
CAGIPS (constant & trend)	−5.69***	−5.18***	−4.22***	−4.16***	−5.40***	−4.77***	−5.75***
CAGDF (constant) t-bar	−4.22***	−3.66***	−3.01***	−2.99***	−3.86***	−3.47***	−4.11***
CAGDF (constant & trend) t-bar	−4.35***	−3.80***	−3.45***	−3.42***	−3.82***	−3.96***	−3.99***
Model 1 (with LECFP)	Test type	Stat score	Probability	Model 2 (with LCDE)	Type of test	Stat score	Probability
	D_tilde	9.60	0.000***		*D_tilde*	12.60	0.000***
	$\mathit{D\_tilde}_{adj}$	11.23	0.000***		$\mathit{D\_tilde}_{adj}$	14.74	0.000***

Note: *$p < 0.01$, **$p < 0.05$, and ***$p < 0.10$ denote 1, 5, and 10% levels of significance, respectively. Δ denotes the first-differenced form.

the model without and with the trend, inferring that the sampled variables exhibit $I(1)$ process. Furthermore, the slope heterogeneity testing found slope heterogeneity outcomes as the null hypothesis is rejected for both models (see Table 6).

4.3. Cointegration results

As the sampled panel series depicts the first-order integration, Westerlund (2007) panel cointegration technique is utilized, and for robustness checks, Kao (1999) panel cointegration approach is also used to check whether there are stable long-run relationships among variables. Table 7 displays the results of the cointegration tests with no constant and trend. The long-term cointegrating link is found to be existent in the case of Model 1, which is suggested by Group$_t$ and Panel$_t$ at a 1% significance level.

Similarly, the cointegration vector is certified for Model 2 by Group$_t$ and Panel$_t$ at a 5% significance level. Results of Westerlund and Kao panel cointegration tests inferred that the null hypothesis of “no cointegration” is rejected, indicating the presence of stable long-run relationships among the inspected variables in OECD countries for 1990–2015. Another important finding is that the cointegration relationship is not sensitive to the proxy of ecological degradation.

4.4. Long-run and short-run elasticities

After validating the existence of a cointegrating relationship among our variables of interest in both models, we used FM-LS and PM-ARDL regression methods to estimate the long-run elasticities, while the short-run estimates were obtained by PM-ARDL only (see Table 8). The baseline model results (FM-LS) are also depicted in Fig. 3. The empirical results are explained as follows:

Our *first finding* enumerates a negative and statistically significant impact of renewable electricity output on both ecological footprint and carbon dioxide emissions for both estimation strategies (i.e., FM-LS and PM-ARDL) at a 1% significance level. In this regard, a 1% addition to renewable electricity output brings about a 0.092% (FM-LS) and 0.147% (PM-ARDL) decrease in ecological footprint, respectively, in the long run. Similarly, a 1% increase in renewable electricity output leads to a 0.138% (FM-LS) and 0.060% (PM-ARDL) decrease in carbon dioxide emissions, respectively, in the long term. However, concerning the short-run estimations, both estimators produced statistically insignificant estimates, implying a neutral role of renewable electricity output in curbing ecological degradation from the short-run perspective.

Table 7
Panel cointegration test results.

Model	Test	Statistic	Value	P-value
Model 1 (with LECFP)	Westerlund (Westerlund, 2007)	Gt	−3.273***	0.000
		Ga	−9.406	0.83
		Pt	−9.982***	0.001
		Pa	−9.137	0.33
	Kao (Kao, 1999)	t-stat	−1.331*	0.092
Model 2 (with LCDE)	Westerlund (Westerlund, 2007)	Gt	−2.765**	0.039
		Ga	−7.266	0.967
		Pt	−8.187**	0.034
		Pa	−6.403	0.741
	Kao (Kao, 1999)	t-stat	−1.934**	0.027

Note: *$p < 0.01$, **$p < 0.05$, and ***$p < 0.10$ denote 1, 5, and 10% levels of significance, respectively.

Table 8
FM-LS and PM-ARDL estimation results.

Variable	Long-run Equation Model 1 (Dependent variable: LECFP)		Long-run Equation Model 2 (Dependent variable: LCDE)	
	Coefficient (FM-LS)	Coefficient (PM-ARDL (1,1,1,1,1,1)	Coefficient (FM-LS)	Coefficient (PM-ARDL (1, 1, 1, 1, 1, 1)
LRGPC	1.661*** (0.000)	19.886*** (0.000)	2.051*** (0.000)	2.379*** (0.000)
LRGPC^2	−0.084*** (0.000)	−0.923*** (0.000)	−0.076*** (0.000)	−0.106*** (0.000)
LEPSI	−0.085*** (0.001)	−0.060*** (0.001)	−0.154*** (0.000)	−0.053*** (0.000)
LCOAL	0.098*** (0.000)	0.102*** (0.005)	0.179*** (0.000)	0.361*** (0.000)
LREO	−0.092*** (0.000)	−0.147*** (0.000)	−0.138*** (0.000)	−0.060*** (0.000)
		Short-run Eq. L(ECFP)		**Short-run Eq. L(ECFP)**
COINTEQ01		−0.372*** (0.000)		−0.287*** (0.002)
D(LRGPC)		9.343 (0.631)		3.837 (0.589)
D(LRGPC^2)		−0.435 (0.635)		−0.173 (0.608)
D(LEPSI)		0.030 (0.181)		0.028* (0.069)
D(LCOAL)		0.055 (0.401)		0.155*** (0.000)
D(LREO)		0.052 (0.135)		−0.018 (0.662)
C		−39.125*** (0.000)		−3.535*** (0.003)
Panel method		Weighted		Weighted
Observations	250	250	250	250
R-squared		0.932		0.986
Sum squared residuals	1.889	0.198	0.903	0.063
Log likelihood		571.669		705.939

Note: *$p < 0.01$ and ***$p < 0.10$ denote 1 and 10% level of significance, respectively. Scores in braces () are probability values.

