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Revaluating the Sustainable Development Thesis: exploring the moderating influence of Technological Innovation on the impact of Foreign Direct Investment (FDI) on Green Growth in the OECD Countries

Germain Stephane Ketchoua[1] · Sodiq Arogundade[1] · Biyase Mduduzi[1]

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Abstract
The Sustainable Development Goals (SDGs) advocate for advancing green growth, a concept that balances economic prosperity with environmental protection. At the core of this vision are principles of sustainable consumption, production, and energy usage, all aimed at mitigating climate change and safeguarding ecosystems. This study investigates how technological innovation influences the relationship between Foreign Direct Investment (FDI) and green growth in OECD member countries. Specifically, we examine two facets of green growth: production-based CO_2 productivity and demand-based CO_2 productivity. We employ empirical analyses using the EKC and STIRPAT framework, which includes Ordinary Least Squares (OLS), smoothed instrumental-variables quantile regression (SIVQR), and System GMM methodologies, to uncover significant insights. Our analysis reveals that FDI impedes green growth, while technological innovation is pivotal in enhancing it. This pattern holds steady across various time frames and renewable energy sources. Furthermore, our findings indicate that combining FDI and technological advancement leads to heightened production-based CO_2 productivity but diminished demand-based CO_2 productivity. We also identify the presence of an environmental Kuznets curve for production-based CO_2 productivity. Adding to significant scientific value by demonstrating how technological innovation moderates FDI's impact on green growth in OECD countries, we advocate for fostering collaborative partnerships between foreign investors and local innovators to leverage global expertise while advancing green objectives. Additionally, policy interventions should focus on stimulating demand for eco-friendly products and services to bolster demand-based CO_2 productivity.

Keywords Green economy · FDI · Technological innovation · OECD

1 Introduction

Economists and environmentalists have long been aware that the current economic growth path places immense strain on the natural environment, thereby threatening long-run economic development. Debates on the unintended consequences of pursuing growth at all costs have underscored the need to consider a growth path that signifies resilience, inclusivity, and sustainability as a critical policy imperative. There is a view that green growth is one of the key strategies that policymakers can use to stimulate the economy and achieve climate objectives simultaneously.

✉ Sodiq Arogundade, arogundadesodiq8@gmail.com; Germain Stephane Ketchoua, 672896728stephan@gmail.com; Biyase Mduduzi, mbiyase@uj.ac.za | [1]School of Economics, College of Business and Economics, University of Johannesburg, Johannesburg, South Africa.

The Organisation for Economic Co-operation and Development (OECD) defines green growth as fostering economic growth and development while ensuring that natural assets continue to provide the resources and environmental services essential to our well-being [1].

Moreover, the relevance of green growth is deeply embedded in the Sustainable Development Goals (SDGs), which promote a balance between economic prosperity and environmental protection [2–4]. Aligning green growth with the SDGs can provide a roadmap for sustainable economic development, ensuring that investments and policies contribute to long-term environmental sustainability. Despite the growing global emphasis on green growth, the impact of economic growth and Foreign Direct Investment (FDI) on achieving this objective remains a contentious issue. Designing effective policies for green growth requires a nuanced understanding of the key factors influencing this growth, with economic growth and FDI being significant factors. Economic growth has long been a double-edged sword for environmental quality. On one hand, it can provide the necessary resources for investing in cleaner technologies and improving environmental standards.

On the other hand, unchecked economic expansion often leads to increased resource consumption, higher emissions, and greater environmental degradation [5, 6]. The relationship between economic growth and environmental quality is complex and varies across different contexts. In many cases, economic growth initially leads to environmental deterioration. Still, as economies mature, there is a shift towards more sustainable practices, a concept known as the Environmental Kuznets Curve (EKC) [7, 8]. Understanding this dynamic is crucial for policymakers aiming to balance economic development with environmental sustainability. This study explores this intricate balance, particularly how technological innovation moderates the effect of Foreign Direct Investment (FDI) on green growth in OECD countries.

The novelty of this paper is evident through its exploration of the moderating influence of technological innovation on the impact of FDI on green growth, which is a gap in the current literature. By examining both production-based and demand-based CO_2 productivity, the study provides a comprehensive understanding of green growth dynamics. Employing advanced methodologies like smoothed instrumental-variables quantile regression (SIVQR) and System GMM offers new empirical insights, contributing significantly to the existing body of knowledge. Peer review documents suggest that technological innovation is pivotal in enhancing eco-efficiency and promoting green growth, playing a dual role in mitigating environmental degradation while simultaneously driving economic progress. For instance, Wang et al. [9] and Zhang & Zhou [10] argue that aligning foreign investment with the host economy's technological capabilities can significantly reduce CO_2 emissions.

Similarly, studies by Bakhsh [11], Radmehr et al. [12] and Zhao et al. [13]emphasize that technological innovation can transform investment into a catalyst for green growth, particularly in regions with robust innovation ecosystems. These technological advancements foster the adoption of cleaner practices, contributing to production and demand-based CO_2 productivity. Consequently, understanding the role of technological innovation is crucial for devising policies that leverage FDI for sustainable development.

The ongoing surge of FDI in OECD economies has ignited debates about its environmental ramifications. Theoretical literature presents conflicting viewpoints on the correlation between FDI and environmental pollution. On one hand, it is argued that FDI influx into countries with lax environmental regulations may exacerbate ecological degradation. This perspective aligns with the pollution haven hypothesis (PHH) first proposed by Brian et al. [14], suggesting that globalization allows firms from countries with strict environmental standards to relocate their polluting activities to countries with less stringent regulations. Conversely, an opposing perspective emphasizes that FDI fosters technological advancements within host countries, thereby improving environmental conditions [15, 16]. Understanding these conflicting views is essential for developing policies that leverage FDI to support green growth without compromising environmental integrity.

In this context, technological innovation improves the eco-efficiency of Foreign Direct Investment (FDI) and instigates structural transformations within industries, influencing their environmental impact. Also, technological spillovers from foreign firms can catalyze domestic innovation capabilities, creating a positive cycle of green technological advancement. However, the extent to which technological innovation mitigates the impact of FDI on the environment and promotes green growth varies among OECD sub-regions due to contextual differences in regulatory frameworks, market structures, and technological capabilities. For example, in regions with stringent eco-role and robust innovation ecosystems, FDI inflows may catalyze the adoption of cleaner technologies and practices, thereby promoting green growth. Conversely, FDI might result in heightened pollution levels and environmental degradation in areas characterized by lenient environmental standards and limited technological capacities.

The relationship between technological innovation, foreign direct investment (FDI), and the green economy, particularly within OECD countries, is not extensively covered in existing literature. This gap is crucial because technological innovation can mitigate or exacerbate the environmental impacts of FDI, depending on the context. In addition, the United Nations Sustainable Development Goals (SDGs) provide a comprehensive framework for achieving sustainable development globally. This study aligns with several SDGs, particularly SDG 9 (Industry, Innovation, and Infrastructure), SDG 13 (Climate Action), and SDG 17 (Partnerships for the Goals). Consequently, by examining how technological innovation shapes the influence of FDI on green growth in the OECD sub-region, this research enhances our understanding of how economic activities can support sustainable development. Specifically, we examine two dimensions of green growth: production-based CO_2 productivity and demand-based CO_2 productivity. To gain meaningful insights into these dynamics, we utilize a range of methodologies.

This research uniquely contributes to environmental economics literature, offering numerous implications and far-reaching impacts. It breaks new ground by investigating the effects of FDI on green growth within OECD member countries. By exploring this relationship using two measures of green growth—production-based CO_2 productivity and demand-based CO_2 productivity—the study provides a comprehensive understanding of the dynamics of carbon emissions. Production-based metrics focus on emissions generated within a country's borders, while demand-based metrics consider emissions embedded in goods and services consumed domestically. Integrating both perspectives enables a holistic assessment of a nation's carbon footprint, facilitating the development of targeted policies addressing production, consumption, and trade-related emissions to mitigate climate change and promote sustainable development effectively.

Additionally, by acknowledging the role of countries' development, the study employs SIVQR (Semi-Parametric Instrumental Variable Quantile Regression) to investigate the nexus across different development levels. This approach provides nuanced insights into varying stages of development, enhancing our understanding of how economic policies and growth trajectories differ globally. Consequently, this method improves the robustness and applicability of the findings across diverse economic contexts. Moreover, the study examines how technological innovation influences the relationship between FDI and green growth. On one hand, this investigation sheds light on whether technological advancements can offset the potential negative environmental impacts of FDI and promote sustainable development.

On the other hand, it provides insights into the dynamics of green growth, informing policymakers on how to leverage FDI and innovation synergies to achieve environmentally sustainable economic growth. Lastly, accounting for time differences in examining this relationship enriches the literature by capturing the dynamic and evolving nature of these relationships. This approach reveals how the impact of FDI on sustainable development changes over time, identifies lag effects, and highlights long-term trends. It enhances the understanding of temporal factors influencing green growth, offering more nuanced and policy-relevant insights into the economic-environmental interplay.

The remainder of the paper unfolds as follows: Sect. 2 provides a concise literature review, followed by Sect. 3, which outlines the data and methodology utilized. Section 4 delves into the findings, and Sect. 5 offers concluding remarks.

2 Literature review

This section examined the theoretical and empirical literature on the nexus between FDI and the green economy. Several hypotheses and accounts on the nexus between FDI and environmental quality have been established in the literature. The nature of the relationship between the two variables can be summarised into two hypotheses called the pollution halo and pollution heaven hypothesis. The proponent of the pollution haven hypothesis asserts that foreign investors essentially take advantage of loosened environmental-related rules in these developing countries by bringing pollution-intensive production units [17]. Supporters of this view, such as Anyanwu [18], also identified factors such as cheap labour and abundant natural resources as the drivers of this process.

