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Research Paper

Promoting green taxation and sustainable energy transition for low-carbon development

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ABSTRACT

Since there is a scientific consensus that the energy sector has brought the planet to the tipping point of climate change, transitioning to sustainable energy sources is inevitable to halt foreseeable climatic adversities. This study looks at how promoting green taxation and sustainable energy transition affected the G7 nations' goal of low-carbon development between 1994 and 2020. This study used Generalized Least Squares Random Effects Regression and Driscoll-Kraay Standard Errors-based Least Sqaures approaches for empirical analysis. The latter approach accounts for cross-sectional dependence, heteroscedasticity, and autocorrelation to provide robust empirical outcomes. The empirical results are as follows: Firstly, through lowering CO_2 intensity and greenhouse gas emissions, the environmental tax revenues have enhanced the condition of the environment. The total tax revenues linked to the environment had a greater overall impact than the tax revenues related to the energy industry. Furthermore, compared to CO_2 intensity, both of the environmental tax revenue factors contributed considerably more to greenhouse gas emissions. Second, the sustainable energy transition helped to lower greenhouse gas and CO_2 intensity. Among covariates, international trade was supportive of low-carbon development, but industrialization and GDP per capita did the opposite. The panel bootstrap causality revealed a unidirectional causal connection from all independent variables, except foreign direct investment, to CO_2 intensity and greenhouse gas emissions. These results demonstrated that the G7 nations' environmental policies supported their commitment to achieving low-carbon development goals. In this respect, the G7 nations' environmental emission reduction efforts benefited more from the overall environmental tax revenues. To secure the industrial emissions reduction for a future with net-zero carbon emissions, it is thus advised to continue using policies that price environmental emissions, such as the carbon taxation regulations. Additionally, plans for the sustainable energy transition that includes a quick rise in renewable energy sources in the overall energy mix are successful in lowering environmental emissions. For environmental sustainability and low-carbon development, it is thus advised to divert the taxation burden from renewable energy technologies to the fossil fuel industry to enhance the sustainable energy transition phenomenon for achieving Sustainable Development Goals (especially SDG-7 and SDG-13).

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1. Introduction

Rapid industrialization is making nations more dependent on energy, especially nonrenewable energy, contributing to the exhaustion of natural resources (Hassan et al., 2023). On account of the increasing usage of fossil-based energy sources, carbon dioxide (CO_2) and sulfur dioxide (SO_2) have been massively emitted into the environment; however, greenhouse gas emissions (GHG) are largely comprised of CO_2 (Balsalobre-Lorente et al., 2021). Long-term climate change is caused by these emissions boosting Earth's average surface temperature. Increased global temperature melts glaciers, raises sea levels, affects average rainfall, and creates droughts in certain locations (Hussain and Dogan, 2021; Su et al., 2023). To prevent climate change, greenhouse gas emissions must be reduced to stop the Earth's temperature from increasing. Several international organizations and efforts are directing states to reduce environmental emissions to address climate change. Kyoto Protocol, Paris Climate Agreement, and Sustainable Development Goals (SDGs) are some of the exemplary initiatives (GFN, 2022). Technological advances in environmental protection might reduce CO_2 emissions and modify the ecosystem (Afshan et al., 2022; Satrovic and Adedoyin, 2023). Thus, it is crucial to determine whether environmental technology can achieve low-carbon development and net zero emissions.

According to the OECD (2020), green taxation is defined as a tax paid on ecologically detrimental actions in order to encourage ecologically favorable activity via fiscal rewards, which contributes to reaping SDGs via reducing the harmful environmental challenges created by industrial operations and increasing biological capital's resistance to such difficulties. It may play a significant part in merging the Sustainable Development Goals with their financial viability, thereby placing them on the road toward environmentally friendly economic structures (Ediriweera and Wiewiora, 2021). According to one standpoint, efficient execution and dissemination of green taxation may lead to environmental sustainability by balancing against the scale effects (Shu et al., 2023). However, green taxation may result in sustainable environments at the expense of stagnation, which refers to the reduction in the use of biodiversity and other factors in order to stabilize financial structures (Khan et al., 2022b). Herein, the energy transformation paradigm enters the picture (Wang et al., 2023c). This concept refers to the achievement of an increased share of renewables in the total energy mix throughout the globe (Khan et al., 2022a; Işık et al., 2024c).

Pigou, the welfare economist, is primarily associated with developing the idea of implementing taxes for addressing adverse environmental effects, especially pollutants; remedial taxes like this tend to be named Pigouvian taxing (Cannan, 1921). The concept is straightforward in that a market failure is represented by an adverse externality, which refers to a situation in which the manufacturing or use of a product causes damage to somebody or entity apart from the purchaser or vendor of the same product. This occurs because the choices made by consumers and vendors fail to consider the cost that is incurred externally (European Parliamentary Research Service, 2020). Because of this, an open marketplace that is not controlled typically ends in an enormous supply of some product that is connected with undesirable externalities. The problem may be solved by taxing the product that is the source of those undesirable externalities (Eurostat, 2013). Whenever the rates of taxation are proportional to the marginal exterior harm (i.e., the entire damage to individuals or organization apart from the purchaser and the vendor for a single more piece of the product), it would need to incorporate that outside expense within the sale, thus guaranteeing that the purchaser covers the entire additional social burden of the product. This is because the additional exterior damage is the complete harm suffered by entities aside from the purchaser and vendor by production and use of one additional piece of the same product (Snape and Souza, 2006). Given this, the motivation that is supplied by taxation guarantees that the marketplace will supply the optimal amount of the product (assuming there are no competing market defects that have not been resolved) (Milne, 2007).

Evidently, green taxation does more than only mitigate the detrimental effects of spillovers. Such taxation additionally boosts earnings, which may be a significant benefit in some circumstances (Bontems and Bourgeon, 2005). This money may be put to use in a variety of ways, including lowering (or preventing the raising of) various types of taxation, lowering the imbalance in the budget, paying for infrastructure improvements, and achieving distribution objectives, among others (Tsiantikoudis et al., 2022). Meanwhile, connections between green taxation and other incumbent levies (most notably wage taxation) have the potential to considerably boost the effectiveness costs linked to green taxation. The *dual dividends* term originally brought forward the notion that the function of green taxation in generating money provides a significant extra incentive to adopt taxation like this. The claim states that the purpose of green taxation in generating wealth further motivates enacting this kind of taxation (Goulder, 1995). The basic premise is straightforward: in order to achieve an effective benefit alongside the different advantages of green taxation, provided the earnings generated by green taxation may be utilized to fund a drop in the rates of taxation for previously present distortionary taxation (e.g., income taxes), then the reduction in taxes will provide an efficacy benefit (Goulder, 1995). The concept of *dual dividends* relates to the assumption that green taxation improves financial effectiveness in two distinct ways: firstly, through mitigating the negative effects of externalities, and secondly, through generating additional income that may be employed in the reduction of different kinds of taxation. Since then, many have begun to refer to the latter type of *dividend* by means of the revenue-recycle impact phenomenon (Nerudová and Dobranschi, 2014). This fundamental idea allows for a wider variety of applications of the tax earnings involving investing the money in infrastructure improvements or alternatively utilizing it to lower the fiscal imbalance, which might both achieve comparable increases in budgetary effectiveness.

While nations work to drag themselves away from a variety of wellness, geopolitical, and financial emergencies, the boundaries of the worldwide shift to renewable energy continue to be in a state of perpetual flux (Chandio et al., 2022). The so-called multidimensional concerns are putting nations in a position where they are obliged to reorganize their financial standing and take action in order to solve immediate concerns about affordable and secure energy (WEF, 2021). Additionally, as a result of this, there has been a chance to reflect on the development of the energy triad in its many components. A singular emphasis on accessibility, inclusivity, and fairness eventually grew to include a commitment to long-term prosperity (IRENA, 2018). When it comes to safeguarding supply, safety has recently shifted its focus to broadening the energy portfolio (Jabeen et al., 2023). In addition, sustainable development today encompasses a more diverse kind of carbon-free energy than only low-carbon development, but preparation for transformation necessitates a greater emphasis on the legal and socioeconomic frameworks (Ahmad et al., 2021; Işık et al., 2024b).

As per recent statistics, the year 2017 saw the electricity industry make major strides forward across important domains. The total amount of electricity generated and the total amount of potential added by clean energy sources set all-time highs (IEA, 2021). Unprecedented hikes were additionally noted in the

application of contemporary biogas, solar power, and geothermal electricity, whereas historical gains have also been observed in the usage of green transportation as well as various kinds of automation of final consumer products (e.g., heating systems) (Fritzbøger, 2022). The general contribution of clean energy sources to aggregated consumed energy is anticipated to have increased by around 0.25%, setting an all-time high of approximately 19% of the overall energy use (IRENA, 2020). Despite this, there is a pressing need for a significant acceleration in the advancement of green power. It is imperative that by 2050, the percentage of green energy in cumulative global energy usage be raised from its current level of 19%. Likewise, the electricity intensity of the world's economies has to decrease by an approximate average of 2.8% annually until the year 2050, relative to around 1.8% per annum reduction that has been accomplished during the past few years (BP, 2020). Notwithstanding the considerable increase in people and GDP that would occur between now and 2050, this scenario would result in world power utilization falling to a rate that is somewhat lower than the present one. The pace of power efficiency growth has declined in recent years, which has contributed to an increase in CO_2 as of 2017 (IEA, 2020). However, according to recent research, there has been some sort of forward movement, and the findings further indicate that the world has a lot of potential to speed up power efficiency globally (Jabeen et al., 2021; Ahmad et al., 2022).

The previous studies did enormous development in testing the impacts of renewables and environmental solutions such as environmental innovation and regulatory variables on carbon emissions. For instance, some studies researched the impact of technological innovation on those emissions (Ahmad and Jabeen, 2023; Zhang et al., 2024). Some researchers tested the effects of sustainable energy transition on such emissions (Ulucak et al., 2020; Cheng et al., 2021; Fu et al., 2022). Finally, several studies analyzed the effects of industrialization, foreign direct investment, and gross domestic product (GDP) on various types of environmental emissions (Sarkodie et al., 2020; Balsalobre-Lorente et al., 2022; Pata et al., 2023). However, those studies took those variables on a piecemeal basis. Additionally, those studies did not consider the impact of twin green taxes measured by environmentally related tax revenues on carbon emissions and greenhouse gas emissions.