Our *second finding* demonstrates stringent environmental regulations’ negative and statistically significant impact on ecological

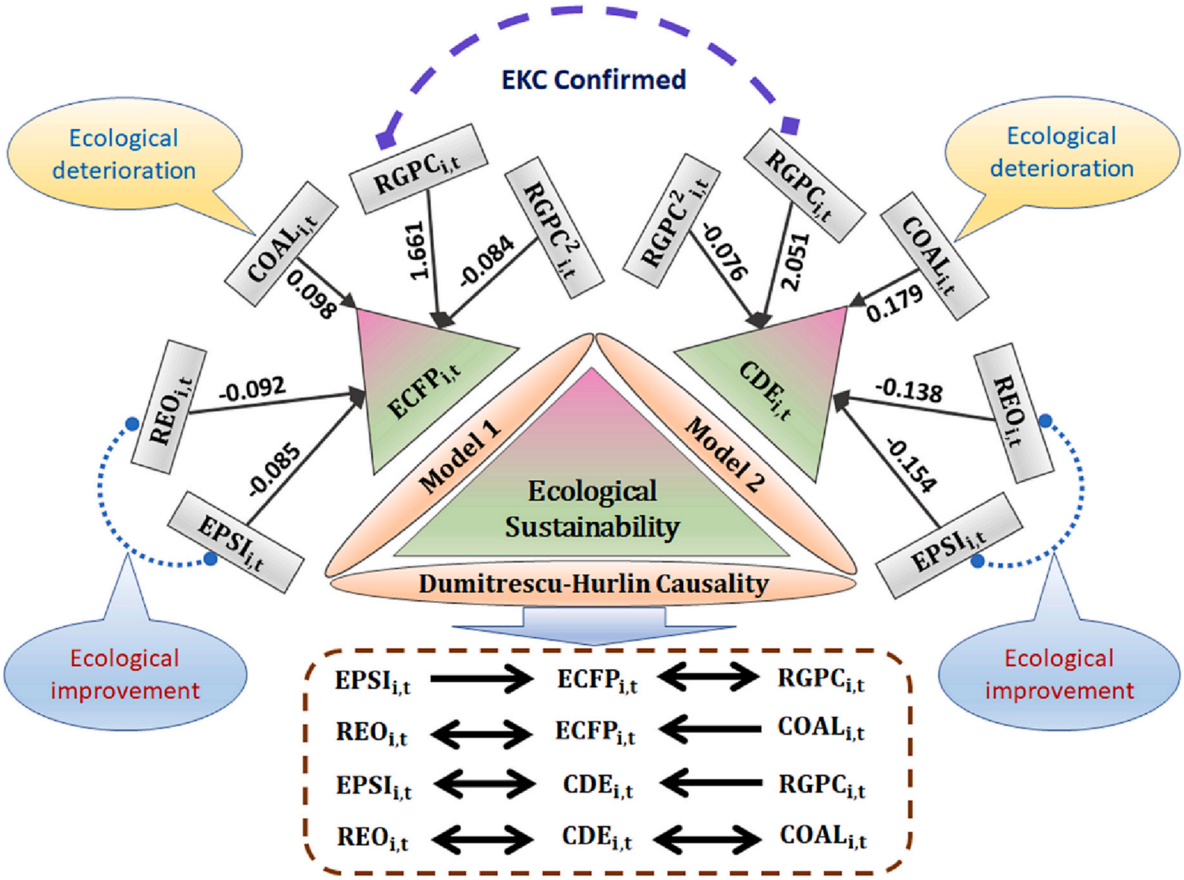

Fig. 3. Outlining long-run empirical findings of baseline models estimated by FM-LS.
(Source: Authors' drawing based on parametric estimations.)

footprint and carbon dioxide emissions at a significance level of 1%. Considering model 1, a 1% increment in the stringency of environmental regulations was associated with 0.085% (FM-LS) and 0.060% (PM-ARDL) reduction in ecological footprint in the OECD region. In comparison, in model 2, a 1% upsurge in the strictness of environmental regulations led to around 0.154% (FM-LS) and 0.053% (PM-ARDL) mitigation in carbon emissions. In the short run, stringent environmental regulations present a statistically insignificant influence on both ecological footprint and carbon emissions, suggesting the neutral role of environmental regulations in the short term.

Our *third finding* discloses a positive and statistically significant effect of coal consumption on both proxies of ecological degradation, namely ecological footprint and carbon dioxide emissions, at a significance level of 1%. Regarding the magnitude of effects, a 1% upscaling in coal consumption results in a 0.098% (FM-LS) and 0.102% (PM-ARDL) increase in ecological footprint in the long run, respectively. Concerning carbon dioxide emissions, a 1% increase in coal consumption leads to a 0.179% (FM-LS) and 0.361% (PM-ARDL) addition in carbon dioxide emissions. Regarding the short-term contribution, coal is insignificant in determining ecological degradation via both environmental proxies.

Our *final finding* uncovers a positive and statistically significant impact of per capita real GDP on both ecological footprint and carbon dioxide emissions. In contrast, a negative and statistically significant influence is noted for the per capita real GDP squared term. It means that increasing per capita real GDP upsurges the ecological footprint and carbon emissions in the long run, whereas the expanding per capita real GDP squared reduces them, ceteris paribus. These findings validate an inverse U-shape linkage of per capita real GDP with both ecological degradation proxies, demonstrating the existence of the EKC hypothesis in the long run. Contrastingly, short-run estimates of linear and squared terms of per capita real GDP remained insignificant, invalidating the presence of EKC in the short term, implying that EKC behavior is a long-term phenomenon. Besides, the convergence speed for FM-LS and PM-ARDL findings is outlined as 37.2% and 28.7%, respectively.

4.5. *Panel granger causality test results*

Considering the Dumitrescu-Hurlin causal direction findings, a significant bilateral causal linkage existed between per capita real GDP and ecological footprint, while a unilateral causal linkage runs from per capita real GDP to carbon dioxide emissions. In addition, a unilateral causal link stems from the stringent environmental regulations index to ecological footprint, whereas a bilateral causality exists between the stringent environmental regulations index and carbon emissions. Similarly, a unidirectional causality flows from coal consumption to ecological footprint. In contrast, a bilateral causal connection is observed between coal consumption and carbon emissions. As for renewable energy, empirical findings illustrate bilateral causality between renewable electricity output and ecological footprint/ carbon emissions. These results are reported in Table 9.