However, some scholars have identified a different perspective, named the pollution halo hypothesis. Followers of this view argue that multinational corporations employ clean technologies in their production processes, thereby contributing to a clean environment [19]. Furthermore, proponents of this viewpoint also emphasize that introducing clean technology has the dual benefits of improving the environment in the host nation and generating jobs through the transferring or linkage effect [20].

Although the perspective of these theories is explanatory and convincing, most scholars do not generally accept their adequacy. The empirical literature on the nexus between FDI and the environment makes the heterogeneity of opinions more apparent. Empirical studies have produced inconsistent results, with a considerable number of studies indicating a positive relationship and a few indicating a negative impact [21]. Some studies argue that the nature of the relationship is characterized by nonlinear or inverted U-shaped patterns, supporting the Environmental Kuznets Curve (EKC) theory.

A good portion of this empirical research, primarily from developing countries, accepts the pollution haven theory. For instance, using the quantile model, Chowdhury et al. [22] accepted the pollution haven hypothesis and argued that FDI positively and significantly impacts the environmental quality of 92 countries. In the same vein, Sabir et al. [23] used the panel autoregressive distributed lag (ARDL) method to examine the short-run and long-run impact of FDI on the environment in a sample of South Asian countries; the study discovered that FDI increases environmental degradation of the countries. Balsalobre-Lorente et al. [24] found similar results, stating that FDI improves air quality as multinational corporations bring cleaner and more efficient technology capable of reducing energy consumption. Similarly, empirical outcomes were observed for Udemba [25] for Turkey, Solarin et al. [26] for Ghana, and Ahmed et al. [27] for a sample of Asia–Pacific countries. Shahbaz et al. [28] examined the impact of FDI, financial development and energy innovations on environmental degradation in France. Using a Fourier ARDL model, the study discovers that FDI deteriorates environmental quality, thereby attesting to the pollution-haven hypothesis.

However, a couple of empirical papers support the pollution halo hypothesis. For instance, Tang and Tan [17] analyzed the relationship between $C0_2$ emission, energy consumption, FDI and economic growth in Vietnam. The study confirms the existence of the pollution halo hypothesis, i.e., FDI improves environmental quality in Vietnam. Similarly, Al-Mulali and Tang [19] investigated the validity of the pollution haven hypothesis in the Gulf Cooperation Council (GCC) countries using Fully Modified OLS. The results suggest that foreign direct investment inflows have a long-run negative relationship with CO_2 emission. Similar empirical outcomes were observed for Kirkulak et al. [29] and Tamazian and Rao [30]. Caglar et al. [31] also examine the impact of economic growth, trade openness, renewable energy, human capital, and competitive industrial performance on the load capacity factor for EU countries. Using the CUP-FM and CUP-BC methodologies that address heterogeneity and cross-sectional dependence, the study lends credence to the pollution haven hypothesis and argues that economic growth, trade openness, and competitiveness worsen environmental quality. In Turkiye, Yavuz et al. [32] also discovered that gross domestic product, natural resource rents, and primary energy consumption accelerate environmental degradation using the newly developed Augmented Autoregressive Distributed Lag (A-ARDL) with Fourier term.

Some studies support the environmental Kuznets curve (EKC) hypothesis despite the evidence supporting the pollution haven and pollution halo hypotheses. According to these studies, environmental degradation occurs when economic growth occurs (through FDI), and a cleaner environment cannot be attained until FDI reaches an appropriate level. For example, Destek and Okumus [33] used second-generation panel data analysis on newly industrialized countries. The findings reveal that FDI has a U-shaped relationship with the ecological footprint. Similarly, Sapkota and Bastola [34] investigated the effect of FDI on pollution emissions in Latin American countries using a fixed-effect model. The study validated the EKC hypothesis. Studies such as Shahbaz et al. [28] and Doytch and Uctum [35] also conclude that FDI and environmental quality have an inverted U-shape relationship.

Furthermore, some studies have begun to examine the role of intermittent variables on the impact of FDI on the environment. Starting with the study by Caetano et al. [36] which analyzed how the energy transition mediates the role of FDI in the green economy. The study concludes that energy transition modulates the impact of FDI on the green economy. Qamri et al. [37] also examined the role of financial development and economic growth on the impact of FDI on the green sector of 21 Asian countries. Using a panel econometric method, the study discovers that economic growth and financial development mediate the positive impact of FDI on the green economy. Padhan and Bhat [38] examined the link between FDI and the environmental quality of BRICS and NEXT-11 using green innovation as an intermittent variable. Using a Driscoll–Kraay (DK) standard error model, the study reveals that green innovation modulated the negative impact of FDI on the environment, indicating that the presence of green innovation and FDI proves the existence of the pollution halo hypothesis. Ofori et al. [39] examined how energy efficiency mediates the impact of FDI on inclusive green growth in Africa. Using a dynamic GMM estimator, the study discovers that energy efficiency reduces the deteriorating impact of FDI on inclusive green economic growth.

While the literature is replete with unremitting debate on the link between FDI and the green economy, there is limited literature on the role of technological innovation on the impact of FDI on the green economy. This study contributes to the extant literature by (1) examining the impact of FDI on the green economy in OECD countries and (2) investigating the role of technological innovation on the nexus between FDI and the green economy.

Table 1 Descriptive Statistics

Variable	Obs	Mean	Std. Dev	Min	Max
PP	999	5.424	2.631	1.05	17.98
DP	999	4.04	1.367	1.31	14.213
FDI	999	50.861	98.052	0.22	2062.057
GDP	999	30,327.281	22,825.76	2167.792	133,711.8
Renewable energy	999	18.797	15.915	0.44	82.79
Solar thermal energy	825	18.418	36.094	0.333	323.333
Wind energy	868	32.151	62.045	0.25	388.3
Globalization	999	77.581	8.977	46.508	90.929
Technology innovation	978	736.156	1862.585	0.167	10,805.966
Urbanisation	999	76.538	10.871	50.622	98.117

3 Methodology

3.1 Data

The study's analysis relies on a dataset comprising 37 OECD countries[1] spanning the years 1995 to 2021. The countries were chosen based on the availability of data during the study period. The OECD countries are typically regarded as advanced economies characterized by high-income levels, stable institutions, and robust statistical systems. This makes them an ideal representative sample for studying economic, social, and environmental trends in developed nations. While the period under consideration includes various economic cycles—growth, recession, and recovery—and encompasses significant policy changes in areas such as globalization, trade, fiscal policy, and social policy. This provides a valuable context for examining long-term trends and assessing the impact of economic cycles and policy shifts on different variables.

The data for green growth, Solar thermal energy, Wind energy, and technological innovation are drawn from the OECD database. The data for globalization is obtained from the KOF Swiss Economic Institute database. The remaining data utilized in the study was obtained from the World Bank's World Development Indicators. Table 1 presents the variables' characteristics in terms of mean, standard deviation, minimum, and maximum values, while Table 2 illustrates the correlations among the variables.

3.2 Justification of variables

3.2.1 Dependent variable

Our dependent variable of interest is the green growth proxy by production-based CO_2 productivity, and demand-based CO_2 productivity aligns with SDG indicators for climate action and sustainable consumption and production patterns. Production-based CO_2 productivity is determined by measuring the real GDP generated per unit of CO_2 emitted (expressed in USD/kg). This includes emissions from the combustion of coal, oil, natural gas, and other fuels. On the other hand, demand-based CO_2 productivity reflects the CO_2 emissions from energy use throughout the diverse stages of producing goods and services consumed within domestic final demand, regardless of where these production stages occurred. Both measures provide insights into the sustainability and environmental impact of economic growth. Appendices 3 and 4 show the production-based and demand-based CO_2 productivity across the OECD countries.

3.2.2 Independent variables

The independent variable of the study is foreign direct investment (FDI). Foreign Direct Investment (FDI) involves investment in a business by an entity from another country, facilitating capital flow and technology transfer. FDI can influence

[1] Australia, Belgium, Canada, Chile, Colombia, Costarica, Czech, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Isreal, Italy Japan, Korea, Latvia, Lithaunia, Luxembourg, Mexico, Netherlands, New zealand, Norway, Poland, Portugal, Slovakia, Slovenia, Spain, Sweden, Switzerland, Turkey, United Kingdom, United States.

Table 2 Matrix of correlations

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
(1) PP	1.000									
(2) DP	0.825	1.000								
(3) FDI	0.185	0.171	1.000							
(4) GDP	0.253	0.095	−0.030	1.000						
(5) renewable energy	0.475	0.313	−0.002	0.137	1.000					
(6) Solar thermal energy	0.018	0.016	0.037	0.088	−0.114	1.000				
(7) Wind energy	0.123	0.085	−0.070	0.127	0.089	−0.035	1.000			
(8) Globalization	0.199	0.071	0.234	0.123	−0.079	−0.024	0.064	1.000		
(9) Tech-innovation	−0.104	−0.074	−0.052	0.053	−0.140	0.040	0.052	0.152	1.000	
(10) Urbanization	−0.019	−0.088	0.108	0.270	0.042	0.026	0.034	0.178	0.020	1.000

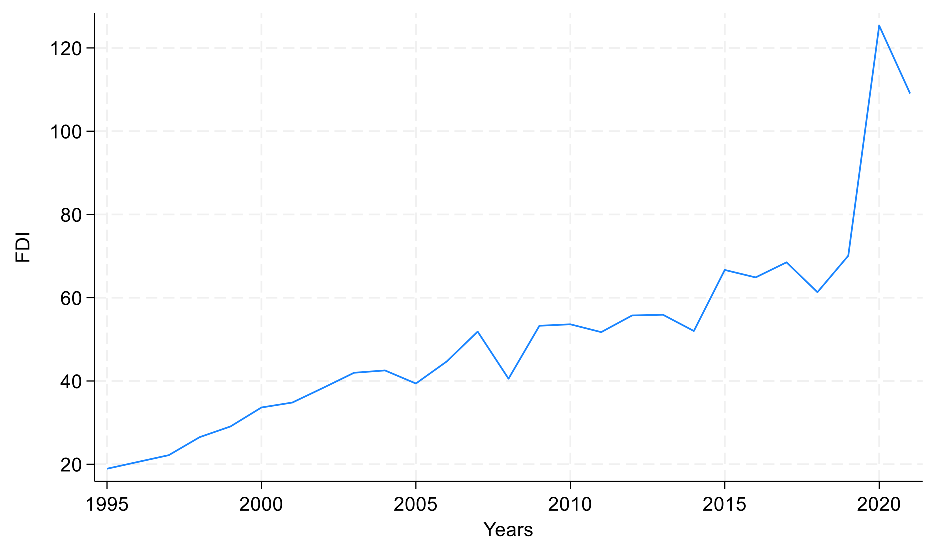


Fig. 1 The trend of FDI in the OECD countries. Source: Authors' computation from WDI database

green growth positively by introducing sustainable technologies, enhancing environmental standards, and promoting renewable energy [2, 3]. Additionally, it can stimulate economic development, leading to increased demand for green products and services. However, without proper regulations, FDI might also exacerbate environmental degradation due to relaxed environmental standards or exploitation of natural resources.