This research aims to analyze whether promoting green taxation and sustainable energy transition leads to low-carbon development by considering the control variables involving industrialization, foreign direct investment, international trade, and GDP per capita. As an investigative sample, we considered G7 countries. From an empirical point of view, we applied graphical analysis and regression modeling, namely Generalized Least Square (GLS) Random Effects Regression and Driscoll-Kraay Standard Errors Ordinary Least Squares (DK-OLS) approach on data from 1994 to 2020. We also employ a novel panel bootstrap causality for inspecting the causality directions of our study variables. This research is novel in the perspective that it uses two types of green taxation indicators: overall environmentally related tax revenues (ETO), and environmentally related tax revenues in the energy sector (ETE). Further, in light of empirical analysis, it extends important policy implications for the G7 countries. The overall data trends of our study variables can be viewed in Fig. 1 and Fig. 2.

The remaining research is divided into the following sections: *Section 2* surveys the most relevant and recent studies. *Section 3* delves into the data explanations, model building, and method elaborations. *Section 4* interprets and explains the empirical outcomes. Last, *Section 5* sums up the study with concluding remarks and policy suggestions.

2. Literature review

Previous research has made substantial strides in assessing the impact of environmental-related taxation and sustainable energy transition on several environmental indicators to yield diversified empirical findings. To identify the literature gaps, we have surveyed the most recent and relevant studies in the following sub-sections.

2.1. Green taxation and low-carbon development

A number of studies evaluated the connection between green taxation and ecological protection variables. In this respect, Wang et al. (2023a) examined the influence of technical advancement, financial growth, renewables/ nonrenewable, and foreign direct investment on the ecological degradation of 14 EU nations from 1995 to 2020. To accomplish their objectives, the authors used Augmented Mean Group (AMG) and Common Correlated Effects Mean Group (CCEMG) estimate methodologies. They discovered that technical advancement and renewable energy decreased environmental degradation, but nonrenewable energy, foreign direct investment, and financial development increased it. Amin et al. (2023) set out to investigate the long-term effects of green technology innovation, institutional quality, renewable energy, trade openness, population growth, and economic advancement on CO_2. The authors employed the Dumitrescu-Hurlin causality test on data from South Asian economies from 1995 to 2020 for this purpose. They discovered that technical progress and renewable energy reduced emissions. Institutional quality, population expansion, trade openness, and economic development, among other factors, all contributed favorably to CO_2.

Furthermore, Ahmad and Wu (2022) examines data from 28 chosen G-20 economies from 1985 to 2017 using a panel quantile regression (PQR) approach to uncover varied outcomes for the studied nations across various degrees of ecological efficiency. They wanted to investigate the effect of depleting natural resources, technical advancement, and economic expansion on environmental intensity. They discovered that reliance on natural resources and technological advancement hindered ecological efficiency. In addition, they unfolded that financial deepening slowed ecological efficiency in the lower and intermediate quantiles while increasing it in the top quantiles. It was further recorded that financial deepening adversely moderated the impact of natural resource dependency and technical advancement on ecological efficiency for the lower and intermediate quantiles, but favorably moderated it for the higher quantiles. Chen et al. (2022) investigated the dynamic relationship between natural resources, technological innovation, and environmental sustainability using a cross-sectionally adjusted autoregressive distributed lag (CSARDL) method to the newly industrialized countries' data from 1990 to 2019. Natural resource rents, according to their long-run findings, impair environmental sustainability. Besides, they unearthed that green technology innovation decreased environmental damage. They discovered comparable results in the short term as well. Danish and Ulucak (2021) sought to study the connection amongst technical development, GDP, renewables, and CO_2 in the USA as well as in the Chinese context. To that purpose, they used a dynamic ARDL simulation approach to study both nations' time series data. They discovered that technical innovation lowered emissions in the United States, but this association was inconsequential when data from China was included. Furthermore, renewable energy reduced emissions in both nations. Furthermore, for both nations, the influence of income level decreased from the short to the long term.

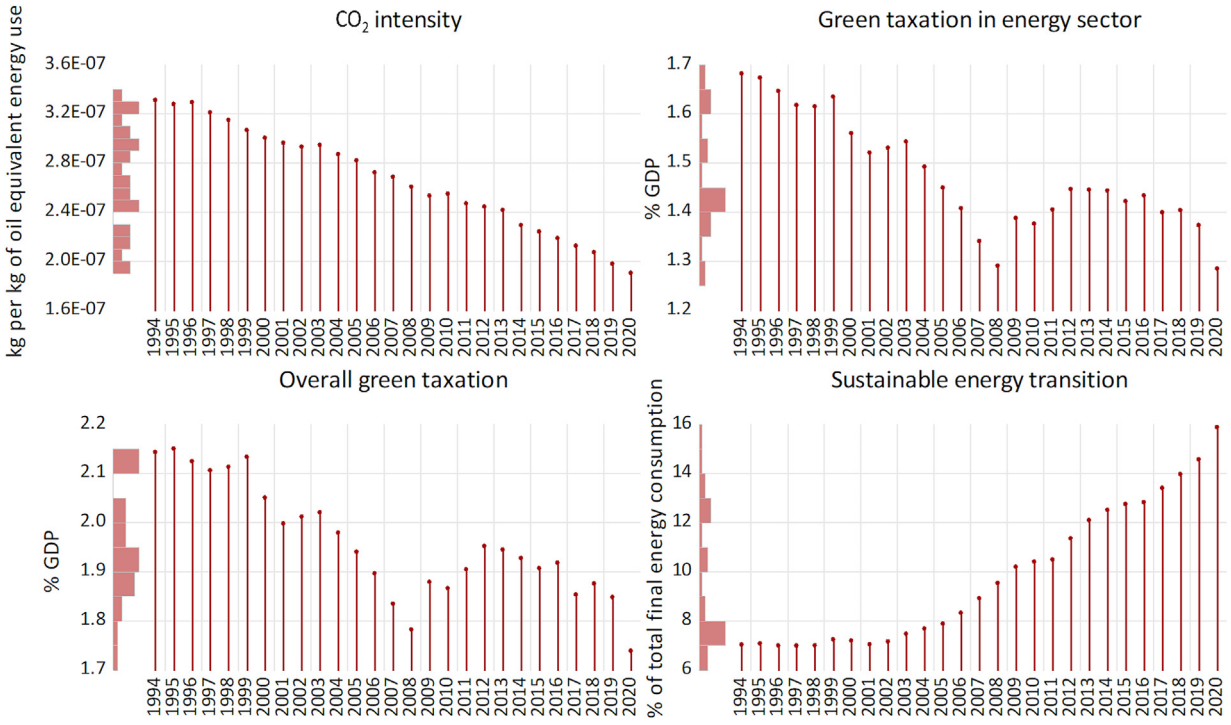


Fig. 1. Overall trends of key study variables in G7 members.

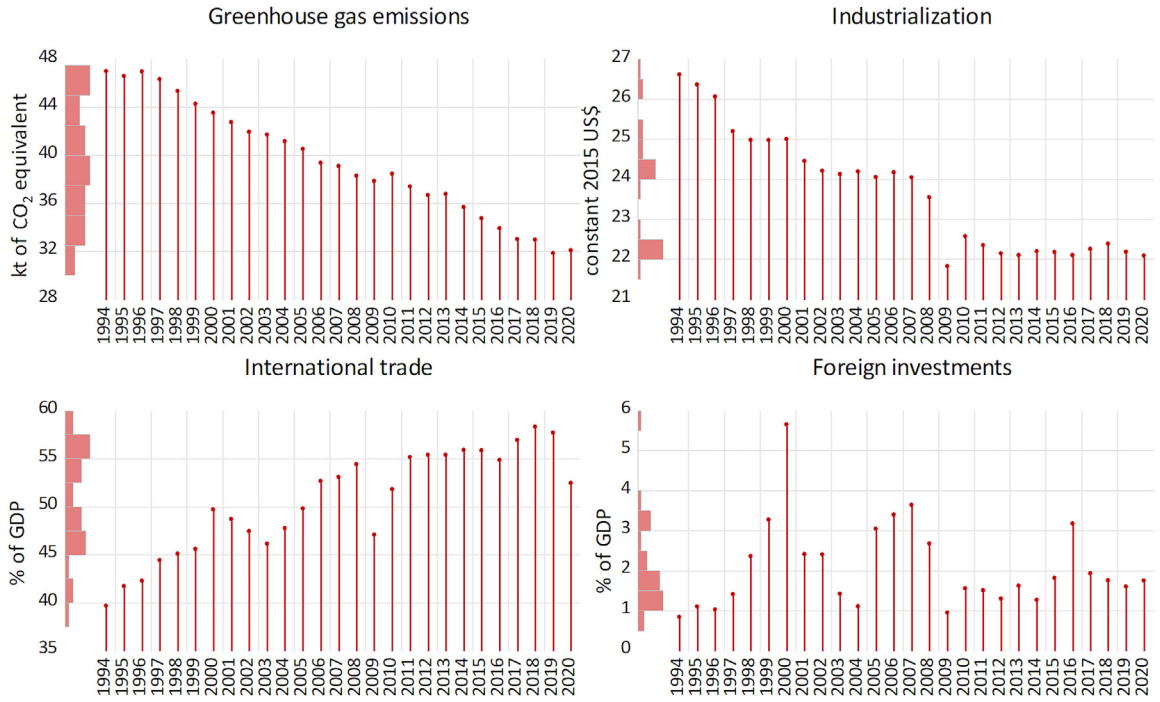


Fig. 2. Overall trends of other covariates in G7 members.

In addition, making use of the panel data of emerging seven (E7) countries, Lu (2022) applied a continuously updated and fully modified (CUFM) technique to evaluate the impact of eco-innovation and green taxation on CO_2 from 1995 through 2018. The authors unfolded that both variables reduced those emissions in the sampled countries. Chang et al. (2023) empirically investigated the influence of green technological innovation on CO_2 across 30 Chinese provincial units during 2003–2019. They employed the system generalized method of moments (SGMM) technique on panel data and uncovered a CO_2 mitigation effect moderated through green technological innovation. In their research, Yıldırım et al. (2022) made use of longitudinal data from 32 OECD economies from 1997 to 2018 and applied a panel smooth transition regression (PSTR) strategy. The authors analyzed and interpreted the presence of the rebound impact of environment-related technological innovation on CO_2 of the OECD nations.