5. Discussion

Our *first finding* revealed that the renewable electricity output induced a negative and statistically significant impact on ecological footprint and carbon emissions. It highlighted that increasing renewable energy share in the energy mix could be a successful policy tool in reducing ecological degradation and achieving sustainable development. It is worth mentioning that a bilateral causal linkage of renewable electricity output with both proxies of ecological degradation is an

Table 9
Dumitrescu and Hurlin's Panel Granger causality test results.

Panel	LRGPC→LECFP	LECFP→LRGPC	LEPSI→LECFP	LECFP→LEPSI
Z-bar	7.005***	2.098*	4.193***	1.329
p-value	0.000	0.060	0.000	0.667
Panel	LRGPC→LCDE	LCDE→LRGPC	LEPSI→LCDE	LCDE→LEPSI
Z-bar	3.963***	1.242	5.08***	2.568***
p-value	0.000	0.790	0.000	0.006
Panel	LCOAL→LECFP	LECFP→LCOAL	LREO→LECFP	LECFP→LREO
Z-bar	5.078***	1.791	4.13***	2.494***
p-value	0.000	0.193	0.000	0.009
Panel	LCOAL→LCDE	LCDE→LCOAL	LREO→LCDE	LCDE→LREO
Z-bar	2.153**	2.799***	2.12*	2.007**
p-value	0.047	0.001	0.055	0.088

Note: Z-bar indicates Statistic. $^{*}p < 0.01$, $^{**}p < 0.05$, and $^{***}p < 0.10$ denote 1, 5, and 10% level of significance, respectively.

indication of strengthening the bilateral responses of environmental and renewable energy policies. It is evident that renewable electricity output, as a source of clean energy, presents a significant potential for OECD member nations to address ecological consequences, promoting a sustainable environment. Our long-run finding lends credence to that of Edziah et al. (2022), as they found carbon emissions curtailment injected by renewable energy utilization in the SSA economies. Similarly, Dogan et al. (2022) obtained the carbon emissions-lowering impact of renewable energy use in the case of South Asia. Furthermore, Adekoya et al. (2022) verified the affirmative influence of renewable power consumption on ecological improvement across net-oil importing/ exporting economies. Likewise, Usman and Makhdum (2021) concluded with the ecologically advantageous influence of renewable energy use across the sample of BRICS and Turkey. Also, Ahmad and Jabeen (2023) came up with positive impacts of the renewable energy transition on ecological efficiency in EU countries. Nevertheless, Raghutla et al. (2022) provided outcomes inconsistent with our results in that they observed ecological degradation impacts of renewable energy use in the N-11 economies. Additionally, a study by Satrovic and Adedoyin (2023) observed that the energy transition increased the CO_2 in Southeastern Europe.

According to our *second finding*, stringent environmental regulations decrease ecological footprint and carbon dioxide emissions in selected OECD economies. Considering the fact that OECD member countries are aware of climate risks and have increasingly stringent environmental regulations as they strive to contribute to sustainable development, in the long run, it is not a surprise that environmental pollution falls when the environmental policies become more stringent. A unidirectional causality running from stringent environmental regulations index to ecological footprint has been found, implying that environmental policies should remain stringent in OECD economies to reduce their ecological footprint. By making pollution more costly, environmental policies tend to change market behavior. However, in the actual situation, the escalated use of coal and higher carbon emissions, even for the stringent environmental regulations in place, narrate a different story. A possible explanation is the over-reliance of the German electric power sector on coal-fired plants (Oei et al., 2020). Additionally, the climate change mitigation policies like EUTS failed to induce their intended outcomes of reduced coal consumption in Germany (DIW Berlin, 2019). Eventually, escalated natural gas prices due to gasoline supply interruptions from Russia during the Russia-Ukraine war shifted the economy to increase the use of coal in electric power production (Adolfsen et al., 2022). Apart from this exception, the stringency of environmental policies is approved to improve ecological sustainability by positively impacting research and development (Martínez-Zarzoso et al., 2019), competitiveness and innovation (Johnstone et al., 2012). Analogous to our long-run finding, Afshan et al. (2022) revealed that the ecological systems of OECD countries were subject to improvement by strict environmental laws. Likewise, Yirong (2022) found the carbon emissions mitigation effect of stringent environmental regulations in the context of the top five global polluters. It also supported the outcomes of Li et al. (2022) as they empirically verified the favorable ecological consequences of strict environmental policies from the OECD perspective. This finding is also consistent with that of Luo and Mabrouk (2022), who unveiled ecologically supportive effects of environmental policy stringency in resource-abundant economies. Besides this, the finding of Zhu et al. (2022) strengthen our evidence because they unfolded that ecological governance was a crucial element affecting ecological sustainability by changing local carbon storage, which is among ecosystems' essential services. Apart from this debate, environmental regulations might improve ecological systems through the pro-environmental behaviors of individuals (Yang and Arhonditsis, 2022), which is a critical role player in ecological sustainability.

Turning to the connection between coal consumption and ecological degradation, our third finding showed a statistically significant positive impact of coal consumption on ecological footprint and carbon dioxide emissions in the long run. The causality analysis provided evidence of a bilateral relationship between coal consumption and carbon dioxide emissions/ ecological footprint. The long-run influence implies that coal consumption stimulates economic activity and adds to ecological deterioration by propelling carbon emissions and ecological footprints. This finding is parallel to that of Ali et al. (2022), as they predicted a carbon emissions promotion impact of coal consumption in six selected Asian economies. Adekoya et al. (2023) also revealed that reducing coal intensity was likely to improve the environmental quality of the world's top coal-consumer economies. Our empirical observation is also consistent with that of Ma et al. (2022), as they revealed a significant role of local energy footprint in determining the overall ecological footprint of China's provincial divisions. By the same token, Qi et al. (2022) uncovered that increasing coal mining was positively correlated with the land use and land cover of China's Datong River region, predominantly changing the local ecological conditions involving alpine deserts and wetlands. It also aligned with the outcomes of Guo et al. (2012) since they figured out that >50% of CO_2 was contributed by coal consumption in the Chinese capital city of Beijing. In addition, our finding is symmetrical with that of Kartal et al. (2023), as they found coal consumption to be a critical driver of carbon emissions in France. Besides, Li and Haneklaus (2022b) put forward similar findings by observing that long-term reliance on coal promoted Indian carbon emissions.