Figure 1 presents the trend of FDI, while Fig. 2 presents a correlation analysis between FDI and green growth proxy by production-based CO_2 productivity (PP) and demand-based CO_2 productivity (DP) in the OECD countries. The correlation analysis serves as preliminary findings on the nature of the relationship between FDI and green growth. The scatter plot indicates a positive effect of FDI on production-based CO_2 productivity (PP) and demand-based CO_2 productivity. The findings on the nature of this relationship are further experimented with using the instrumental quantile regression that accounts for initial levels of FDI and also addresses potential endogeneity.

3.2.3 The moderating variable

The moderating variable of the study is technological innovation to assess progress toward SDG 9. Technological innovation refers to the development of new or improved technologies, processes, or products that enhance efficiency, productivity, or functionality [13, 40]. In the context of green growth, technological innovation plays a pivotal role by enabling the creation of sustainable solutions. Advancements in green technology, waste management, and resource-efficient technologies mitigate environmental impact, reduce carbon emissions, and promote eco-friendly practices [41, 42]. Such innovations drive economic growth while preserving natural resources, fostering a greener

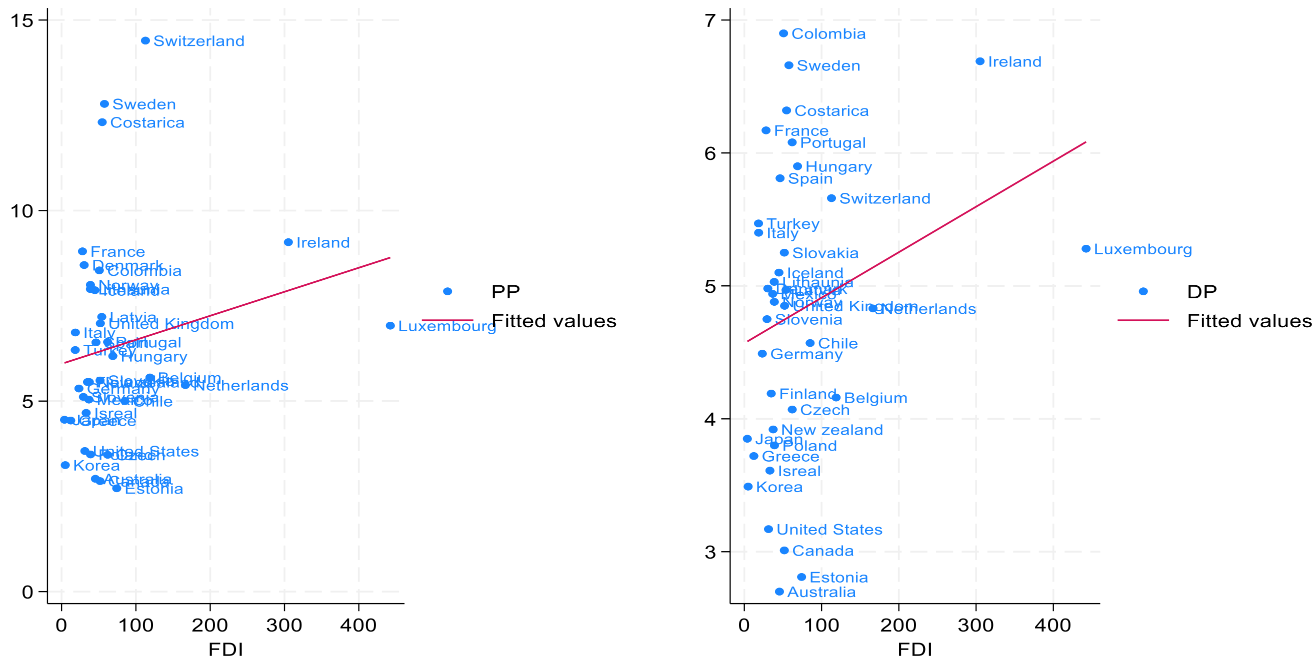
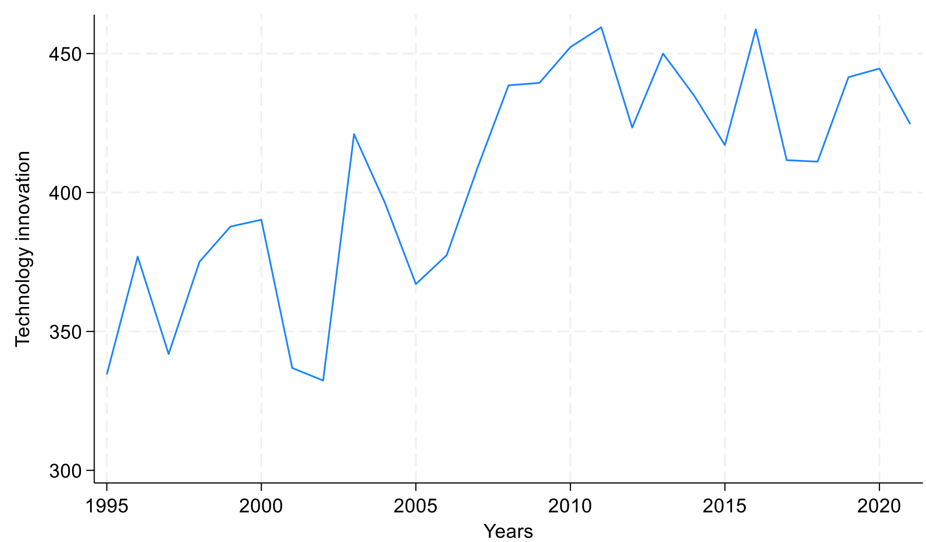


Fig. 2 The correlation between FDI and green growth. Source: Authors' computation

Fig. 3 The trend of technology innovation in the OECD countries. Source: Authors' computation from the OECD database



and more sustainable future. The study uses patents as a proxy for technological innovation. Figure 3 shows the evolution of technology innovation in the OECD countries.

3.2.4 Control variables

The selection of the control variables is based on the environmental sustainability literature. First, GDP per capita, a measure of economic output per person, affects environmental sustainability from its reliance on resource consumption and production. High GDP often correlates with increased resource extraction, energy use, and waste generation, contributing to environmental degradation and climate change [5]. Second, renewable energy consumption (% of total final energy consumption) promotes environmental sustainability by reducing greenhouse gas emissions, mitigating air and water pollution, and minimizing dependence on finite fossil fuel resources. It contributes to climate change mitigation and fosters a transition towards cleaner, more sustainable energy systems, thereby preserving ecosystems and enhancing the planet's health. Third, globalisation impacts the green economy through increased trade and industrialisation, leading to resource depletion, pollution, and unequal distribution of environmental burdens and benefits, necessitating comprehensive global and local action [43–45]. Fourth, urbanization, indicated by the urban population as a percentage of the total population impacts green growth by intensifying resource consumption, pollution, and habitat fragmentation [46, 47]. Increased infrastructure development often leads to land degradation and loss of biodiversity. However, well-planned urbanization can promote sustainability by fostering compact, efficient cities with green spaces, public transportation, and renewable energy integration.

3.3 Theoretical and estimation strategy

The theoretical foundation of this paper is grounded in the pollution halo and pollution haven hypotheses (see Brian et al. [14]; Tang and Tan [17]; Al-Mulali and Tang [19]), as well as the Environmental Kuznets Curve (EKC) hypothesis and the Stochastic Impacts by Regression on Population, Affluence, and Technology (STIRPAT) framework [47–49]. The EKC hypothesis postulates an inverted U-shaped relationship between environmental degradation and economic growth. Initially, economic growth leads to increased environmental degradation, but after reaching a certain level of income per capita, the trend reverses, leading to environmental improvements. This theory provides a foundational framework for examining of how economic activities, including FDI, impact environmental outcomes at different stages of development. On the other hand, the STIRPAT framework extends the IPAT model (Impact = Population × Affluence × Technology) by incorporating stochastic elements to analyze the impacts of human activities on the environment. The framework allows for the inclusion of multiple variables and their interactions, making it suitable for complex econometrics.