Besides, Ofori et al. (2023) made use of the STIRPAT framework to analyze the role of environmental taxation and green power technologies on CO_2 of E7 nations during 2000–2020. Applying the Driscoll-Kraay estimator, the authors found CO_2 reduction in response to promoting environmental taxation and green power technologies in the sampled nations. Utilizing the method of moments quantile regression (MMQR) technique on data from 21 OECD members over the 1990–2020 period, Wang et al. (2023d) investigated the influence of environmental taxation and green funds on consumption-driven CO_2. They uncovered that both variables mitigated the intensity of those emissions in OECD. In their research, Khaddage-Soboh et al. (2023) studied the contribution of environmental taxation in sustainable development across G7 member nations by applying the MMQR strategy to data spanning from 1990 through 2020. The authors revealed environmental tax could achieve sustainable environments through CO_2 abatement practices. Likewise, Sarpong et al. (2023) utilized the MMQR tool to data from E7 nations during 2000–2020 to explore the links between environmental taxes and GHG. They concluded that ecological taxes significantly contributed to GHG curtailment; however, foreign investments upsurged those emissions.

Analyzing the data from 51 developed and developing nations from 2006 to 2020, Zhu et al. (2023) delved into the effects of environmental taxation and renewable energy utilization on CO_2 by using the panel threshold modeling (PTM) approach. They found some interesting outcomes: though environmental taxation inhibited domestic CO_2, it promoted the same in the neighboring nation, showing adverse spillover effects. A study by Sadiq et al. (2024) inspected the data from BRICS (Brazil, Russia, India, China, and South Africa) nations during the period spanning 2001–2020 to evaluate the effects of green funding and carbon taxes on CO_2. Making use of the CSARDL approach, they unveiled the inhibition effect of both variables on CO_2 in the sampled countries. In the same vein, Mehboob et al. (2024) used the CSARDL technique on the data from the top five polluting nations over the 1990–2020 period to examine the influence of environmental taxes and nuclear energy use on consumption-driven CO_2. The authors declared a favorable impact of both variables on those kinds of ecological emissions during the sampled period. Finally, applying kink regression analysis on panel data of G7 nations during 1994–2020, Rakpho et al. (2023) investigated the role of environmental taxation in determining CO_2 and found a favorable emissions reduction effect of the same.

2.2. Sustainable energy transition and low-carbon development

The existing body of literature made progress in establishing empirical connections between sustainable energy transition and various environment-associated variables to find heterogeneous outcomes. In this regard, we review several recent and relevant studies presenting the nexus between the two paradigms. For example, Dong et al. (2022) analyzed the asymmetric effects of renewable energy on CO_2 in 32 developed countries from 2000 through 2018. They made use of PTM and discovered that renewable energy was a driver of CO_2 efficiency in the selected countries. Gao and Chen (2023) applied the PQR technique to data from 21 highly industrialized nations from 1990 to 2020 in order to inspect the effect of renewable-based electricity and green taxation in driving down consumption-based CO_2. They exposed a significantly negative effect of both variables on CO_2. A different empirical research by Nam and Jin (2021) tested the panel data from 109 global economies from 2010 to 2017 by applying the PQR method. They found an insignificant influence of sustainable energy transition on CO_2, while energy intensity positively impacted the same.

Moreover, Wiredu et al. (2023) intended to delve into the empirical connection between renewable energy transition and CO_2 by using the CSARDL approach on panel data from five selected African economies during 1990–2020. The authors found a significant link between the said variables. Employing the data from 71 global nations during 2003–2019, Wang et al. (2023a) conducted an analysis of the contribution of the energy transformation on worldwide CO_2. They utilized the SGMM technique and uncovered that sustainable energy transition was a bottleneck of CO_2, while metallic minerals proved the driving force for the same. They also unveiled that metallic minerals made the CO_2 curtailment effect of sustainable energy transition less intensive. Ahmad and Jabeen (2024) analyzed the contribution of green innovation and sustainable energy transition to eco-efficiency in 13 EU economies during 1995–2014. They disclosed positive and significant contributions of the said variables to eco-efficiency improvements.

Additionally, Imran et al. (2024) attempted to examine 29 selected nations' data from 2007 through 2020. They used the GMM approach and put forward that a hike in renewable energy consumption was responsible for CO_2 mitigation. They further found a negative influence of green financing on the levels of CO_2 in the sampled countries. Using the PQR method on data from selected five emerging nations during 1997–2020, Tiwari et al. (2024) delved into the association among sustainable energy transition, circular economy, and CO_2 and found that the former two variables were successful in reducing CO_2. Eventually, Wang et al. (2023b) inspected data from 24 selected global economies from 2001 to 2020 by utilizing the fully modified least squares (FMLS) strategy. The authors observed that nuclear energy as well as overall renewable energy, contributed to CO_2 abatement and improved the environmental quality.

On top of that, Zhang et al. (2023) assessed the influence of energy transformation and economic development on GHG in selected 40 global economies from 2010 through 2020. Using the FMLS econometric tool, the authors reached the conclusion that energy transformation was an inhibitor of GHG, while economic development boosted those emissions. In their study, Saqib and Dincă (2024) implemented CCEMG and AMG techniques to examine data from China, France, Germany, Japan, the UK, South Korea, Spain, India, the USA, and Italy during 1995–2020. They explored and revealed that renewable energy utilization and economic complexity were significant forces driving down the CO_2 in the sampled countries. Battisti (2023) made an assessment of the prospective GHG from 2020 through 2050 in the case of selected OECD and non-OECD nations. The authors opted for the life cycle analytical techniques and found that the forecasted adoption of renewables will merely account for partial mitigation of GHG by 2050 according to the present scenario of renewable capacity. Applying a panel vector autoregressive (PVA) strategy to data collected from 35 developed nations from 1996 through 2020, Lin and Okoye (2023) studied financial development and governance indicators' contribution to renewable energy consumption and GHG. The authors claimed that both variables partially explained the variations in renewables and those emissions in the sampled countries.

Considering the case of Chinese cities Suzhou and Beijing, Si et al. (2023) applied the decomposition analysis to data from 2010 to 2020. The authors explored and found that Beijing needed to promote a demand-sider response, while Suzhou was required to expand the potential of clean energy development domestically and from outsider sources. Imran et al. (2024) inspected the role of nuclear power promotion and R&D financing on CO_2 in 29 European and Asian nations from 2007 to 2020. Employing GMM statistical tools to the said data, the authors discovered that a hike in demand for nuclear power effectively mitigated CO_2; however, the lack of R&D funds impeded the achievement of such a goal in the sampled economies. A different work by Jin et al. (2024) applied multiple econometric strategies to examine the role of

Table 1
Explanation of data and variables.

Variable	Label	Data measurements	Source
Carbon dioxide emissions intensity	CO_2 intensity	CO_2 intensity (kg per kg of oil equivalent energy use)	(WDI, 2023)
Greenhouse gas emissions	GHG	Total greenhouse gas emissions (kt of CO_2 equivalent)	(WDI, 2023)
Sustainable energy transition	ETR	Renewable energy consumption (% of total final energy consumption)	(WDI, 2023)
Industrialization	INDS	Industry (including construction), value added (constant 2015 US$)	(WDI, 2023)
International trade	TRD	Trade (% of GDP)	(WDI, 2023)
Foreign direct investment	FDI	Foreign direct investment, net inflows (% of GDP)	(WDI, 2023)
Gross domestic product per capita	GDPP	GDP per capita (constant 2015 US$)	(WDI, 2023)
Green taxation	GTX		(OECD, 2022)
Overall environmentally related tax revenues	ETO	Overall environmentally related tax revenues (% of GDP)	(OECD, 2022)
Environmentally related tax revenues in energy sector	ETE	Environmentally related tax revenues in energy sector (% of GDP)	(OECD, 2022)

renewable energy transformation and R&D investments in improving the load capacity factor of Germany during 1974–2018. They uncovered that nuclear energy increased the load capacity factor, while R&D investments did the opposite. Finally, Tiwari et al. (2024) used the PQR methodology to inspect the connection between renewable energy transition, industrial development, and CO_2 of high-income countries over the 1997–2020 period. The authors figured out that both variables significantly contributed to CO_2 in the short and long-term contexts.

2.3. Literature gaps

Despite the paramount attention of mainstream researchers on green taxation and sustainable energy transition, certain vital gaps were left unaddressed, which are bridged by this present research. First, none of the previous studies examined the combined effect of green taxation and sustainable energy transition on low-carbon development goals, which is the backbone of climate change mitigation strategies. Second, none of the existing studies measured green taxations through ETO and ETE variables, which present insightful findings with rich policy implications in the current research. Finally, no previous work has been noted to employ the novel Driscoll-Kray Standard Errors OLS strategy (DK-OLS) while analyzing the contributions of green taxation and energy transformation on low-carbon development targets.

3. Materials and methods

3.1. Data

We collected data for this research from different secondary sources. For instance, we collected data on green taxes from the OECD.Stat website. Moreover, we used the World Development Indicators (WDI) website to acquire data on carbon dioxide emissions (CO_2), greenhouse gas emissions (GHG), sustainable energy transition (ETR), industrialization (INDS), international trade (TRD), foreign direct investment (FDI), and gross domestic product per capita (GDPP). We conducted a panel data study by considering Group of Seven (G7) countries to have a better comprehensive analysis. These countries include Canada, France, Germany, Italy, Japan, the United Kingdom, and the United States. The selection of G7 countries' sample was made on the following grounds: G7 nations are committed to coordinating their approaches and regulatory procedures in order to provide assistance to all of the member governments in tackling environmental challenges. Moreover, these countries are among the top global contributors to green energy consumption, making them a great lesson for the rest of the world. Additionally, due to the fact that the G7 demonstrates increasing financial and ecological cooperation, it is predicted that interconnectivity among those nations will emerge as an important issue for the study that is now being considered. The data description is provided in Table 1.