Our *final finding* unveiled strong evidence of the EKC phenomenon to be valid for ecological footprint and carbon emissions in the long run, as the coefficients with per capita real GDP and per capita real GDP squared are positively and negatively related to the ecological degradation indicators. However, the short-run estimates did not support the EKC hypothesis for the sampled OECD countries. Considering the Granger causality results, bi-directional causality existed between ecological footprint and per capita real GDP, whereas a unidirectional causal link stemmed from per capita real GDP to carbon dioxide emissions. The long-run finding is in line with Satrovic et al. (2022), as they found the EKC existent in the case of Southeastern European economies. This finding also supported the empirical outcomes of Liddle (2015), who observed EKC behavior among the OECD member economies. It was also found supportive of the U-type linkage between income and environmental emissions by Verbič et al. (2022) and Satrovic et al. (2023) in the sample of Southeastern Europe and the seven most innovative global economies, respectively. However, Yao et al. (2015) empirically proved that economic growth was a strong driving force of CO_2 in the context of G-20 member states.

6. Concluding remarks

Unlike mainstream studies, we delved into the combined role of renewable electricity output, stringent environmental regulations, and coal consumption in ecological sustainability in the presence of linear and squared terms of per capita real GDP by employing modern panel data approaches robust to cross-sectional dependency and slope heterogeneity to data from ten selected OECD member nations. We derived the following conclusive points:

First, we observed a long-term stability connection between renewable electricity output, stringent environmental regulations, and coal consumption during the sampled period, suggesting that after experiencing a short-term shock, these variables are expected to converge to an equilibrium in the long term. Second, an increasing level of renewable electricity output is linked with a reduction in ecological footprint and carbon emissions in the long term, indicating an ecological improvement effect of renewables. Third, a rise in stringent environmental regulations is associated with ecological sustainability improvement in terms of mitigation of both ecological footprint and carbon emissions from the long-term perspective, which is indicative of the conclusion that high pollution cost successfully transforms the behavior of economic agents (households and firms) to produce less of environmental pollution and ecological degradation. Fourth, increased coal consumption is found to deter ecological sustainability by boosting ecological footprint and carbon emissions from the long-term perspective. Nonetheless, from the short-term aspect, all three variables were neutral in determining ecological sustainability. Fifthly, for the carbon emissions model, the strength of the favorable effects of renewable energy (0.138) lagged that of the deterring effects of coal consumption (0.179) in FM-LS estimations. For PM-ARDL, the coal consumption coefficient exceeded that of renewable energy too. While for the ecological footprint model, this outcome was mixed in the case of two estimation procedures. Sixthly, an EKC phenomenon was verified in the long term, while short-term results failed to confirm its validity. Finally, concerning causality directions, renewable electricity output established a bilateral causal association with both ecological footprint and carbon emissions. Nevertheless, stringent environmental regulations, coal consumption, and per capita real GDP produced mixed causal connections in relation to ecological footprint and carbon emissions.

We offer the following policy suggestions stemming from our empirical outcomes of this study: Renewable energy alternatives and environmental regulations turned out to be effective policy tools in mitigating ecological degradation, along with active reduction of coal consumption in the OECD region. Thus, on the one hand, we suggest the deployment of renewables by introducing innovative and cost-effective technology solutions. On the other hand, the policy toolbox should contain market- and non-market environmental regulations to comprehensively curb environmental emissions and promote clean energy systems. Among market-based regulations, trading/certification schemes, pollution taxation, and feed-in-tariffs can be suggested to transform the behavior of economic agents to prefer the production and consumption of clean energy. Moreover, the non-market regulations involving R&D subsidization for renewable energy generation and emissions trading schemes to limit the values of emissions may accelerate the mitigation process of ecological degradation. Besides, our empirical findings unfolded that the carbon emissions promotion effect of coal consumption exceeded the emissions mitigation effect of renewable solutions. Therefore, a combined coal reductive and renewables promotion energy policy would prove an effective role player in achieving the climate action plan of SDGs. Eventually, since coal consumption reduction is an effective policy instrument for climate change mitigation, upgrading industrial structure by prohibiting the old and dirty technology setup. Herein, a comprehensive policy toolbox impregnated with these above-stated ingredients of renewables, stringent environmental rules, and mitigation of coal consumption would induce multifaceted climate change mitigation for long-term sustainable development via Net-zero emissions and the low carbon agenda of the United Nations and COP27.

Despite advancing vital contributions, we faced limitations worthwhile mentioning for the follow-up studies. Firstly, this work incorporated the influence of overall renewable electricity output on ecological sustainability. However, in order to comprehend its micro-level impacts, future works may consider renewable energy use at the firm level, as it would allow estimating industry-specific effects, assisting the mitigation strategies on an industrial scale. Secondly, we incorporated the national-level comprehensive index of environmental regulations stringency, which cannot account for stringency effects at sectoral levels. Upcoming studies should include or introduce some stringency measurement to capture environmental regulations' sectoral ecological sustainability impacts. Thirdly, this work made use of ecological footprint and carbon emissions proxies of ecological sustainability. Future studies may consider a more comprehensive measure of eco-efficiency by adjusting ecological footprint and carbon emissions for economies' GDP. In closing, this work used marginal effects estimation strategies incapable of accounting for distributional characteristics. Therefore, follow-up studies might apply the panel quantile technique to determine the ecological contributions of diversified factors across heterogenous quantile levels to gain even better empirical implications for global economies.

Declaration of Competing Interest

None.

Data availability

Data will be made available on request.

Acknowledgment

This achievement is partially funded by the Zhejiang soft science research base "digital economy and open economy integration innovation research base".

References

Abid, M., Sakrafi, H., Gheraia, Z., Abdelli, H., 2022. Does renewable energy consumption affect ecological footprints in Saudi Arabia? A bootstrap causality test. Renew. Energy 189, 813–821. https://doi.org/10.1016/j.renene.2022.03.043.

Acuña-Alonso, C., Novo, A., Rodríguez, J.L., Varandas, S., Álvarez, X., 2022. Modelling and evaluation of land use changes through satellite images in a multifunctional catchment: social, economic and environmental implications. Ecol. Inform. 71 https://doi.org/10.1016/j.ecoinf.2022.101777.

Adekoya, O.B., Oliyide, J.A., Fasanya, I.O., 2022. Renewable and non-renewable energy consumption – ecological footprint nexus in net-oil exporting and net-oil importing countries: policy implications for a sustainable environment. Renew. Energy 189, 524–534. https://doi.org/10.1016/j.renene.2022.03.036.