The empirical rigor of this paper is evident from the outset, starting with the specification of models to test the relationships between FDI, technological innovation, and green growth. First, we establish a baseline model to explore the Environmental Kuznets Curve (EKC) hypothesis and examine the impact of control variables on green growth. Finally, adhering to the STIRPAT framework, which accommodates multiple variables and their interactions, we introduce an interaction term to assess how FDI and technological innovation jointly influence green growth. The models are specified as follows:

$$GG_{it} = \beta_0 + \beta_1 FDI_{it} + \varepsilon_{it} \tag{1}$$

$$GG_{it} = \beta_0 + \beta_1 tech_{it} + \varepsilon_{it} \tag{2}$$

The baseline model is specified in (3) as:

$$GG_{it} = \beta_0 + \beta_1 GDP_{it} + \beta_3 GDP_{it}^2 + \beta_4 FDI_{it} + \beta_5 tech_{it} + \sum_{p=1}^{n} \delta_h K_{pi(t-\tau)} + \varepsilon_{it} \tag{3}$$

To capture the joint effect of FDI and technology innovation, Eq. (3) is modified to obtained (4)

$$GG_{it} = \beta_0 + \beta_1 GG_{i(t-1)} + \beta_2 GDP_{it} + \beta_3 GDP_{it}^2 + \beta_4 FDI_{it} + \pi_1 (TC)_{it} + \sum_{h=1}^{k} \delta_h K_{hi(t-\tau)} + \mu_i + \gamma_t + \varepsilon_{it} \tag{4}$$

where *i* and *t* represent individual countries and time periods respectively, *GG* signifies green growth, *GDP* denotes GDP per capita and it squared, *FDI* represents foreign direct investment as a percentage of GDP, tech signifies technology innovation, *TC* indicates the transmission channel through which the effect of FDI on green growth is modulated, with its estimated coefficient denoted by π_i. The TC variable summarises (FDI*tech), *K* represents control variables which are renewable energy consumption, globalization, urbanization along with their corresponding estimated coefficients ($\boldsymbol{\delta_h}$), ε representing the error term.

3.4 Estimation technique

The study utilizes a smoothed instrumental-variables quantile regression (SIVQR) approach to address potential endogeneity concerns. This methodology is of significant importance in assessing the influence of foreign direct investment (FDI) on the distribution of green growth. By analyzing distinct quantile levels within the conditional distribution, the quantile regression method facilitates the identification of countries characterized by varying degrees of green growth, thereby classifying them into low, intermediate, and high levels. The merit of this method, as highlighted by Wirajing et al. [50], lies in its capacity to elucidate the initial levels of the exogenous variable. Unlike ordinary least squares (OLS) regression, which frequently yields oversimplified and broadly generalized policy suggestions, instrumental quantile regression identifies precise quantiles where independent variables notably impact the dependent variable. This contrasts OLS, which depends on mean values and may result in broad policy implications.

Moreover, the instrumented quantile strategy aims to minimize absolute deviations across various quantile estimates, offering insights that hinge on the prevailing levels of Foreign Direct Investment (FDI) impact on green growth. This methodology diverges from Ordinary Least Squares (OLS), which prioritizes the reduction of the sum of squared residuals. In response to the shortcomings of OLS, quantile regression is being tailored by addressing the maximization problem outlined in Eq. 5.

$$\min_{\beta \varepsilon R^k}\{\sum\nolimits_{i\varepsilon\{i:yi>x'\beta}\theta|y_i - x'| + 1\sum\nolimits_{i\varepsilon\{i:yi>x'\beta}(\theta - 1)|y_i - x'|\} \quad (5)$$

where θ represents different quantile levels at the conditional distribution of the outcome variable, which belongs to {0, 1}. θ can take 0.10, 0.25, 0.50, 0.75 and 0.90. The conditional quantile of green growth is presented in Eq. 6 by weighing the residuals.

$$Q_y(\theta/x_i) = x'\beta_0 \quad (6)$$

Equation 6 introduces y, which symbolizes green growth proxy by production-based CO_2 productivity and demand-based CO_2 productivity. To address potential endogeneity issues with FDI and other control variables in the quantile model, we instrument production-based CO_2 productivity and demand-based CO_2 productivity by utilizing lag values of FDI, while also instrumenting all control variables across quantile levels ranging from the lower (10th and 25th) to the upper (75th and 90th) quantiles.

To optimize computational efficiency and statistical accuracy, this study employs the sivqr quantile instrumentation, integrating the smoothed estimator introduced by Kaplan and Sun [51]. Standard errors are computed using the Bayesian bootstrap method, employing a selection of 100 at all quantile levels, and are compatible with bootstrap prefixes, thereby ensuring the robustness and reliability of findings. However, it's important to note that quantile regression encounters challenges in addressing cross-sectional dependence, which necessitates supplementation with the Generalised Method of Moments (GMM) strategy.

4 GMM specification

The study additionally employs the system GMM strategy to analyze the indirect effects. Specifically, it examines how technological innovation serves as a pathway through which FDI impacts green growth, moderating the relationship. By employing the GMM strategy, the study offers flexibility in modelling complex relationships, accommodates various types of data, and allows for robust statistical inference. It addresses potential endogeneity issues and tackles problems associated with unobserved heterogeneity, such as time-invariant omitted variables and concerns regarding reverse causality. System GMM was chosen to yield results with a net effect for policy recommendation, which applies to all OECD countries, a feature not easily accommodated by quantile regression. This strategy generates efficient estimates under specific conditions. The primary condition for adopting the GMM is met in our study, as it deals with 37 OECD countries over 26 years from 1995 to 2021, where the number of cross-sections exceeds the time series [52]. Additionally, the study satisfies the requirement for employing the GMM in panel data analysis.

The two-step system GMM strategy adopted in the study is summarised in the first difference (6) as follows:

$$\begin{aligned} GG_{it} - GG_{i(t-\tau)} = & \beta_1(GG_{i(t-\tau)} - GG_{i(t-2\tau)}) + \beta_2(GDP_{it} - GDP_{i(t-\tau)}) \\ & + \beta_3(GDP^2_{it} - GDP^2_{i(t-\tau)} \\ & + \beta_4(FDI_{it} - FDI_{i(t-\tau)}) + \pi_1\left(TC_{it} + TC_{i(t-\tau)}\right) \\ & + \sum_{h=1}^{k}\delta_h\left(K_{hi(t-\tau)} + K_{hi(t-2\tau)}\right) + (\gamma_t - \gamma_{(t-\tau)}) + \left(\varepsilon_{it} - \varepsilon_{i(t-\tau)}\right) \end{aligned} \quad (7)$$

K signifies the vector of control variables. μ_i represents the country-specific effect, γ_t indicates the time-specific constant term, represents the error term and τ the lagging coefficient.

Additionally, to prevent generic policy recommendations, we calculate the net effect of the modulating variable by utilizing the coefficients of both the direct and indirect effects, as outlined in Eq. 8.

$$net\ effect = \beta_1 + (\Omega * \pi_1) \quad (8)$$

Ω denotes the average policy-modulating variable. The computation of the net effect is performed exclusively when β_1 and π_1 are both significant and demonstrate opposing signs.

5 Results and discussions

In this section, we delve into the findings of the study and offer a comprehensive analysis. To ensure clarity, the results are categorized into four sub-sections: Firstly, we present the fundamental findings derived from the baseline analysis. Secondly, we present the estimates from the quantile instrumental test results, accompanied by quantile regression plots provided in Appendix 1 and 2. Thirdly, we provided robustness checks by considering time variation and renewable energy by sources. Lastly, we discuss the results concerning the transmission effect and the determination of modulating thresholds obtained from the Two-Step System GMM estimates.

5.1 The Baseline results

The baseline results presented in Table 3 stem from the ordinary least squares model (OLS). These results reveal that FDI, GDP, renewable energy, and globalization exhibit positive correlations with both production-based CO_2 productivity and demand-based CO_2 productivity. Conversely, technological innovation and urbanization demonstrate negative effects. The study refrains from relying on the results of the OLS estimates for its conclusive remarks due to its failure to address

Table 3 Baseline results of the ordinary least square model

	(1)	(2)
VARIABLES	PP	DP
FDI	0.00450***	0.00226***
	(0.000689)	(0.000384)
GDP	0.00175***	0.000344**
	(0.000245)	(0.000137)
Renewable energy	0.0817***	0.0247***
	(0.00424)	(0.00236)
Globalisation	0.0722***	0.0238***
	(0.00798)	(0.00445)
Tech-innovation	−0.000503*	−0.000157
	(0.000269)	(0.000150)
Urbanisation	−0.0281***	−0.0193***
	(0.00651)	(0.00363)
Constant	−0.460	2.978***
	(0.702)	(0.391)
Observations	978	978
R-squared	0.376	0.165
R2 adjusted	0.372	0.160
Rank	7	7

Standard errors in parentheses *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

PP = production-based CO_2 productivity, DP = demand-based CO_2 productivity issues of endogeneity and unobserved heterogeneity. In lieu of this, the present study opts for instrumental quantile regression as a more robust approach, the findings of which are outlined in Sect. 4.2.

5.2 The instrumental quantile regression estimates

The quantile approach illustrates the estimated impact of FDI on green growth. These findings, derived from the quantile regression approach, are detailed in Table 4 of the study. The table showcases the results of instrumented quantile regression estimates at various quantiles, including the 10th, 25th, 50th, 75th, and 90th percentiles. Quantile regressions are widely adopted in both contemporary and non-contemporary literature as a robust regression technique, enabling a more typical assumption of normality for the residual term [50, 53].

Even after addressing the issue of endogeneity in the OLS results, the discovery of the exclusive positive impact of FDI on production-based CO_2 productivity and demand-based CO_2 productivity remains consistent with the findings of the OLS analysis. Foreign Direct Investment (FDI) often leads to increased industrialization and economic activity, contributing to higher CO_2 emissions. Production-based CO_2 productivity decreases as FDI boosts manufacturing output, intensifying emissions. Similarly, demand-based CO_2 productivity declines as FDI drives consumption, heightening energy use and emissions. Consequently, the correlation between FDI and production-based and demand-based CO2 productivity tends to be positive due to the environmental implications of the heightened economic activity facilitated by FDI. These findings are in line with Tukhtamurodov et al. [15], Salahuddin et al. [54], and Zhang and Zhou [10], who argued that FDI often introduces technologies or production methods that are environmentally unfriendly or energy-inefficient, thus worsening the green growth.