For basic empirical analysis, we did a graphical analysis by drawing area plots to see the trends of variables graphically and by drawing scatter matrix plots to see the correlation among the study variables. Moreover, we applied cross-sectional dependency, slope heterogeneity, and multicollinearity tests before applying the unit root analysis. These primary tests were followed by stationarity analysis by employing second-generation tests.

As a starting point, we plotted the data trends of variables included in this study. Figs. 1 and 2 show the data trends of those variables for each of the seven countries included as the study sample. In this regard, CO_2 exhibited declining trends in almost all countries except Canada. In addition, Canada showed overall increasing trends in CO_2 during 1994–2020. Similarly, the data trends for all of the variables can be seen in Fig. 3 and Fig. 4.

After that, Fig. 5 shows the scatter matrix of the variables used in this research. As can be seen in this figure, CO_2 established a negative relationship with all of the variables except for ETE and ETO. These two variables showed a positive association with CO_2.

3.2. Theoretical model and hypotheses

In this study, we start with setting up our theoretical model based on the well-established notion that environmental deterioration (ENVD) is determined by economic activity, which is captured by the aggregate production or output of the economy (Y). This phenomenon was first determined by Grossman and Krueger (1991) and was popularized as the environmental Kuznets curve (EKC). Along these lines, we kick off with the following simplest functional form:

$$ENVD = f(Y) \tag{1}$$

where $f(.)$ represents the functional form of the model. On the one hand, environmental economists argue that human-driven economic activities are the culprit behind environmental catastrophes (Pandey et al., 2020; Sharif et al., 2020; Khan and Ozturk, 2021). To achieve growth in its economy and society, a country must use a variety of energy sources and develop its manufacturing industries. Given the limitations imposed by the natural world and energy resources, monitoring the progress of sustainable energy transition and its impact on the transformation towards a sustainable and environmentally friendly business is crucial (Lin et al., 2022; Verbič et al., 2022). However, when examining the actual process of economic expansion and the steps required to achieve it, one discovers notable limitations that hinder the transition to a more environmentally friendly approach. These constraints include the exhaustion of energy resources, fluctuations in economic expansion, dependence on one particular sector, and environmental degradation (Zhou et al., 2022).

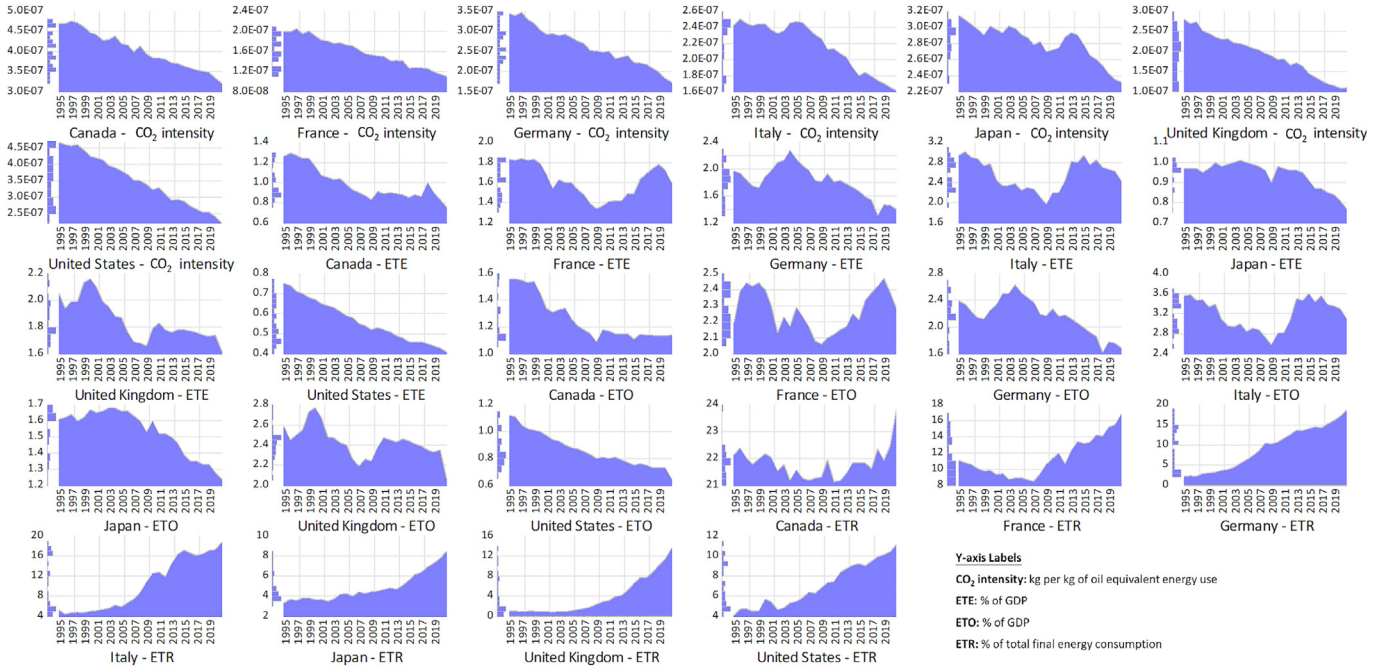


Fig. 3. Data trends of CO_2, ETE, ETO, and ETR across G7 countries.

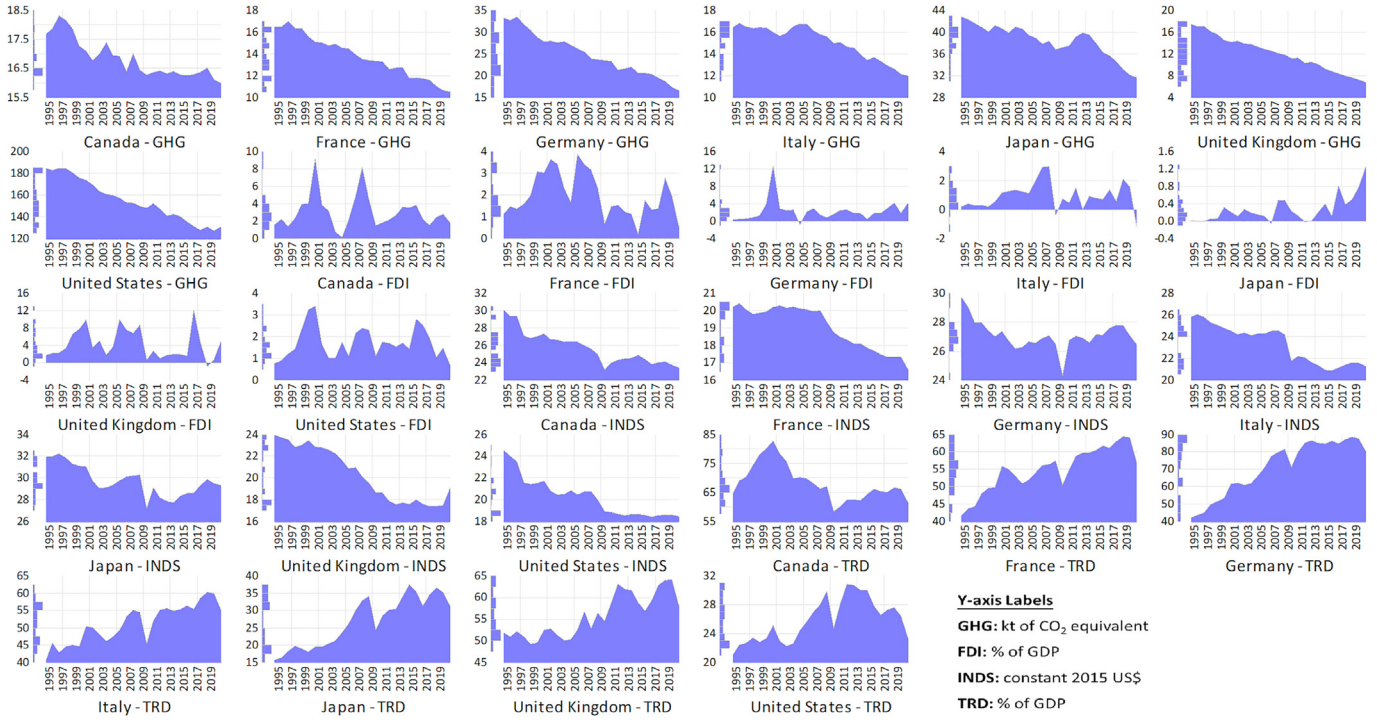


Fig. 4. Data trends of GHG, FDI, TRD, and INDS across G7 countries.

In order to overcome the limitations hindering the progress of low-carbon development, it is necessary to enhance the degree of sustainable energy transition in an efficient manner. To mitigate the exhaustion of energy resources, it is essential that we utilize them judiciously in this particular situation (Jena et al., 2022; Wang and Kang, 2024). Hence, it is essential to investigate low-carbon development in order to foster the establishment of a diverse production structure that addresses the exhaustion of fuel sources. Furthermore, the sustainable energy transition scale refers to the extent to which businesses enhance their capacity for environmentally friendly innovation and implement sustainable practices in their supply networks (Işık et al., 2024a). As a result, the economy's structure can be tailored with greater efficiency, leading to the achievement of energy carbon neutrality and effective recycling of industrial debris (Bu and Ren, 2023). In general, the industrial infrastructure has the capacity to create a sustainable and eco-friendly low-carbon structure while also promoting the development of the sustainable energy transition. Organizations