Adekoya, O., Oliyide, J.A., Kenku, O.T., 2023. On the Cop26 and the Coal's phase-out agenda: striking a balance among the environmental, economic, and health impacts of coal consumption. J. Environ. Manag. 328, 116872 https://doi.org/10.2139/ssrn.4142023.

Adolfsen, J.F., Kuik, F., Lis, E.M., Schuler, T., 2022. The impact of the war in Ukraine on euro area energy markets (no. 4/2022). In: ECB Economic Bulletin. Frankfurt.

Afshan, S., Ozturk, I., Yaqoob, T., 2022. Facilitating renewable energy transition, ecological innovations and stringent environmental policies to improve ecological sustainability: evidence from MM-QR method. Renew. Energy 196, 151–160. https://doi.org/10.1016/j.renene.2022.06.125.

AGR, 2022. Too Little, Too Slow puts world at risk [WWW Document]. Appl. GAP Rep. 2022. URL. https://www.un.org/en/climatechange/reports (accessed 12.10.22).

Ahmad, M., Jabeen, G., 2023. Relating economic openness and export diversification to eco-efficiency: is green innovation critical? Int. J. Financ. Econ. https://doi.org/10.1002/ijfe.2825.

Ahmad, M., Satrovic, E., 2023. Relating fiscal decentralization and financial inclusion to environmental sustainability : criticality of natural resources. J. Environ. Manag. 325, 116633 https://doi.org/10.1016/j.jenvman.2022.116633.

Ahmad, M., Wu, Y., 2022a. Combined role of green productivity growth, economic globalization, and eco-innovation in achieving ecological sustainability for OECD economies. J. Environ. Manag. 302, 113980 https://doi.org/10.1016/j.jenvman.2021.113980.

Ahmad, M., Wu, Y., 2022b. Natural resources, technological progress, and ecological efficiency: does financial deepening matter for G-20 economies ? Res. Policy 77, 102770. https://doi.org/10.1016/j.resourpol.2022.102770.

Ahmad, M., Zhu, X., Wu, Y., 2022. The criticality of international tourism and technological innovation for carbon neutrality across regional development levels. Technol. Forecast. Soc. Change 182, 121848. https://doi.org/10.1016/j.techfore.2022.121848.

Ali, I., Sun, H., Tariq, G., Ali, H., Baz, K., Mahmood, H., Khan, I., Yao, J., 2022. Asymmetric impact of coal and gas on carbon dioxide emission in six Asian countries: using asymmetric and non-linear approach. J. Clean. Prod. 367, 132934 https://doi.org/10.1016/j.jclepro.2022.132934.

Baltagi, B.H., Kao, C., Peng, B., 2016. Testing cross-sectional correlation in large panel data models with serial correlation. Econometrics 4, 1–24. https://doi.org/10.3390/econometrics4040044.

BP, 2019. BP Statistical Review of World Energy Statistical Review of World, 68th edition. BP Stat. Rev. World Energy.

BP, 2021. British Petroleum [WWW Document]. Br. Pet. Stat. Rev. World Energy. URL. https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html (accessed 8.11.21).

Breusch, A.T.S., Pagan, A.R., 1980. The Lagrange multiplier test and its applications to model specification in econometrics. Rev. Econ. Stud. 47, 239–253.

Broska, L.H., 2021. It's all about community: on the interplay of social capital, social needs, and environmental concern in sustainable community action. Energy Res. Soc. Sci. 79, 102165 https://doi.org/10.1016/j.erss.2021.102165.

Caglar, A.E., Yavuz, E., 2023. The role of environmental protection expenditures and renewable energy consumption in the context of ecological challenges: insights from the European Union with the novel panel econometric approach. J. Environ. Manag. 331, 117317 https://doi.org/10.1016/j.jenvman.2023.117317.

CCDR, 2022. Türkiye - Country Climate and Development Report. Türkiye - Ctry. Clim. Dev. Rep. https://doi.org/10.1596/37521.

Chang, S., Chen, B., Song, Y., 2023. Militarization, renewable energy utilization, and ecological footprints: evidence from RCEP economies. J. Clean. Prod. 391, 136298 https://doi.org/10.1016/j.jclepro.2023.136298.

Chien, F., Sadiq, M., Nawaz, M.A., Hussain, M.S., Tran, T.D., Le Thanh, T., 2021. A step toward reducing air pollution in top Asian economies: the role of green energy, eco-innovation, and environmental taxes. J. Environ. Manag. 297, 113420 https://doi.org/10.1016/j.jenvman.2021.113420.

Damrah, S., Satrovic, E., Atyeh, M., Shawtari, F.A., 2022a. Employing the panel quantile regression approach to examine the role of natural resources in achieving environmental sustainability: does globalization create some difference? Mathematics 10, 1–19. https://doi.org/10.3390/math10244795.

Damrah, S., Satrovic, E., Shawtari, F.A., 2022b. How does financial inclusion affect environmental degradation in the six oil exporting countries ? The moderating role of information and communication technology. Front. Environ. Sci. 1–17 https://doi.org/10.3389/fenvs.2022.1013326.

Davidson, D.J., 2019. Exnovating for a renewable energy transition. Nat. Energy 4, 254–256. https://doi.org/10.1038/s41560-019-0369-3.

Depren, K.S., Kartal, M.T., Çoban Çelikdemir, N., Depren, Ö., 2022. Energy consumption and environmental degradation nexus: a systematic review and meta-analysis of fossil fuel and renewable energy consumption. Ecol. Inform. 70 https://doi.org/10.1016/j.ecoinf.2022.101747.

Dinda, S., 2004. Environmental Kuznets curve hypothesis : a survey. Ecol. Econ. 49, 431–455. https://doi.org/10.1016/j.ecolecon.2004.02.011.

DIW Berlin, 2019. Phasing out Coal in the German Energy Sector: Interdependencies, Challenges and Potential Solutions. German Institute for Economic Research, Wuppertal Institute, Ecologic Institute, Berlin.

Dogan, E., Majeed, M.T., Luni, T., 2022. Revisiting the nexus of ecological footprint, unemployment, and renewable and non-renewable energy for south Asian economies: evidence from novel research methods. Renew. Energy 194, 1060–1070. https://doi.org/10.1016/j.renene.2022.05.165.