Moreover, the result indicates that GDP increases production-based CO2 productivity- and demand-based CO_2 productivity among the selected OECD countries. As a measure of economic output, GDP often incentivizes consumption and production without regard for environmental consequences. This hinders green growth, which aims for economic development while preserving the environment. GDP-driven policies prioritize short-term gains over long-term sustainability, leading to overexploitation of natural resources, pollution, and ecosystem degradation. Additionally, GDP fails to account for negative externalities such as carbon emissions and habitat destruction, undervaluing the true cost of economic activities. Consequently, investments in environmentally harmful industries might appear beneficial for GDP growth despite their adverse effects on the planet.

On the other hand, the GDP squared has a favourable effect on green growth, albeit not significant for demand-based CO_2 productivity, possibly reflecting heightened awareness of environmental concerns leading to policies advocating sustainability and the reduction of CO_2 emissions as a byproduct of economic progress. These findings align with the Environmental Kuznets Curve literature, which suggests that economic activities often escalate energy consumption in early growth stages, primarily from fossil fuels and major CO_2 emission sources. Conversely, in later stages, maturing economies tend to embrace cleaner technologies, renewable energy sources, and enhanced production methods [7, 8].

Furthermore, the results indicate that renewable energy exacerbates production- and demand-based CO_2 productivity in OECD countries. This may stem from the energy-intensive processes involved in renewable infrastructure production and maintenance and the intermittent nature of some renewables, necessitating backup systems that can increase CO_2 emissions. Additionally, manufacturing renewable infrastructure involves energy-intensive processes, contributing to CO_2 emissions. Also, globalization unfavourably impacts green growth by amplifying production-based and demand-based CO_2 productivity through increased trade, transportation, and industrial activities. Meeting global demand results in heightened energy consumption, primarily from fossil fuels. Outsourcing manufacturing to regions with lax environmental regulations further escalates emissions, worsening the global climate crisis. This aligns with Kirikkaleli and Addai's [55] findings, highlighting how globalization, prioritizing profit over environmental concerns, drives up resource extraction, production-based, and demand-based CO_2 productivity through expansive trade networks.

The results further demonstrate that technological innovation fosters green growth. Specifically, within the OECD sub-region, technological advancements enhance environmental sustainability by improving efficiency, conserving resources, and reducing pollution. These innovations diminish reliance on fossil fuels, thereby curbing greenhouse

Table 4 Quantile estimates on the effect of FDI on green growth

	(0.10)	(0.25)	(0.50)	(0.75)	(0.90)	(0.10)	(0.25)	(0.50)	(0.75)	(0.90)
VARIABLES Production-based CO_2 productivity						Demand-based CO_2 productivity				
FDI	0.00156*	0.00229***	0.00492**	0.00706***	0.0136**	0.000957***	0.00446***	0.00557***	0.00570**	0.00854**
	(0.000911)	(0.000310)	(0.00217)	(0.00265)	(0.00544)	(0.000118)	(0.00111)	(0.00116)	(0.00242)	(0.00411)
GDP	0.00110***	0.000633**	0.00143***	0.00221***	0.00251***	−7.37e−05	0.000255	0.000476**	0.000846**	0.000514
	(0.000370)	(0.000322)	(0.000259)	(0.000419)	(0.000516)	(0.000187)	(0.000173)	(0.000198)	(0.000382)	(0.000403)
GDPsquared	−0.000385*	−0.000272	−0.000772***	−0.00112***	−0.00111***	−7.16e−06	−0.000282	−0.000339	−0.000519	0.000158
	(0.000209)	(0.000225)	(0.000283)	(0.000361)	(0.000221)	(0.000145)	(0.000198)	(0.000275)	(0.000485)	(0.000370)
Renewable energy	0.0720***	0.0621***	0.0716***	0.120***	0.143***	0.0135***	0.0179***	0.0204***	0.0338***	0.0452***
	(0.00767)	(0.00439)	(0.00587)	(0.0161)	(0.0150)	(0.00233)	(0.00239)	(0.00271)	(0.00934)	(0.00524)
globalisation	0.0584***	0.0665***	0.0417***	0.0319***	0.0768***	0.0546***	0.0200*	0.00276	0.00965	−0.0183**
	(0.0206)	(0.0175)	(0.0103)	(0.0108)	(0.00894)	(0.00980)	(0.0119)	(0.00770)	(0.0180)	(0.00886)
Tech-innovation	−0.000539	−0.000772**	−0.000499	−0.000626	−0.000933***	−1.06e−05	−0.000237	−0.000480**	−0.000658**	−0.000996***
	(0.000393)	(0.000317)	(0.000370)	(0.000384)	(0.000358)	(0.000173)	(0.000183)	(0.000218)	(0.000311)	(0.000310)
Urbanisation	−0.0144**	−0.00630	−0.0215***	−0.0295**	−0.0361**	−0.0158***	−0.0173***	−0.0293***	−0.0343***	−0.0292**
	(0.00706)	(0.00479)	(0.00643)	(0.0145)	(0.0152)	(0.00436)	(0.00421)	(0.00625)	(0.00795)	(0.0122)
Constant	−8.056***	−1.540	2.050**	3.625**	1.215	−0.617	2.758**	5.713***	7.568***	8.397***
	(1.898)	(1.304)	(1.017)	(1.450)	(1.306)	(0.712)	(1.092)	(0.853)	(1.270)	(1.313)
Observations	839	768	768	768	978	978	643	643	643	643
reps	100	100	100	100	100	100	100	100	100	100
bwidth_req	0.418	0.440	0.441	0.484	0.548	0.293	0.297	0.306	0.309	0.337
bwidth_max	1.010	0.941	2.684	1.036	0.926	0.482	0.823	1.908	0.676	0.777
q	0.100	0.250	0.500	0.750	0.900	0.100	0.250	0.500	0.750	0.900

Standard errors in parentheses

*** p < 0.01, ** p < 0.05, * p < 0.1

gas emissions. Smart grid technologies optimize energy distribution, minimizing wastage, while advancements in waste management, such as recycling and composting, reduce landfill usage. Moreover, innovations in transportation, including electric vehicles and efficient logistics, contribute to carbon emission reductions. Indeed, studies by Suki et al. [56], Nosheen et al. [57], and Mensah et al. [58] affirm that technological innovation cultivates a more sustainable balance between human activities and the environment.

Finally, the findings also reveal that urbanization has a negative and significant effect on both production-based and demand-based CO_2 productivity in the OECD countries. This indicates that urbanization contributes to green growth by fostering denser living arrangements, thereby decreasing per capita resource consumption and carbon emissions. Compact cities promote public transportation and shared infrastructure, mitigating urban sprawl and conserving natural habitats. Moreover, centralized services enhance efficiency in waste management and energy distribution, promoting a more environmentally sustainable urban environment.

5.3 Sensitivity check

This section validates the findings by examining potential sources of bias, bolstering the study's credibility, and confirming the generalisability and consistency of the analytical approach. It incorporates assessments of time variances and renewable energy sources to ensure the consistency of the results.

5.3.1 Does time matter in green growth and the FDI relationship?

Different time periods affect green growth due to evolving societal attitudes, technological advancements, and policy frameworks. In the early days, limited awareness of environmental issues led to unsustainable practices. Industrial revolutions accelerated resource exploitation, causing environmental degradation. However, with the emergence of environmental movements in the mid-twentieth century, awareness grew, prompting the adoption of conservation measures and early environmental regulations. As we progressed into the twenty-first century, concerns about climate change intensified, leading to increased emphasis on sustainable practices and green technologies. Today, with a greater understanding of the urgency to address climate change, there's a global push for green growth.

Policies supporting green technologies, circular economies, and sustainable development goals shape contemporary approaches. Therefore, the trajectory of green growth is shaped by the socio-economic context and the level of commitment to sustainable practices across different time periods. Tables 5 and 6 present the effect of FDI on production-based and demand-based CO_2 productivity accounting for different time periods. However, the results generally align with the baseline, although with minor exceptions; for example, GDP's negative impact on demand-based CO_2 productivity in the first quantile across different periods, albeit statistically insignificant.

5.3.2 Robustness checks accounting for renewable energy by sources

Renewable energy sources such as solar and wind power exhibit availability and technological application variability, uniquely affecting their contributions to sustainable development and green growth. Solar thermal energy capitalizes on sunlight to produce heat or electricity, diminishing dependence on fossil fuels and lowering greenhouse gas emissions. Conversely, wind energy employs turbines to generate electricity, reducing carbon emissions. However, wind energy's effectiveness relies on wind availability, whereas solar thermal energy can offer more consistency in specific regions. Both technologies are pivotal in broadening the spectrum of renewable energy sources and advancing sustainable development goals.