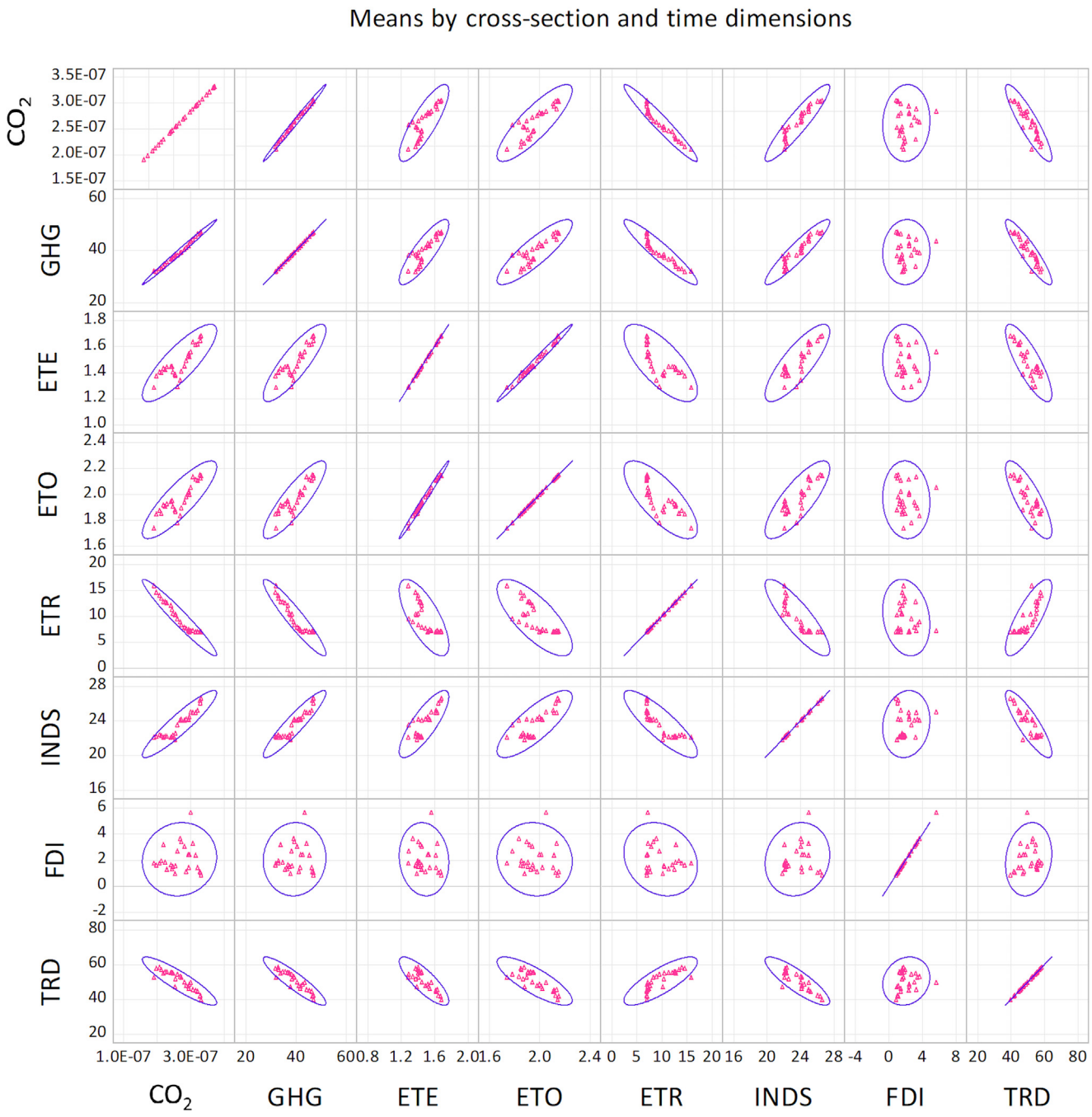


Fig. 5. Scatter plot of study variables.

may reduce their expenses in creating and using sources of power by implementing sustainable energy transition modes (Damrah et al., 2022; Ahmad and Satrovic, 2024). For example, when there is a more efficient shift towards using green energy, it reduces the expenses of producing goods for a firm. This allows the corporation to allocate more funds towards acquiring advanced scientific and technological supplies. Manufacturers are enhancing their green technology provision and revenue growth via the use of advanced technology and expanded research and development (Xie et al., 2023; Jabeen et al., 2024). On the other hand, energy economists emphasize the restructuring of the existing energy mix by including an enhanced share of renewables, leading to a sustainable energy transition phenomenon, which would lead to a reduction in environmental emissions and an improvement in environmental sustainability (Khan et al., 2022c; Hao et al., 2023). This argument leads to the following testable hypothesis:

Hypothesis 1. *Sustainable energy transition is expected to promote low-carbon development (i.e.,* $\frac{\partial ETR_{i,t}}{\partial ENVD_{i,t}} < 0$*).*

Furthermore, environmental innovators comment that the introduction of environmentally friendly processes as well as environment-related technologies will strengthen environmental protection (Vélez-Henao et al., 2019; Mao et al., 2023), which is supportive of environment-related taxation. In this regard, some recent theoretical developments have noted that the decentralization of environmental policies has a beneficial effect on regulation and may mitigate the negative impacts of economic development

targets on the ecosystem. Various forms of decentralized environmental governance influence the relationship between financial development goal restrictions and harmful emissions. Decentralizing environmental management and monitoring can diminish the beneficial impact of financial development targets on global warming. Conversely, enhancing the decentralization of ecological surveillance can amplify economic development objectives' beneficial implications in curbing environmental destruction (Ren et al., 2023). These arguments show that environmental interventions can be meaningful for environmental protection, provided that accurate regulations are in place. These arguments guide the formulation of the following testable relationship:

Hypothesis 2. *Green taxation is likely to gear low-carbon development (i.e.,* $\frac{\partial ERTR_{i,t}}{\partial ENVD_{i,t}} < 0$*).*

Hence, by incorporating the sustainable energy transition (ETR) and environment-related tax revenues (ERTR) into Eq. (1) provides the following expression:

$$ENVD = f(Y, ETR, ERTR) \tag{2}$$

In addition, in the face of industrialization, globalization, and economic integration of global economies, international economic activities have a paramount contribution to environmental quality (Khan et al., 2021; Ozili, 2023; Primanthi and Kalirajan, 2023). Therefore, we also include foreign direct investment (FDI), international trade (TRD), and industrialization (INDS) as control factors to Eq. (2), providing the following new expression:

$$ENVD = f(Y, ETR, ERTR, FDI, TRD, INDS) \tag{3}$$

By applying the natural logarithmic transformation, we convert Eq. (3) into an econometric formulation and assign each variable with panel data dimensions (i.e., time and cross-sectional dimensions) to give the following model:

$$ENVD_{it} = \phi_0 + \phi_1 Y_{it} + \phi_2 ETR_{it} + \phi_3 YERTR_{it} + \phi_4 FDI_{it} + \phi_5 TRD_{it} + \phi_6 INDS_{it} + \epsilon_{it} \tag{4}$$

where ϕ_0 is the constant, also known as the intercept or drift parameter. The rest of the ϕ s are the elasticity coefficients of the explanatory variables, while ϵ_{it} indicates the error term of the model.

3.3. Estimation methods

For preliminary analysis, we made use of cross-sectional dependency (also known as CDP) testing since disregarding this problem could misguide the implications of unit root analysis and final empirical estimations. To this end, we employed the Pesaran (2015) testing tool. The application of CDP is followed by heterogeneous slopes testing by Pesaran and Yamagata (2008). After that, we used a stationarity testing tool called the Cross-sectional Augmented Dickey-Fuller (CDF) test by Pesaran (2007). The flow of methodological phases is exhibited in Fig. 6. We employ normality testing through quantile normality plots. The plots show that all the variables' observations remain within confidence intervals, implying that the data used in this study are normally distributed (see Fig. 7). Thus, applying linear regression will be feasible to estimate viable estimates.

For regression analysis, we primarily applied the Generalized Least Square (GLS) – Random Effects Regression (RER) method. In the RER method, the regressand is speculated to be a function of both some observables and some unobservables. The parameters of the observables are often thought to be stable across time and between persons, but this is not always the case. Some of these unobservables are unique to the entity and time observed, while others remain the same at the entity level across the course of time. This is the simplest possible scenario. Therefore, the following describes what is known as the one-way error-component model:

$$y_{it} = \beta_0 + x_{it}\beta_1 + \mu_i + \varepsilon_{it} \tag{5}$$

where $\mu_i + \varepsilon_{it} = \eta_{it}$ In the abovementioned model, y_{it} denotes the regressand for the cross-sectional unit i in period t, x_{it} indicates a $1 \times K$ vector of explanatory variables, β_0 represents the drift parameter, β_1 indicates a K×1 vector of parameters, and η_{it} is the demonstration of a unit-specific and time-invariant stochastic error (i.e., μ_i+ε_{it}). This model includes a variable μ_i that accounts for unobserved heterogeneity at the individual level (i.e., in the present case, country level), such as features that remain constant throughout time. However, as we shall show, it produces estimations distinct from Ordinary Least Squares (OLS). Additionally, the model determines the distribution of μ_i and ε_{it} moments. In the simplest scenario, $\varepsilon_{it} \sim \text{iid}(\sigma_\varepsilon^2)$ and $\mu_{it} \sim \text{iid}\left(\sigma_\mu^2\right)$ are independent of each other as well as to that of X_i, the whole T×K matrix of variables for the ith cross-sectional unit (i.e., country).

Due to the composite character of the error η_{it}, its variance–covariance matrix shows a time-reliant dependency on observations of y_{it}. The T×1 vector of η_i has a constant variance but non-zero correlation due to the time-constant term μ_i:

$$Cov(\eta_i) = E(\eta_i \acute{\eta_i}) = \Omega = \begin{bmatrix} \sigma_\mu^2 + \sigma_\varepsilon^2 & \sigma_\mu^2 & \cdots & \sigma_\mu^2 \\ \sigma_\mu^2 & \sigma_\mu^2 + \sigma_\varepsilon^2 & \cdots & \sigma_\mu^2 \\ \vdots & \vdots & \vdots & \vdots \\ \sigma_\mu^2 & \sigma_\mu^2 & \cdots & \sigma_\mu^2 + \sigma_\varepsilon^2 \end{bmatrix} \tag{6}$$

Despite being consistent, OLS regression on pooled data is considered inefficient due to the non-spherical covariance structure of the composite error η_i, which comprises the constant component μ_i. The GLS-RER estimator considers error structure to provide an efficient estimation model given as follows:

$$\widehat{\beta}_{GLS} = \left(\sum_{i=1}^{N} \acute{X}_i \Omega^{-1} X_i\right)^{-1} \left(\sum_{i=1}^{N} \acute{X}_i \Omega^{-1} y_i\right) \tag{7}$$

This model is capable of being generalized in a number of different ways. Relaxing the requirements of homoskedasticity of both μ_i and ε_{it} and the absence of serial correlation of the latter may lead to GLS estimators that employ more broad covariance matrices than those in Eq. (3). In addition, characteristics that are shared by all entities (i.e., countries in the present case) within a certain time period may be included, which results in what we call two-way error factor model (Baltagi, 2008), which is shown as follows:

$$y_{it} = \beta_0 + x_{it}\beta_1 + \mu_i + \lambda_t + \varepsilon_{it} \tag{8}$$

$$\mu_i + \lambda_t + \varepsilon_{it} = \eta_{it}$$

Because of the availability of panel data and the need to include unobserved heterogeneity in the modeling specification, the GLS-RER approach has seen widespread use in the fields of economics and social sciences, among others. Under the aforementioned conditions, the GLS-RER method has the significant benefit of being more efficient than the conventional fixed effects panel data models.