Dogan, E., Hodžić, S., Šikić, T.F., 2023. Do energy and environmental taxes stimulate or inhibit renewable energy deployment in the European Union? Renew. Energy 202, 1138–1145. https://doi.org/10.1016/j.renene.2022.11.107.

Dumitrescu, E.I., Hurlin, C., 2012. Testing for granger non-causality in heterogeneous panels. Econ. Model. 29, 1450–1460. https://doi.org/10.1016/j.econmod.2012.02.014.

Edziah, B.K., Sun, H., Adom, P.K., Wang, F., Agyemang, A.O., 2022. The role of exogenous technological factors and renewable energy in carbon dioxide emission reduction in sub-Saharan Africa. Renew. Energy 196, 1418–1428. https://doi.org/10.1016/j.renene.2022.06.130.

GFN, 2019. Global Footprint Network: Advancing the Science of Sustainability [WWW Document]. Natl. Footpr. Biocapacity Accounts. URL. https://www.footprintnetwork.org/resources/data/ (accessed 3.3.21).

Gokul, P.R., Mathew, A., Bhosale, A., Nair, A.T., 2023. Spatio-temporal air quality analysis and PM2.5 prediction over Hyderabad City, India using artificial intelligence techniques. Ecol. Inform. 76, 102067 https://doi.org/10.1016/j.ecoinf.2023.102067.

Grossman, G.M., Krueger, A.B., 1991. Environmental impacts of a North American free trade agreement. Natlional Bureau of Economic Research, Working Paper No. 3914, Cambridge. https://doi.org/10.3386/w3914.

Guo, S., Shao, L., Chen, H., Li, Z., Liu, J.B., Xu, F.X., Li, J.S., Han, M.Y., Meng, J., Chen, Z. M., Li, S.C., 2012. Inventory and input-output analysis of CO2 emissions by fossil fuel consumption in Beijing 2007. Ecol. Inform. 12, 93–100. https://doi.org/10.1016/j.ecoinf.2012.05.005.

Gyamfi, B.A., Adedoyin, F.F., Bein, M.A., Bekun, F.V., Agozie, D.Q., 2021. The anthropogenic consequences of energy consumption in E7 economies: juxtaposing roles of renewable, coal, nuclear, oil and gas energy: evidence from panel quantile method. J. Clean. Prod. 295, 126373 https://doi.org/10.1016/j.jclepro.2021.126373.

Hao, X., Wen, S., Xue, Y., Wu, H., Hao, Y., 2023. How to improve environment, resources and economic efficiency in the digital era? Res. Policy 80, 103198. https://doi.org/10.1016/j.resourpol.2022.103198.

Hassan, T., Khan, Y., He, C., Chen, J., Alsagr, N., Song, H., Khan, Naveed, 2022. Environmental regulations, political risk and consumption-based carbon emissions: evidence from OECD economies. J. Environ. Manag. 320, 115893 https://doi.org/10.1016/j.jenvman.2022.115893.

Hassan, S.T., Batool, B., Wang, P., Zhu, B., Sadiq, M., 2023. Impact of economic complexity index, globalization, and nuclear energy consumption on ecological footprint: first insights in OECD context. Energy 263, 125628. https://doi.org/10.1016/j.energy.2022.125628.

Im, S.K., Pesaran, M.H., Shin, Y., 2003. Testing for unit roots in heterogeneous panels. J. Econ. 115, 53–74. https://doi.org/10.1016/S0304-4076(03)00092-7.

Intergovernmental Panel on Climate Change, 2022. IPCC Sixth Assessment Report [WWW Document]. Impacts, Adapt. Vulnerability. URL. https://www.ipcc.ch/report/ar6/wg2/ (accessed 9.12.22).

Jabeen, G., Ahmad, M., Zhang, Q., 2021. Perceived critical factors affecting consumers ' intention to purchase renewable generation technologies : rural-urban heterogeneity. Energy 218, 119494. https://doi.org/10.1016/j.energy.2020.119494.

Jabeen, G., Ahmad, M., Zhang, Q., 2023a. Combined role of economic openness, financial deepening, biological capacity, and human capital in achieving ecological sustainability. Ecol. Inform. 73, 101932 https://doi.org/10.1016/j.ecoinf.2022.101932.

Jabeen, G., Wang, D., Işık, C., Alvarado, R., Ongan, S., 2023b. Role of energy utilization intensity, technical development, economic openness, and foreign tourism in environmental sustainability. Gondwana Res. https://doi.org/10.1016/j.gr.2023.03.001.

Javed, Aamir, Rapposelli, A., Khan, F., Javed, Asif, 2023. The impact of green technology innovation, environmental taxes, and renewable energy consumption on ecological footprint in Italy: fresh evidence from novel dynamic ARDL simulations. Technol. Forecast. Soc. Change 191, 122534. https://doi.org/10.1016/j.techfore.2023.122534.

Jia, Z., Wen, S., Sun, Z., 2022. Current relationship between coal consumption and the economic development and China's future carbon mitigation policies. Energy Policy 162, 112812. https://doi.org/10.1016/j.enpol.2022.112812.

Jia, W., Li, L., Lei, Y., Wu, S., 2023. Synergistic effect of CO2 and PM2.5 emissions from coal consumption and the impacts on health effects. J. Environ. Manag. 325, 116535 https://doi.org/10.1016/j.jenvman.2022.116535.

Jiang, W., Sun, Y., 2023. Which is the more important factor of carbon emission, coal consumption or industrial structure? Energy Policy 176, 113508. https://doi.org/10.1016/j.enpol.2023.113508.

Johnstone, N., Haščič, I., Poirier, J., Hemar, M., Michel, C., 2012. Environmental policy stringency and technological innovation: evidence from survey data and patent counts. Appl. Econ. 44, 2157–2170. https://doi.org/10.1080/00036846.2011.560110.

Jonek-Kowalska, I., 2022. Towards the reduction of CO2 emissions. Paths of pro-ecological transformation of energy mixes in European countries with an above-average share of coal in energy consumption. Res. Policy 77, 102701. https://doi.org/10.1016/j.resourpol.2022.102701.

Kao, C., 1999. Spurious regression and residual-based tests for cointegration in panel data. J. Econ. 90.