This study's choice of solar thermal and wind energy is predicated on data availability for the covered time period. Tables 7 and 8 unveil the impact of FDI on production-based and demand-based CO_2 productivity while considering renewable energy sources, specifically solar thermal and wind energy. After accounting for the difference in renewable energy to check the consistency of our result, we observed that the result remained unchanged. Upon examining the control variables, we observe minimal alterations. For instance, urbanization positively impacts

Table 5 FDI and production-based CO_2 productivity accounting for time differences

	(0.10)	(0.25)	(0.50)	(0.75)	(0.90)	(0.10)	(0.25)	(0.50)	(0.7)	(10)
1995–2009						2010–2021				
Variables Production-based CO_2 productivity						Production-based CO_2 productivity				
FDI	0.00944**	0.00764**	0.00453**	0.00354*	0.00400*	0.00733	0.00205***	0.00193***	0.00117*	0.00197***
	(0.00456)	(0.00307)	(0.00220)	(0.00214)	(0.00214)	(0.00827)	(0.000201)	(0.000300)	(0.000707)	(0.000472)
GDP	0.00303***	0.00155*	0.00155***	0.00206***	0.00396***	0.00247***	0.00106***	0.00239***	0.00246***	0.00345***
	(0.000989)	(0.000848)	(0.000350)	(0.000598)	(0.000861)	(0.000749)	(0.000407)	(0.000728)	(0.000653)	(0.000511)
GDPsquared	−0.000910	−0.000223	−0.000631	−0.00139***	−0.00197***	−0.00118**	−0.00102***	−0.00189***	−0.00150**	−0.00154***
	(0.000765)	(0.000627)	(0.000416)	(0.000410)	(0.000362)	(0.000572)	(0.000369)	(0.000643)	(0.000613)	(0.000539)
Renewable energy	0.0695***	0.0516***	0.0551***	0.0814***	0.0886***	0.0764***	0.0616***	0.0853***	0.122***	0.112***
	(0.0207)	(0.00786)	(0.00513)	(0.0189)	(0.0148)	(0.0114)	(0.00616)	(0.0102)	(0.0194)	(0.0116)
Globalisation	0.0262	0.0105	0.0300*	0.00998	0.0197	4.19e−05	0.0627***	0.0343	0.0710***	0.0896***
	(0.0340)	(0.0387)	(0.0155)	(0.0206)	(0.0127)	(0.0387)	(0.0195)	(0.0243)	(0.0160)	(0.0161)
Tech-innovation	−0.00149	−0.00146**	−0.000284	−0.000943	−0.00169***	−0.00128**	−0.00148***	−0.00164***	−0.00183***	−0.00166**
	(0.00101)	(0.000733)	(0.000325)	(0.000752)	(0.000582)	(0.000525)	(0.000427)	(0.000581)	(0.000479)	(0.000682)
Urbanisation	−0.0377*	−0.0234	−0.0290***	−0.0326***	−0.0553**	−0.0380**	−0.00962	−0.0308***	−0.0342	−0.0543***
	(0.0198)	(0.0152)	(0.00823)	(0.00721)	(0.0252)	(0.0150)	(0.00772)	(0.00956)	(0.0211)	(0.0122)
Constant	−5.419	3.731	3.237***	5.943***	7.348***	2.360	−0.201	4.316*	2.243	6.293***
	(3.670)	(3.215)	(1.053)	(1.769)	(1.487)	(3.949)	(1.696)	(2.363)	(2.077)	(1.471)
Observations	32	147	256	256	183	408	434	434	434	434
reps	100	100	100	100	100	100	100	100	100	100
bwidth_req	0.883	0.535	0.406	0.470	0.605	0.519	0.548	0.547	0.600	0.646
bwidth_max	2.291	1.427	2.866	1.164	1.245	1.393	1.265	3.595	1.664	1.184
q	0.100	0.250	0.500	0.750	0.900	0.100	0.250	0.500	0.750	0.900

Standard errors in parentheses

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

Table 6 FDI and demand-based CO_2 productivity accounting for time differences

	(0.10)	(0.25)	(0.50)	(0.75)	(0.90)	(0.10)	(0.25)	(0.50)	(0.7)	(10)
1995–2009						2010–2021				
VARIABLES Demand-based CO_2 productivity						Demand-based CO_2 productivity				
FDI	0.00421***	0.00494***	0.00461***	0.00400**	0.00412***	0.000513***	0.00474***	0.00486***	0.00388**	0.00710**
	(0.00140)	(0.00144)	(0.00115)	(0.00156)	(0.00127)	(0.000177)	(0.000950)	(0.00140)	(0.00196)	(0.00347)
GDP	−6.69e−05	0.000364	0.00101***	0.00115***	0.00176***	−0.000407	8.33e−05	0.000335	0.000961*	0.000902**
	(0.000357)	(0.000252)	(0.000240)	(0.000272)	(0.000292)	(0.000399)	(0.000244)	(0.000308)	(0.000524)	(0.000393)
GDPsquared	0.000448**	8.65e−05	−0.000788***	−0.000931***	−0.00107***	−0.000524**	−0.000149	−0.000299	3.67e−05	0.000144
	(0.000197)	(0.000211)	(0.000252)	(0.000258)	(0.000262)	(0.000228)	(0.000417)	(0.000457)	(0.000526)	(0.000280)
Renewable energy	0.00945**	0.00929*	0.0173***	0.0268***	0.0273***	0.0127**	0.0108***	0.0145***	0.0154	0.0385***
	(0.00379)	(0.00560)	(0.00566)	(0.00575)	(0.00572)	(0.00560)	(0.00394)	(0.00379)	(0.0103)	(0.00693)
Globalisation	0.0462***	0.0198	−0.0168	−0.0131	−0.0359**	0.0155	0.0117	0.00282	−0.0126	−0.0199**
	(0.0169)	(0.0163)	(0.0131)	(0.0119)	(0.0160)	(0.0178)	(0.0163)	(0.0184)	(0.0148)	(0.00859)
Tech-innovation	−0.000672***	−0.000561*	−0.000509	−0.000834*	−0.000981**	−0.000344	−0.000522*	−0.000562*	−0.00110***	−0.00145***
	(0.000250)	(0.000313)	(0.000350)	(0.000465)	(0.000433)	(0.000242)	(0.000304)	(0.000306)	(0.000343)	(0.000369)
Urbanisation	−0.0167***	−0.0211***	−0.0210***	−0.0313***	−0.0371***	−0.000159	−0.0282***	−0.0323***	−0.0451***	−0.0393***
	(0.00559)	(0.00427)	(0.00498)	(0.00621)	(0.00810)	(0.00885)	(0.00569)	(0.00518)	(0.0146)	(0.0129)
Constant	0.0522	2.745**	6.158***	7.165***	9.721***	2.288	5.034***	6.466***	9.382***	9.787***
	(1.508)	(1.269)	(1.017)	(0.940)	(1.457)	(1.635)	(1.522)	(1.503)	(1.778)	(1.224)
Observations	209	209	209	209	209	434	338	432	434	434
reps	100	100	100	100	100	100	100	100	100	100
bwidth_req	0.344	0.302	0.279	0.266	0.307	0.357	0.354	0.339	0.349	0.386
bwidth_max	0.695	0.942	2.025	0.722	0.626	0.655	0.844	2.228	0.873	0.840
q	0.100	0.250	0.500	0.750	0.900	0.100	0.250	0.500	0.750	0.900

Standard errors in parentheses

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

Table 7 FDI and production-based CO_2 productivity accounting for renewable energy by sources

	(0.10)	(0.25)	(0.50)	(0.75)	(0.90)	(0.10)	(0.25)	(0.50)	(0.7)	(10)
Variables Production-based CO_2 productivity										
FDI	0.00284***	0.00261***	0.00231***	0.00815***	0.00189***	0.00286***	0.00291**	0.00239***	0.00241***	0.00262***
	(0.000229)	(0.000469)	(0.000259)	(0.00244)	(0.000567)	(0.000229)	(0.00143)	(0.000267)	(0.000243)	(0.000534)
GDP	0.000460	0.000941**	0.00167***	0.00404***	0.00352***	0.000174	0.000946**	0.00151***	0.00350***	0.00302***
	(0.000380)	(0.000478)	(0.000390)	(0.000465)	(0.000405)	(0.000459)	(0.000457)	(0.000369)	(0.000425)	(0.000484)
GDPsquared	−0.000198	−0.000667**	−0.000914**	−0.000351	−0.000230	−0.000139	−0.000578**	−0.000696**	−0.000264	−0.000156
	(0.000306)	(0.000299)	(0.000398)	(0.000395)	(0.000458)	(0.000329)	(0.000292)	(0.000323)	(0.000357)	(0.000333)
Solar thermal	0.000991	0.00134	0.000630	0.000531	−0.000496					
	(0.00122)	(0.00125)	(0.00144)	(0.00211)	(0.00245)					
Wind energy						3.85e−05	0.000372	0.00117	0.00420***	0.00411***
						(0.00101)	(0.000973)	(0.00142)	(0.00138)	(0.00142)
Globalisation	0.0604**	0.0291*	0.0238	0.00985	0.0416**	0.0560**	0.0294**	0.0357**	0.0175	0.0429***
	(0.0266)	(0.0163)	(0.0165)	(0.0150)	(0.0184)	(0.0232)	(0.0135)	(0.0141)	(0.0151)	(0.0158)
Tech-innovation	−0.000750*	−0.00105***	−0.00162***	−0.00202***	−0.00235***	−0.000694**	−0.000983***	−0.00128***	−0.00191***	−0.00182***
	(0.000406)	(0.000378)	(0.000527)	(0.000409)	(0.000502)	(0.000323)	(0.000303)	(0.000456)	(0.000371)	(0.000404)
Urbanisation	0.00852	−0.00942	−0.0263***	−0.0795***	−0.0479***	0.00568	−0.0108*	−0.0194***	−0.0547***	−0.0252**
	(0.0164)	(0.00816)	(0.00729)	(0.0153)	(0.0131)	(0.0152)	(0.00573)	(0.00732)	(0.0193)	(0.0102)
Constant	−2.583	2.507	5.534***	11.09***	11.38***	−1.773	2.764**	3.800***	8.491***	9.996***
	(2.044)	(1.586)	(1.696)	(1.565)	(1.833)	(1.490)	(1.137)	(1.213)	(1.534)	(1.534)
Observations	661	661	661	661	661	705	705	733	733	733
reps	100	100	100	100	100	100	100	100	100	100
bwidth_req	0.620	0.618	0.616	0.702	0.665	0.604	0.592	0.594	0.649	0.638
bwidth_max	1.074	1.349	3.829	1.746	1.153	1.038	1.280	3.643	1.395	1.265
q	0.100	0.250	0.500	0.750	0.900	0.100	0.250	0.500	0.750	0.900