As a robustness check, our study also employs the ordinary least squares with Driscoll-Kraay standard errors (DK-OLS) because it accounts for cross-sectional dependence, heteroscedasticity, and autocorrelation.

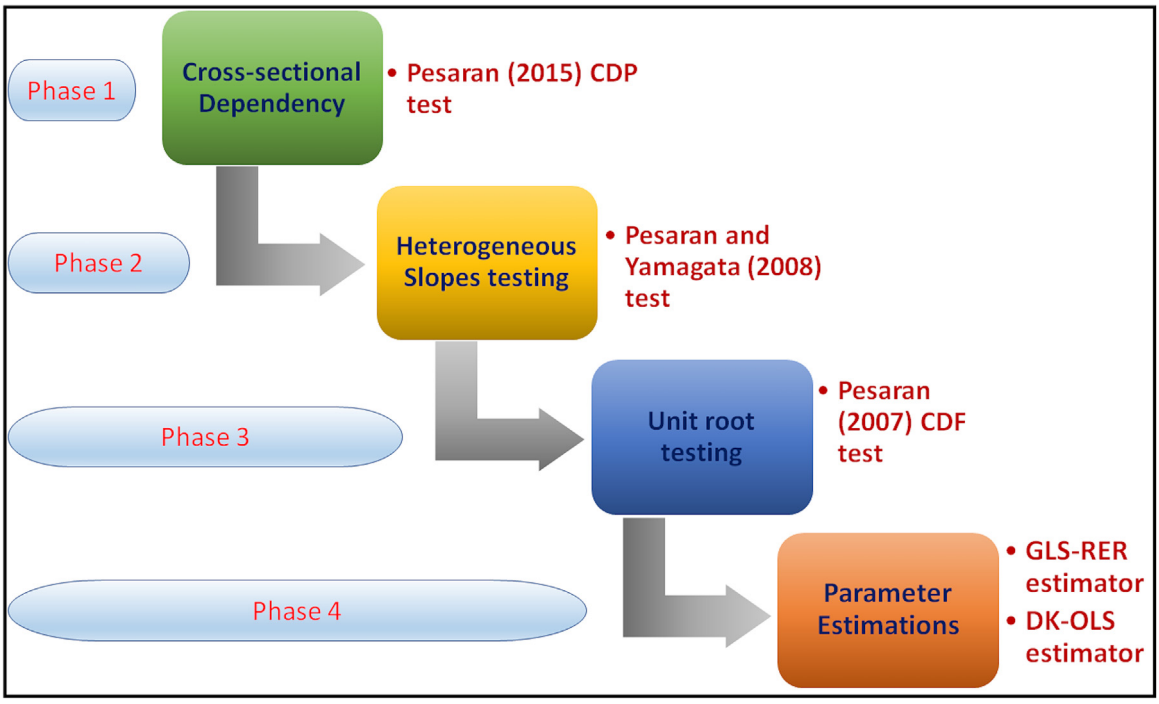


Fig. 6. Methodological phases of the present research.

4. Results

4.1. Preliminary results

It is essential to address issues with panel data, such as the stationarity of series, if one wishes to steer clear of erroneous conclusions on regression. According to Chudik and Pesaran (2015), the severity of this issue worsens with data that have larger cross-sectional panels and longer time periods. The trend of the independent variables may suggest that there is a strong correlation between them. In addition, testing for CDP is required before testing the unit root. This is the case due to the fact that first-generation unit root tests would provide biased findings in the event that CDP was present. Pesaran's (2015) approach was utilized to analyze CDP, and it presupposed those particular nations were not independent of one another. In addition to that, a variance inflation factor technique (VIF) is used in order to test for the presence of a multicollinearity issue in the data. In addition to that, Pesaran and Yamagata's (2008) heterogeneous slopes testing strategy was used. Table 2 discovered that every single series had CDP, yet not a single one of them had multicollinearity issues. Finally, heterogeneous slopes problems were present.

In order to evaluate the stationary property, two distinct kinds of unit root testing approaches are used. The Im, Pesaran, and Shin testing approach (IPST) from Im et al. (2003) evaluates the non-stationary null hypothesis. Initially, we took into consideration a first-generation panel unit root test, which is IPST. After that, we employed Pesaran's (2007) CDF test, which is considered among the best tools for analyzing stationarity. It is of the kind known as the second generation, which presupposes the presence of CDP for all individual cross-sections. The results of the underlying stationarity tests are shown in Table 3. Both of IPST and CDF found all growth rate form variables to be stationary at both levels and first differenced form. It means that all the variables in the growth rate form are integrated of zero order, i.e., $I(0)$, which rules out the application of cointegration techniques in this study. It implies that we can directly estimate the mean effects of the regressors on our regressand variables.

4.2. Main estimation results

For impact analysis, we have estimated four types of regression models, as shown in Tables 1 to 4. Regression models 1 and 2 have CO_2 intensity as a dependent variable. Further, Regression Model 1 contains ETO as an independent variable among other independent variables. On the other hand, the Regression Model 2 contains ETE as an independent variable among other independent variables. Considering Regression models 3 and 4, GHG is used as a dependent variable. Whereas Regression Model 3 contains ETO as an independent variable among other independent variables. While, the Regression Model 4 contains ETE as an independent variable among other independent variables.

In Regression Model 1, the regressors ETR, TRD, and ETO showed a CO_2 intensity reduction effect, yet the other regressors involving INDS, GDPP, and constant term manifested a positive impact on the same. Though, except for FDI, all variables had a statistically significant impact on CO_2 intensity, but FDI presented an insignificant effect on the same. Among other variables, ETR, ETO, and TRD had a significant impact at a 1% level of significance, while INDS and GDPP had a significant coefficient at a 5% level of significance. Moreover, the significant probability value of the Wald test at a significance level of 1% shows the overall significance of the Regression Model 1. Table 4 presents the aforementioned outcomes.

In Regression Model 2, ETR, TRD, and ETE exhibited negative impacts on CO_2 intensity, but INDS, GDPP, and constant term showed a positive impact on the same. Nevertheless, regarding the statistical significance of the coefficients of all considered variables, only ETR, TRD, and ETE had a statistically significant impact on CO_2 intensity, but INDS, FDI, and GDPP presented insignificant effects on CO_2 intensity. Among the significant variables, ETR and ETE had a significant impact at a 1% level of significance, while TRD had a significant coefficient at a 10% level of significance. Moreover, the significant probability value of the Wald test at a significance level of 1% shows the overall significance of the Regression Model 2. These results can be seen in Table 5.

In Regression Model 3, ETR, TRD, and ETO negatively contributed to GHG, while INDS, GDPP, and intercept coefficient

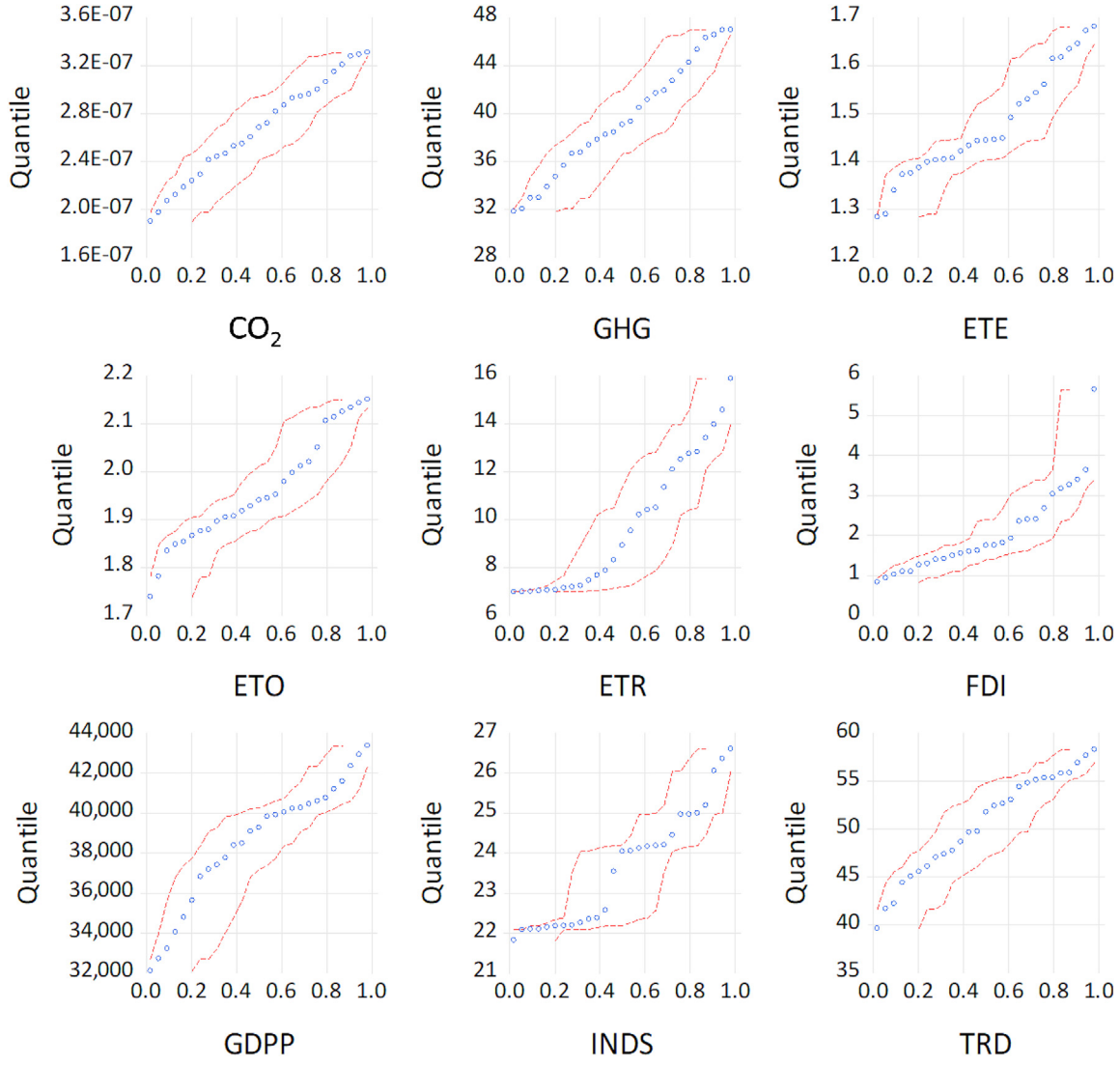


Fig. 7. Normality plots of study variables.