Kartal, M.T., Pata, U.K., Kılıç Depren, S., Depren, Ö., 2023. Effects of possible changes in natural gas, nuclear, and coal energy consumption on CO2 emissions: evidence from France under Russia's gas supply cuts by dynamic ARDL simulations approach. Appl. Energy 339, 120983. https://doi.org/10.1016/j.apenergy.2023.120983.

Li, B., Haneklaus, N., 2021. The role of renewable energy, fossil fuel consumption, urbanization and economic growth on CO2 emissions in China. Energy Rep. 7, 783–791. https://doi.org/10.1016/j.egyr.2021.09.194.

Li, B., Haneklaus, N., 2022a. Reducing CO2 emissions in G7 countries: the role of clean energy consumption, trade openness and urbanization. Energy Rep. 8, 704–713. https://doi.org/10.1016/j.egyr.2022.01.238.

Li, B., Haneklaus, N., 2022b. The potential of India's net-zero carbon emissions: analyzing the effect of clean energy, coal, urbanization, and trade openness. Energy Rep. 8, 724–733. https://doi.org/10.1016/j.egyr.2022.01.241.

Li, B., Haneklaus, N., 2022c. The role of clean energy, fossil fuel consumption and trade openness for carbon neutrality in China. Energy Rep. 8, 1090–1098. https://doi.org/10.1016/j.egyr.2022.02.092.

Li, Z., Kuo, Y.K., Mahmud, A.R., Nassani, A.A., Haffar, M., Muda, I., 2022. Integration of renewable energy, environmental policy stringency, and climate technologies in realizing environmental sustainability: evidence from OECD countries. Renew. Energy 196, 1376–1384. https://doi.org/10.1016/j.renene.2022.07.084.

Liao, J., Liu, X., Zhou, X., Tursunova, N.R., 2023. Analyzing the role of renewable energy transition and industrialization on ecological sustainability: can green innovation matter in OECD countries. Renew. Energy 204, 141–151. https://doi.org/10.1016/j.renene.2022.12.089.

Liddle, B., 2015. What are the carbon emissions elasticities for income and population? Bridging STIRPAT and EKC via robust heterogeneous panel estimates. Glob. Environ. Chang. 31, 62–73. https://doi.org/10.1016/j.gloenvcha.2014.10.016.

Liu, H., Zhang, J., Huang, H., Wu, H., Hao, Y., 2022. Environmental good exports and green total factor productivity: lessons from China. Sustain. Dev. 1–23 https://doi.org/10.1002/sd.2476.

Liu, W., Shen, Y., Razzaq, A., 2023a. How renewable energy investment, environmental regulations, and financial development derive renewable energy transition: evidence from G7 countries. Renew. Energy 206, 1188–1197. https://doi.org/10.1016/j.renene.2023.02.017.

Liu, X., Yuan, S., Yu, H., Liu, Z., 2023b. How ecological policy stringency moderates the influence of industrial innovation on environmental sustainability: the role of renewable energy transition in BRICST countries. Renew. Energy 207, 194–204. https://doi.org/10.1016/j.renene.2023.01.045.

Luo, S., Mabrouk, F., 2022. Nexus between natural resources, globalization and ecological sustainability in resource-rich countries: dynamic role of green technology and environmental regulation. Res. Policy 79, 103027. https://doi.org/10.1016/j.resourpol.2022.103027.

Ma, H., Liu, Y., Li, Z., Wang, Q., 2022. Influencing factors and multi-scenario prediction of China's ecological footprint based on the STIRPAT model. Ecol. Inform. 69, 101664 https://doi.org/10.1016/j.ecoinf.2022.101664.

Mao, J., Xie, J., Hu, Z., Deng, L., Wu, H., Hao, Y., 2023. Sustainable development through green innovation and resource allocation in cities: evidence from machine learning. Sustain. Dev. 1–16 https://doi.org/10.1002/sd.2516.

Martínez-Zarzoso, I., Bengochea-Morancho, A., Morales-Lage, R., 2019. Does environmental policy stringency foster innovation and productivity in OECD countries? Energy Policy 134, 110982. https://doi.org/10.1016/j.enpol.2019.110982.

Meng, X., Yu, Y., 2023. Can renewable energy portfolio standards and carbon tax policies promote carbon emission reduction in China' s power industry? Energy Policy 174, 113461. https://doi.org/10.1016/j.enpol.2023.113461.

Niu, XiaoQin, Dong, W., Niu, XiaoDong, Wasif Zafar, M., 2023. The transition to clean energy and the external balance of goods and services as determinants of energy and environmental sustainability. Gondwana Res. https://doi.org/10.1016/j.gr.2023.03.003.

NOAA, 2022. National Centers for Environmental Information [WWW document]. Mon. glob. Clim. Rep. Novemb, p. 2022. URL. https://www.ncei.noaa.gov/access/monitoring/monthly-report/global/202211 (accessed 12.19.22).

OECD, 2017. Organisation for Economic co-Operation and Development [WWW Document]. OECD Environ. Policy Stringency Index. URL. https://stats.oecd.org/Index.aspx?DataSetCode=EPS (accessed 8.11.21).

Oei, P.-Y., 2018. Greenhouse gas emission reductions and the phasing-out of coal in Germany. In: von Hirschhausen, C., Gerbaulet, C., Kemfert, C., Lorenz, C., Oei, P.-Y. (Eds.), Energiewende "Made in Germany": Low Carbon Electricity Sector Reform in the European Context. Springer Cham, Berlin, pp. 45–48. https://doi.org/10.1515/9781503617261-005.

Oei, P.-Y., Hermann, H., Herpich, P., Holtemöller, O., Lünenbürger, B., Schult, C., 2020. Coal phase-out in Germany – implications and policies for affected regions. Energy 196, 117004. https://doi.org/10.1016/j.energy.2020.117004.

Oluoch, S., Lal, P., Susaeta, A., Wolde, B., 2021. Public preferences for renewable energy options: a choice experiment in Kenya. Energy Econ. 98, 105256 https://doi.org/10.1016/j.eneco.2021.105256.

Pedroni, P., 2000. Fully modified OLS for heterogeneous cointegrated panels. Adv. Econ. https://doi.org/10.1016/S0731-9053(00)15004-2.

Pesaran, M.H., 2004. General Diagnostic Tests for Cross Section Dependence in Panels. IZA Discuss. Pap.