Standard errors in parentheses

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

Table 8 FDI and demand-based CO_2 productivity accounting for renewable energy by sources

	(0.10)	(0.25)	(0.50)	(0.75)	(0.90)	(0.10)	(0.25)	(0.50)	(0.7)	(10)
Variables Demand-based CO_2 productivity										
FDI	0.000843***	0.00288**	0.00866*	0.00452***	0.00749**	0.000920***	0.000842***	0.00689*	0.00446*	0.0221***
	(0.000118)	(0.00132)	(0.00524)	(0.00173)	(0.00337)	(0.000163)	(0.000101)	(0.00409)	(0.00244)	(0.00216)
GDP	0.000184	0.000418**	0.000721***	0.000864**	0.000906**	−8.08e−05	0.000326**	0.000623***	0.000532**	0.000585
	(0.000211)	(0.000197)	(0.000210)	(0.000385)	(0.000396)	(0.000239)	(0.000152)	(0.000223)	(0.000227)	(0.000436)
GDPsquared	1.34e−06	−0.000417**	−0.000718***	0.000292	0.000596*	9.32e−05	−0.000283**	−0.000531***	−0.000207	0.000117
	(0.000223)	(0.000203)	(0.000269)	(0.000507)	(0.000317)	(0.000194)	(0.000143)	(0.000190)	(0.000298)	(0.000235)
Solar thermal	0.00133*	0.000375	0.000301	0.000858	0.00189					
	(0.000793)	(0.000891)	(0.000783)	(0.00126)	(0.00162)					
Wind energy						0.000507	0.000765*	0.00159**	0.00204***	0.00113*
						(0.000589)	(0.000449)	(0.000635)	(0.000672)	(0.000661)
Globalisation	0.0566***	0.0192	0.00173	−0.0259**	−0.0268***	0.0575***	0.0390***	0.00660	−7.17e−05	−0.0290***
	(0.0139)	(0.0159)	(0.0130)	(0.0113)	(0.00934)	(0.0134)	(0.00470)	(0.0121)	(0.00907)	(0.00780)
Tech-innovation	−0.000544***	−0.000482**	−0.000387	−0.000946***	−0.00110***	−0.000266*	−0.000246*	−0.000328	−0.000567**	−0.000813**
	(0.000195)	(0.000228)	(0.000267)	(0.000257)	(0.000384)	(0.000139)	(0.000134)	(0.000276)	(0.000243)	(0.000345)
Urbanisation	−0.0129**	−0.0169***	−0.0304***	−0.0335***	−0.0453***	−0.0106*	−0.0158***	−0.0289***	−0.0264***	−0.0179
	(0.00589)	(0.00442)	(0.00617)	(0.0102)	(0.0137)	(0.00582)	(0.00197)	(0.00654)	(0.00627)	(0.0134)
Constant	−0.710	3.185**	6.254***	9.322***	10.78***	−0.973	1.356***	5.311***	6.449***	8.352***
	(1.120)	(1.507)	(1.097)	(1.565)	(1.088)	(0.786)	(0.381)	(0.977)	(0.791)	(1.110)
Observations	561	561	717	561	561	705	805	828	828	762
reps	100	100	100	100	100	100	100	100	100	100
bwidth_req	0.372	0.346	0.302	0.359	0.387	0.339	0.315	0.289	0.303	0.343
bwidth_max	0.660	0.965	1.856	0.873	0.706	0.582	0.802	1.742	0.641	0.774
q	0.100	0.250	0.500	0.750	0.900	0.100	0.250	0.500	0.750	0.900

Standard errors in parentheses

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

production-based CO_2 productivity, although this effect is deemed insignificant. Additionally, globalization negatively influences demand-based CO_2 productivity in the last two quantiles.

5.4 Indirect effect result

The indirect effect analysis investigates the moderating role of technology innovation on the effect of FDI on green growth within the OECD member state. The indirect effect results have been conducted to examine whether the quest technology advancement enables FDI recipients to adopt cleaner production methods, reduce resource consumption, and minimize environmental impacts. Investments in environmental technology, smart grids, and sustainable infrastructure can be facilitated through technological advancements, promoting green growth [57, 58]. Additionally, innovations in waste management, water purification, and pollution control help mitigate negative externalities associated with FDI. Through technology, FDI can catalyze the development and deployment of environmentally friendly solutions, fostering a more sustainable and resilient economy [9, 12, 13]. This synergy between technology innovation and FDI contributes to achieving long-term environmental objectives while stimulating economic growth.

Table 9 Indirect effect results

	(1)	(2)
Variables	PP	DP
L.Production-based CO_2	0.974***	
	(0.00853)	
L.Demand-based CO_2		0.104***
		(0.000479)
FDI	*0.869****	*0.200***
	(0.0775)	*(0.754)*
GDP	0.493**	−0.0456***
	(0.217)	(0.0166)
GDP squared	−0.0165	−0.196***
	(0.0186)	(0.0234)
Renewable energy	0.0184***	0.186***
	(0.00203)	(0.0254)
Globalisation	0.222*	−0.178***
	(0.130)	(0.0268)
Tech-innovation	−0.181***	0.0720**
	(0.0173)	(0.0267)
Urbanisation	−0.0488**	0.0123***
	(0.0205)	(0.00311)
*FDI*tech-innovation*	*0.0435****	*−0.118****
	(0.00159)	*(0.312)*
Net effect		*−86.666*
Constant	−0.695***	−0.00273***
	(0.207)	(0.000365)
Observations	944	839
Number of Country	37	37
ar1p	5.51e−05	0.000105
ar2p	0.264	0.134
Instrument	37	37
hansenp	0.427	0.426

Standard errors in parentheses

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

The introduction of the indirect effect guides us towards avoiding broad policy approaches. It offers a framework for devising strategies to enhance green growth within the OCED countries with inadequate environmental management. In this section of the study, the Two-Step System GMM strategy is employed to determine a consolidated net effect of FDI interaction with tech-innovation in the OECD sub-region to easy policy orientation. By utilizing the GMM strategy, the study ensures that the findings are unaffected by endogeneity, cross-sections, autocorrelation, and heteroscedasticity, as suggested by Wirajing et al. [50]. The outcomes of the system GMM analysis are presented in Table 9. The findings suggest that FDI exerts a notable and positive influence on production—and demand-based CO_2 productivity, aligning with the core findings. Upon interaction with technological innovation, we discern a positive impact on production-based CO_2 productivity but a negative impact on demand-based CO_2 productivity. This suggests that technological innovation can moderate the influence of FDI on demand-based CO_2 productivity. This finding supports the role of innovation in achieving SDG 9 and underscores the importance of fostering collaborative partnerships between foreign investors and local innovators (SDG 17).

Technological advancements within OECD countries often attract FDI due to their growth potential and profitability. This prioritizes efficiency enhancements over environmental sustainability, consequently boosting production-based CO_2 productivity. Conversely, the synergy between technological innovation and FDI fosters the advancement of cleaner technologies and energy-efficient processes. This leads to a decline in demand-based CO_2 productivity, stemming from reduced energy consumption across various stages of goods and services production consumed domestically, regardless of the production locations.

5.5 Conclusion and policy implication

The Sustainable Development Goals advocate for advancing green growth, which entails fostering economic prosperity while safeguarding the environment. Central to this agenda are the principles of sustainable consumption, production, and energy utilization aimed at addressing climate change and preserving ecosystems. This study examines the moderating influence of technological innovation on the relationship between Foreign Direct Investment (FDI) and green growth within OECD member states. Our examination focuses on two dimensions of green growth: production-based CO_2 productivity and demand-based CO_2 productivity. Employing the EKC and STIRPAT frameworks, we analyze data from 1995 to 2021 across 37 OECD countries. Methodologically, our empirical approach involves employing Ordinary Least Squares (OLS), instrumental quantile, and System GMM methodologies. The results indicate that FDI hinders green growth, while technological innovation is pivotal in enhancing it. This dynamic holds across various periods and renewable energy sources. Moreover, our study reveals that FDI, in conjunction with technological innovation, leads to an increase in production-based CO_2 productivity but a decrease in demand-based CO_2 productivity. Additionally, we observe the presence of an environmental Kuznets curve for production-based CO_2 productivity.

Adding to significant scientific value by demonstrating how technological innovation moderates FDI's impact on green growth in OECD countries, we propose the implementation of a policy framework aimed at fostering domestic technological innovation while prudently managing foreign direct investment (FDI) to support sustainable growth. Also, policy frameworks should prioritize investments in research and development, creating an enabling environment for innovation and the advancement of sustainable technologies. Encouraging collaborative ventures between foreign investors and local innovators can also harness global expertise while furthering green objectives. Concurrently, policies should stimulate demand for environmentally friendly products and services to bolster demand-based CO_2 productivity. Moreover, investing in research and development (R&D) for green technologies is crucial. Lastly, integrating green criteria into FDI agreements and providing tax incentives for eco-friendly innovations will harmonize FDI with environmental goals.

5.6 Limitations and future recommendations

This study offers valuable insights into the interplay between Foreign Direct Investment (FDI), technological innovation, and green growth in OECD countries. However, several limitations stem from the design and methodology constraints, which may impact the interpretation of our findings:

First, the dataset covers 37 OECD countries over 26 years (1995–2021). While comprehensive, this temporal and spatial scope may not capture all relevant fluctuations and anomalies, especially short-term economic shocks or policy changes that could influence FDI and green growth dynamics. Second, using proxies, such as patents for technological innovation and production-based and demand-based CO2 productivity for green growth, introduces potential measurement errors. These proxies may not fully encapsulate the multi-faceted nature of technological innovation and environmental sustainability. Third, the focus on OECD countries, typically advanced economies, limits the generalizability of the findings to developing countries with different economic structures, regulatory frameworks, and technological capabilities. Also, the methodologies employed, including Ordinary Least Squares (OLS), smoothed instrumental-variables quantile regression (SIVQR), and System GMM, each have inherent limitations. For instance, OLS may not adequately address endogeneity issues, while SIVQR and System GMM require strong assumptions about the instruments and error distributions, which might not hold in all cases. Finally, technological innovation is a broad concept, and this study's focus on patents may overlook other forms of innovation, such as process improvements, managerial practices, and informal knowledge transfers that also significantly impact green growth.