Table 2
CDP, VIF, and Slope heterogeneity findings.

Variables	Pesaran's (2015) CDP test	
	Statistic	VIF
CO_2 intensity	22.584***	3.593
GHG	15.493***	1.448
ETR	36.680***	6.710
INDS	23.265***	2.562
TRD	19.572***	5.370
FDI	11.118***	4.281
GDPP	51.510***	7.119
ETO	33.641***	2.179
ETE	27.360***	1.851
Pesaran and Yamagata (2008) test		
Δ-base	4.913	0.001
Adjusted-Δ	6.483	0.000

Note: *** indicates the significance level at 1%. Any VIF scores less than 10 indicate the absence of multicollinearity.

displayed a positive impact on the same. However, considering the statistical significance of the coefficients of all considered variables, all variables had a statistically significant impact on GHG, but FDI expressed an insignificant effect on the same. Among other variables, TRD had a significant impact at a 10% level of significance, while all other variables with significant coefficients had a significant impact at a 1% level of significance. Moreover, the significant probability value of the Wald test at a significance level of 1% shows the overall significance of the Regression Model 3. These results are shown in Table 6.

In Regression Model 4, ETR, TRD, and ETE displayed negative impacts on GHG; however, INDS, GDPP, and intercept term had a positive impact on the same. Considering the statistical significance of the coefficients of all considered variables, only ETR, INDS, and ETE had a statistically significant impact on GHG, but TRD, FDI, and GDPP presented insignificant effects on GHG. Among the significant variables, ETR and ETE had a significant impact at a 1% level of significance, while INDS depicted a significant coefficient at a 5% level of significance. Moreover, the significant probability value of the Wald test at a significance level of 1% shows the overall significance of the Regression Model 4. These results can be seen in Table 7.

As a final step of our empirical analysis, we applied bootstrap causality to test the short-run direction of linkages between study variables. Table 8 presents the results of bootstrap causality. The causality findings confirmed unidirectional causal linkage from ETR, INDS, TRD, ETE, ETO, and GDPP to both CO_2 intensity and

Table 3
Stationarity findings.

Variables	@ Level		@ 1st Difference	
	IPST	CDF	IPST	CDF
CO_2 intensity	−13.253***	72.563***	−10.564***	45.378***
GHG	−11.791***	43.221***	−14.336***	81.563***
ETR	−9.479***	64.695***	−10.791***	89.470***
INDS	−10.573***	49.305***	−8.425***	66.115***
TRD	−10.001***	57.492***	−9.920***	75.348***
FDI	−14.649***	40.584***	−12.772***	56.261***
GDPP	−12.558***	78.264***	−11.301***	71.594***
ETO	−11.521***	81.495***	−13.029***	76.541***
ETE	−8.563***	44.261***	−7.694***	69.092***

Note: *** indicates the significance level at 1%.

Table 4
Panel data estimates of Regression Model 1 (Dependent variable: CO_2 intensity).

	GLS-RER estimation				DK robustness
Variables	Coefficients	SE	T-statistic	Probability	Estimates
ETR	−0.3454***	0.0628	−5.50	0.000	−0.3319***
INDS	0.4121*	0.2154	1.91	0.056	0.4037***
TRD	−0.3756***	0.1439	−2.61	0.009	−0.3502***
FDI	−0.0238	0.0161	−1.48	0.139	−0.0290
ETO	−1.6491***	0.1289	−12.79	0.000	−1.3872***
GDPP	0.5680**	0.2908	1.95	0.051	0.5417***
Constant	23.9990***	3.3231	7.22	0.000	23.1056***
Observations	189				
Cross-sections	7				
R-square	0.8092				
Wald Chi-square	771.93				
Chi-square Prob.	0.000				

Note: SE: standard errors, DK: Driscoll-Kraay. *, **, and *** indicate the significance levels of 10%, 5%, and 1%, respectively.

Table 5
Panel data estimates of Regression Model 2 (Dependent variable: CO_2 intensity).

	GLS-RER estimation				DK robustness
Variables	Coefficients	SE	T-statistic	Probability	Estimates
ETR	−0.2765***	0.0725	−3.81	0.000	−0.2618***
INDS	0.1144	0.2372	0.48	0.630	0.1082
TRD	−0.3390*	0.1850	−1.83	0.067	−0.3219***
FDI	−0.0136	0.0180	−0.76	0.448	−0.0115
ETE	−1.3251***	0.1377	−9.63	0.000	−1.3028***
GDPP	0.2515	0.3327	0.76	0.450	0.2478
Constant	18.8193***	3.6732	5.12	0.000	23.3682***
Observations	189				
Cross-sections	7				
R-square	0.8199				
Wald Chi-square	876.11				
Chi-square Prob.	0.000				

Note: SE: standard errors, DK: Driscoll-Kraay. * and *** indicate the significance levels of 10% and 1%, respectively.

GHG. However, FDI established no causal linkage with both dependent variables. These findings are consistent with our main estimation results, suggesting that our study has revealed logical relationships in the four estimated models, which are reliable for policy implications.

5. Discussion

According to the *first finding*, both types of green taxes successfully mitigate CO_2 intensity and GHG, with more prominent effects for overall green taxes compared to the green taxes in the energy sector. The justification of this finding is straightforward: increased green taxation increases the cost of polluting the environment for producers, provoking them to spend on environmentally friendly solutions to curtail environmental emissions, promoting low-carbon development. This finding lends credence to Ofori et al. (2023), who confirmed the CO_2 mitigation effects of environmental taxes in the E7 countries, claiming that the polluter pays principle induces the manufacturers to invest in clean technologies and energy-efficient solutions to protect the environment. This finding also aligns with the outcome of Khaddage-Soboh et al. (2023), as they evidenced the negative influence of environmental taxation on CO_2 across G7 countries, stating that industries were inclined to spend on environmental protection practices in response to market-based taxation tools. Likewise, Sadiq et al. (2024) also observed the same findings while exploring the carbon taxation-CO_2 linkage: the former drove down the latter in BRICS economies. In the actual scenario, several types of green taxes exist in G7 countries, including fuel taxation, pollution taxation, vehicle taxation, carbon taxation, and emissions trading schemes, among others.

Table 6
Panel data estimates of Regression Model 3 (Dependent variable: GHG).

	GLS-RER estimation				DK robustness
Variables	**Coefficients**	**SE**	**T-statistic**	**Probability**	**Estimates**
ETR	−0.3748***	0.0583	−6.43	0.000	−0.3641***
INDS	0.7894***	0.1996	3.95	0.000	0.7695***
TRD	−0.2432*	0.1334	−1.82	0.068	−0.2310***
FDI	−0.0192	0.0149	−1.29	0.198	−0.0125
ETO	−1.7208***	0.1196	−14.39	0.000	−1.5832***
GDPP	0.8000***	0.2696	2.97	0.003	0.7268***
Constant	27.4117***	3.0818	8.89	0.000	27.1023***
Observations	189				
Cross-sections	7				
R-square	0.8242				
Wald Chi-square	853.29				
Chi-square Prob.	0.000				

Note: SE: standard errors, DK: Driscoll-Kraay. * and *** indicate the significance levels of 10% and 1%, respectively.

Table 7
Panel data estimates of Regression Model 4 (Dependent variable: GHG).

	GLS-RER estimation				DK robustness
Variables	**Coefficients**	**SE**	**T-statistic**	**Probability**	**Estimates**
ETR	−0.3066***	0.0688	−4.46	0.000	−0.2912***
INDS	0.4858**	0.2249	2.16	0.031	0.4657***
TRD	−0.1943	0.1755	−1.11	0.268	−0.1829
FDI	−0.0088	0.0170	−0.52	0.606	−0.0057
ETE	−1.3920***	0.1306	−10.66	0.000	−1.3584***
GDPP	0.4857	0.3156	1.54	0.124	0.4621
Constant	22.1660***	3.4840	6.36	0.000	21.5680***
Observations	189				
Cross-sections	7				
R-square	0.7935				
Wald Chi-square	695.57				
Chi-square Prob.	0.000				

Note: SE: standard errors, DK: Driscoll-Kraay. ** and *** indicate the significance levels of 5% and 1%, respectively.

Table 8
Panel bootstrap causality results.