Pesaran, M.H., 2007. A simple panel unit root test in the presence of cross-section dependence. J. Appl. Econ. 22, 265–312. https://doi.org/10.1002/jae.

Pesaran, M.H., 2015. Testing weak cross-sectional dependence in large panels. Aust. Econ. Rev. 34, 1089–1117. https://doi.org/10.1080/07474938.2014.956623.

Pesaran, H.M., Yamagata, T., 2008. Testing slope homogeneity in large panels. J. Econ. 142, 50–93. https://doi.org/10.1016/j.jeconom.2007.05.010.

Pesaran, M.H., Shin, Y., Smith, R.P., 1999. Pooled mean group estimation of dynamic heterogeneous panels. J. Am. Stat. Assoc. 94, 621–634. https://doi.org/10.1080/01621459.1999.10474156.

Qi, X. Lian, Xu, H. Jie, Chen, T., Shan, S. Yao, Chen, S. Yun, 2022. Effects of climate change, coal mining and grazing on vegetation dynamics in the mountain permafrost regions. Ecol. Inform. 69, 101684 https://doi.org/10.1016/j.ecoinf.2022.101684.

Raghutla, C., Padmagirisan, P., Sakthivel, P., Chittedi, K.R., Mishra, S., 2022. The effect of renewable energy consumption on ecological footprint in N-11 countries: evidence from panel quantile regression approach. Renew. Energy 197, 125–137. https://doi.org/10.1016/j.renene.2022.07.100.

Satrovic, E., Adedoyin, F.F., 2023. The role of energy transition and international tourism in mitigating environmental degradation: evidence from SEE countries. Energies 16. https://doi.org/10.3390/en16021002.

Satrovic, E., Abul, S.J., Al-Kandari, A., 2022. Modeling the dynamic linkages between agriculture, electricity consumption, income and pollutant emissions for southeastern Europe. Pol. J. Environ. Stud. 31, 4259–4267. https://doi.org/10.15244/pjoes/147825.

Satrovic, E., Cetindas, A., Akben, I., Damrah, S., 2023. Do natural resource dependence, economic growth and transport energy consumption accelerate ecological footprint in the most innovative countries? The moderating role of technological innovation. Gondwana Res. https://doi.org/10.1016/j.gr.2023.04.008.

Shimbar, A., Ebrahimi, S.B., 2020. Political risk and valuation of renewable energy investments in developing countries. Renew. Energy 145, 1325–1333. https://doi.org/10.1016/j.renene.2019.06.055.

Swamy, 1970. Efficient inference in a random coefficient regression model. Econometrica 38, 311–323.

Tchorzewska, K.B., Garcia-Quevedo, J., Martinez-Ros, E., 2022. The heterogeneous effects of environmental taxation on green technologies. Res. Policy 51, 104541. https://doi.org/10.1016/j.respol.2022.104541.

Usman, M., Makhdum, M.S.A., 2021. What abates ecological footprint in BRICS-T region? Exploring the influence of renewable energy, non-renewable energy, agriculture, forest area and financial development. Renew. Energy 179, 12–28. https://doi.org/10.1016/j.renene.2021.07.014.

Verbič, M., Satrovic, E., Mujtaba, A., 2022. Assessing the driving factors of carbon dioxide and Total greenhouse gas emissions to maintain environmental sustainability in southeastern Europe. Int. J. Environ. Res. 16, 1–14. https://doi.org/10.1007/s41742-022-00486-7.

Wang, X., Cai, Y., Liu, G., Zhang, M., Bai, Y., Zhang, F., 2022. Carbon emission accounting and spatial distribution of industrial entities in Beijing—combining nighttime light data and urban functional areas. Ecol. Inform. 70, 101759 https://doi.org/10.1016/j.ecoinf.2022.101759.

WB, 2021. World Bank [WWW Document]. World Dev. Indic. URL. https://databank.worldbank.org/source/world-development-indicators (accessed 10.1.21).

Westerlund, J., 2007. Testing for error correction in panel data. Oxford Bull. Econ. Financ. 69, 709–748. https://doi.org/10.1111/j.1468-0084.2007.00477.x.

Wu, H., Zhong, R., Wang, Z., Qu, Y., Yang, X., Hao, Y., 2024. How does industrial intellectualization affect energy intensity? Evidence from China. Energy J. 45, 830047 https://doi.org/10.5547/01956574.45.2.hawu.

Xie, P., Xu, Y., Tan, X., Tan, Q., 2023. How does environmental policy stringency influence green innovation for environmental managements ? J. Environ. Manag. 338, 117766 https://doi.org/10.1016/j.jenvman.2023.117766.

Yang, C., Arhonditsis, G.B., 2022. What are the primary covariates of environmental attitudes and behaviours in Canada? A national-scale analysis of socioeconomic, political, and demographic factors. Ecol. Inform. 69, 101661 https://doi.org/10.1016/j.ecoinf.2022.101661.

Yao, C., Feng, K., Hubacek, K., 2015. Driving forces of CO2 emissions in the G20 countries: an index decomposition analysis from 1971 to 2010. Ecol. Inform. 26, 93–100. https://doi.org/10.1016/j.ecoinf.2014.02.003.

Yirong, Q., 2022. Does environmental policy stringency reduce CO2 emissions? Evidence from high-polluted economies. J. Clean. Prod. 341, 130648 https://doi.org/10.1016/j.jclepro.2022.130648.

Zhang, X., Song, X., Lu, J., Liu, F., 2022. How financial development and digital trade affect ecological sustainability: the role of renewable energy using an advanced panel in G-7 countries. Renew. Energy 199, 1005–1015. https://doi.org/10.1016/j.renene.2022.09.028.

Zhou, K., Luo, H., Qu, Z., 2023. What can the environmental rule of law do for environmental innovation? Evidence from environmental tribunals in China. Technol. Forecast. Soc. Change 189, 122377. https://doi.org/10.1016/j.techfore.2023.122377.

Zhu, X., Li, J., Cheng, H., Zheng, L., Huang, W., Yan, Y., Liu, H., Yang, X., 2022. Assessing the impacts of ecological governance on carbon storage in an urban coal mining subsidence area. Ecol. Inform. 72, 101901 https://doi.org/10.1016/j.ecoinf.2022.101901.