	H_0: *X* does not cause *Y*					H_0: *Y* does not cause *X*			
	Statistic	**Bootstrap critical score**				**Statistic**	**Bootstrap critical score**		
		@1%	**@5%**	**@10 %**			**@1%**	**@5%**	**@10 %**
ETR→CO_2	45.72***	42.10	24.29	10.35	CO_2 → ETR	7.31	38.19	18.25	9.35
INDS→CO_2	13.25*	39.21	18.16	8.74	CO_2 → INDS	8.49	48.21	24.57	11.23
TRD→CO_2	21.13**	40.25	19.32	8.99	CO_2 → TRD	6.08	32.15	23.62	9.01
FDI→CO_2	8.33	54.28	31.19	10.56	CO_2 → FDI	10.22	51.56	30.87	12.19
ETE→CO_2	49.11***	45.84	27.35	11.19	CO_2 → ETE	8.51	31.39	20.85	9.37
ETO→CO_2	45.27***	43.29	25.10	10.38	CO_2 → ETO	8.00	33.08	22.80	9.14
GDPP→CO_2	31.57**	50.15	31.09	10.22	CO_2 → GDPP	10.36	55.84	33.54	11.99
ETR→GHG	48.55***	47.68	29.51	11.05	GHG→ETR	7.38	44.31	21.25	8.20
INDS→GHG	12.18*	37.45	19.23	9.66	GHG→INDS	9.22	48.17	29.24	10.78
TRD→GHG	10.49*	36.59	17.58	8.97	GHG→TRD	8.10	38.12	18.97	9.26
FDI→GHG	9.17	50.10	32.75	11.81	GHG→FDI	7.33	51.37	34.28	9.31
ETE→GHG	58.33***	53.89	30.64	10.95	GHG→ETE	8.05	29.11	17.31	10.35
ETO→GHG	52.71***	51.35	29.16	11.34	GHG→ETO	7.96	32.07	15.88	9.26
GDPP→GHG	11.74*	41.57	24.12	8.90	GHG→GDPP	10.51	59.26	33.64	11.58

Note: *, **, and *** indicate the significance levels of 10%, 5%, and 1%, respectively.

Regarding the *second finding*, sustainable energy transition tends to attain low-carbon development goals by reducing CO_2 intensity as well as GHG in all the model specifications, supporting SDG13 (i.e., Climate Action Plan). Transitioning to sustainable energy alternatives plays a dual role in that, on the one hand, it replaces the nonrenewable natural resource consumption with clean energy consumption. On the other hand, it increases the aggregated renewable energy sources, which are carbon neutral, thereby driving down the CO_2 intensity and GHG on the whole. This finding supports those of Saqib and Dincă (2024) since they observed the carbon mitigation effects of renewable energy utilization in the case of China, France, Germany, Japan, the UK, South Korea, Spain, India, the USA, and Italy. Conversely, Battisti (2023) revealed some distinguished results, evidencing that though renewable energy consumption was a strong driver of GHG reduction in the OECD as well as non-OECD countries, they will achieve this objective in partial by 2050. Herein, Imran et al. (2024) pinpointed a crucial viewpoint that though nuclear energy deploy-

ment mitigated CO_2 in 29 economies from Europe and Asia, the absence of appropriate R&D financing in the renewable energy sector impeded those mitigation levels.

Concerning the control variables, international trade promoted the low-carbon development in G7 countries, supporting the technology transfer effect of international trade. Through trading activities, countries transfer technology and knowledge to their trade partners, which equip the managerial strategies with energy-efficient features, improving industrial cleaner production and promoting environmental quality. The transfer of improved and advanced ecological technologies enables the trade partnering countries to increase industrial productivity through technological sophistication, inducing those industries to adopt green and innovative production modes to protect environmental sustainability. In contrast, Haibara (2024) showed that domestic adverse environmental externalities were supportive of the climatic effects of trade in the US and China. Nevertheless, in parallel to our finding, Jiang et al. (2023) uncovered that international trade promoted green growth, hence promoting a low-carbon development agenda in E7 nations. In contrast, industrialization is found to deter environmental quality by propagating CO_2 intensity and GHG. It shows that the industrial sector of the sampled G7 nations is still more dependent on fossil fuels, which degrade the environmental integrity through pollutant emissions. Consistent with this outcome, Aladejare and Nyiputen (2023) claimed the ecological deterioration effects of industrialization in 32 African economies. Unlike our result, Ali et al. (2023) exhibited that industrialization was an inhibitor of CO_2 intensity in Saudi Arabia.

Furthermore, GDPP is revealed as a detrimental factor to achieving low-carbon development goals, indicating that G7 countries' economic progress drive is still stronger than ecological concerns and net-zero emissions goals. This finding is inconsistent with the EKC hypothesis, claiming the initial deterioration of environmental quality in response to GDP growth, followed by ecological revival driven by further economic progress. However, this outcome supports those of Raihan et al. (2023), who experienced ecological destruction effects of economic output in the Egyptian context. Likewise, Jiang and Yu (2023) empirically emphasized the fact that economic progress and CO_2 were driving forces for each other in China. Eventually, foreign investments demonstrated a neutral effect on CO_2 intensity and GHG and remained unable to explain variations in those variables. It can be attributed to the scenario that the scale and composition effects of foreign investments may be nullified by the technique and technology transfer effects of those investments, thereby producing their neutral effects on low-carbon development. Unlike our finding, Yue et al. (2023) unveiled that foreign direct investment affirmatively drove shadow prices of pollutant emissions in China, promoting environmental sustainability. Besides, Yi et al. (2023) concluded that foreign investment was fruitful to CO_2 mitigation in the industrial sector, particularly the labor-intensive manufacturing industries in China, implying that those investments were more helpful in transferring green human resource practices across Chinese manufacturing industries.

6. Conclusions

This research examined the contributions of green taxation as well as sustainable energy transition on the low-carbon development objective of G7 countries over the 1994–2020 period. For analysis purposes, this research applied regression analysis based on GLS-RER and DK-OLS estimation strategies. To investigate the causality directions, we employed a novel panel bootstrap causality test. Given our analytical outcomes, the main conclusions are drawn as follows.

First, environmentally related tax revenues in both forms improved the environmental quality by reducing carbon emissions intensity and greenhouse gas emissions. Concerning the intensity of effects, the overall environmentally related tax revenues had a more substantial effect than those of tax revenues in the energy sector. Furthermore, both environmentally related tax revenue variables contributed relatively more to greenhouse gas emissions than to carbon emissions intensity. Second, sustainable energy transition was helpful in reducing carbon emissions intensity and greenhouse gas emissions. Among the rest of the control variables, international trade was supportive of low-carbon development and GHG reduction. However, industrialization and GDP per capita increased those emissions, while foreign investments had a neutral effect in all the models. Finally, panel bootstrap causality results revealed that a unilateral relationship was found running from all variables, except for foreign direct investment, to both CO_2 intensity and greenhouse gas emissions.

Based on empirical results, the following policy implications are obtained.

Firstly, the findings showed that the environmental policies in G7 countries were supportive of the low-carbon development targets. In this regard, the environmentally related taxes were more favorable for the environmental emissions reduction in the G7 countries. Therefore, it is suggestable to keep on employing emissions taxation policies such as carbon tax to ensure industrial emissions reduction for a zero-carbon future. G7 members can enhance the depth of green taxation to have more viable and accelerated environmental benefits. In addition to carbon taxation, an ecotax can be implemented on the production of environmentally hazardous products, discouraging the companies from adopting environmentally sustainable production modes by the polluter pays principle. Likewise, energy taxes should be applied on a discriminatory basis in that fossil-based energy consumption should be taxed more than renewable energy consumption. Similarly, to mitigate traffic congestion and transport energy consumption, transportation taxes would be helpful in low-carbon development. Besides, waste disposal taxes would prevent the production of alarming levels of waste, diverting the economy to a circular economy and ultimately promoting a low-carbon transition. *Secondly*, the sustainable energy transition policies involving the rapid increase of renewables in the total energy mix are effective in reducing environmental emissions. Thus, low-carbon development impacts of sustainable energy transition can be achieved by (i) deviating resources from fossil-based energy production to renewable and green energy production and consumption through phasing out fossil energy policies to culminate the sustainable development goal of environmental sustainability; (ii) cultivating energy-efficient technologies in industrial, building, and transportation sectors to reduce fuel cost and mitigated utilization of energy to promote low-carbon agenda; (iii) promoting green transport systems by cutting taxes on manufacturing electric vehicles and building charging infrastructure for long-term economic-environmental development. Aligned with these policy proposals, some of the G7 countries opt for ambitious plans to achieve sustainable energy transition. In this regard, Germany has introduced the *Renewable Energy Act*, which aims to subsidize the manufacturing of green power generators. Additionally, to gain 100% clean energy by 2050, the French government has implemented the *French Energy Transition Law*, which subsidizes a diverse range of renewable energy deployment projects. In the bottom line, implementing and operationalizing those and upcoming green taxation and sustainable energy transition policy initiatives would pave the pathways to low-carbon development in G7 members.

Despite extending significant contributions to the modern literature, this research has some limitations that need the attention of follow-up studies. *First*, this research has used the market-based

instruments of green taxation involving overall green taxes and those of the energy sector, which provide an insightful picture of the market forces-driven impacts of green taxation on low-carbon development. However, non-market solutions could also play a potential role in achieving a carbon–neutral economy. Hence, future studies must include some non-market instruments to investigate their prospective influence on environmental quality. *Second*, this research utilized the average impact estimator, which gives an overall idea of the impact mechanisms of green taxation and sustainable energy transition on low-carbon development; however, it cannot account for those effects across diversified quantile levels. Thus, it is suggested that future studies employ a quantile regression estimator to deal with this issue for even better and fruitful policy implications at various low-carbon development scales. *Third*, this research accounted for CO_2 intensity and GHG as the indicators of low-carbon development, while there exist air quality and water-based emissions that could potentially contribute to carbon neutrality goals. Therefore, future studies may devise a comprehensive environmental pollution index to capture those effects in a multidimensional context. *Finally*, this research has taken G7 countries as a sample, which makes it a regional study. These nations are representative of the developed world because of their environmental protection and sustainable energy transition measures. Nonetheless, there is a huge discrepancy between the developing and developed world in terms of renewable energy investment and environmental regulations. Therefore, future studies need to cover the sample representative of the global economies with better representative empirical results and their associated policy outcomes.

CRediT authorship contribution statement

Gul Jabeen: Conceptualization, Formal analysis, Writing – original draft. **Dong Wang:** Investigation, Supervision, Validation, Writing – review & editing, Funding acquisition, Project administration. **Stefania Pinzón:** Investigation, Methodology, Writing – review & editing. **Cem Işık:** Data curation, Investigation, Software, Writing – review & editing. **Munir Ahmad:** Formal analysis, Methodology, Software, Visualization, Writing – review & editing. **Ali Rehman:** Data curation, Investigation, Validation, Writing – review & editing. **Muhammad Khalid Anser:** Investigation, Methodology, Software, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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