Building on the findings and addressing the aforementioned limitations, the following recommendations are proposed for future research:

Future studies should incorporate a more extensive dataset, including non-OECD countries, to enhance the generalizability of the findings. Including data from emerging and developing economies could provide a more comprehensive understanding of the FDI-green growth nexus across different economic contexts. Moreover, employing alternative or supplementary measures for technological innovation, such as R&D expenditures, innovation indices, and qualitative assessments of technological capabilities, can provide a more nuanced understanding of its impact on green growth. Also, utilizing advanced econometric techniques that better handle endogeneity, non-linearity, and dynamic relationships, such as panel vector autoregression (PVAR) and machine learning approaches, can provide more robust insights. These methods can also help uncover complex interactions and causal relationships.

In addition, conducting in-depth case studies and sector-specific analyses can reveal contextual nuances and sectoral variations in the FDI-green growth relationship. This approach can identify best practices and policy interventions tailored to specific industries or regions. Lastly, integrating insights from other disciplines, such as political science, sociology, and environmental science, can enrich the analysis by considering broader socio-political and ecological dimensions influencing the FDI-green growth nexus. By addressing these limitations and following the outlined recommendations, future research can build on robust foundations, yielding valuable insights that inform practical applications and policy decisions to foster sustainable economic development.

Author contributions GSK prepared the analysis, interpretation and data curation. SA prepared the literature review, and BM prepared the introduction, editing and supervision of the manuscript.

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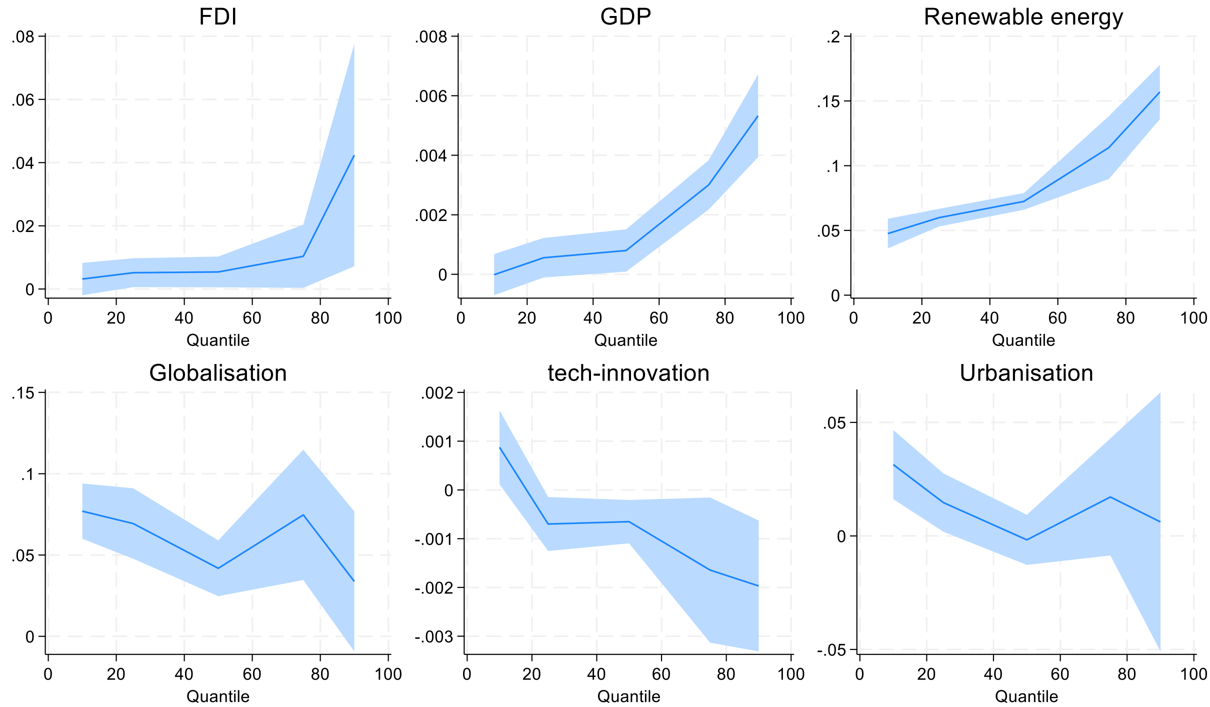
Data availability The data used in this study is available upon request from the corresponding author.

Declarations

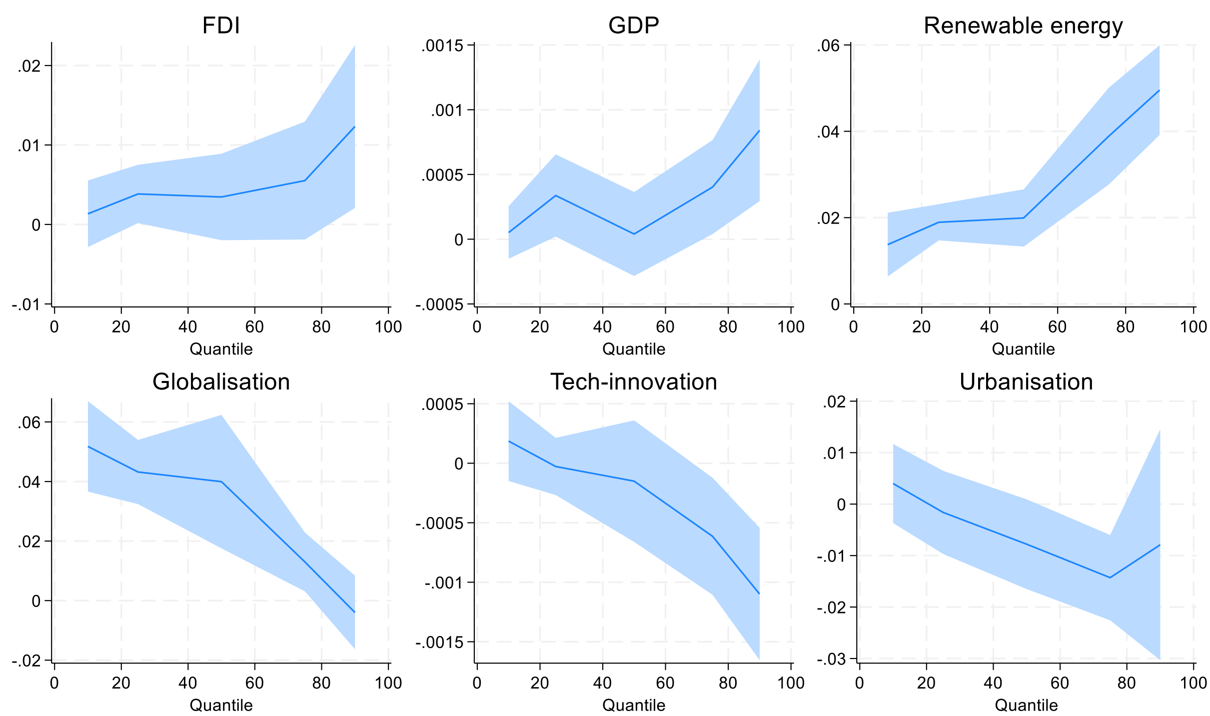
Conflict of Interests The authors declare no competing interests.

Appendix

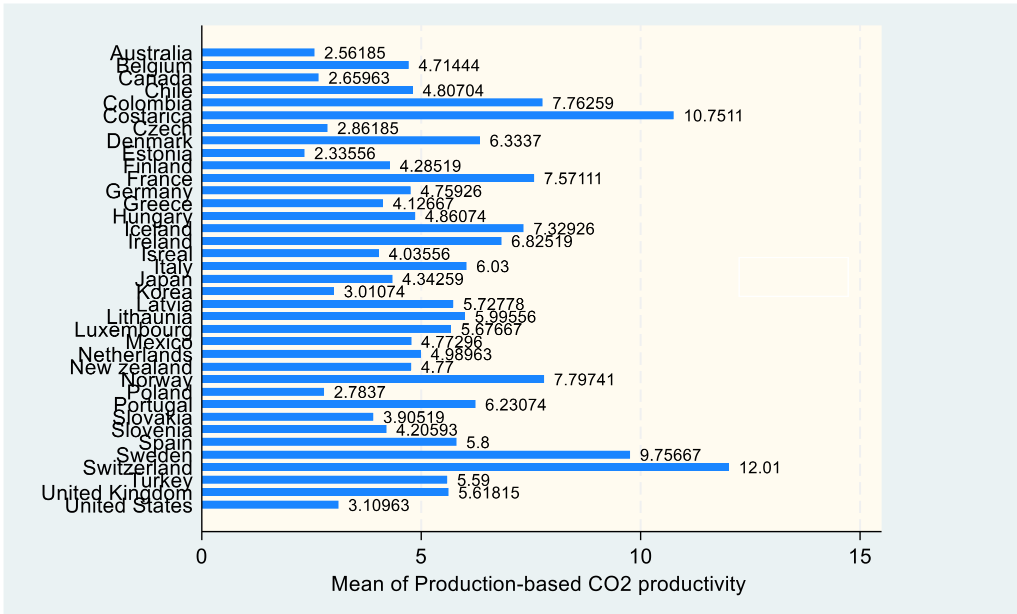
Appendix 1: The quantile plot on the determinants of production-based CO_2 productivity



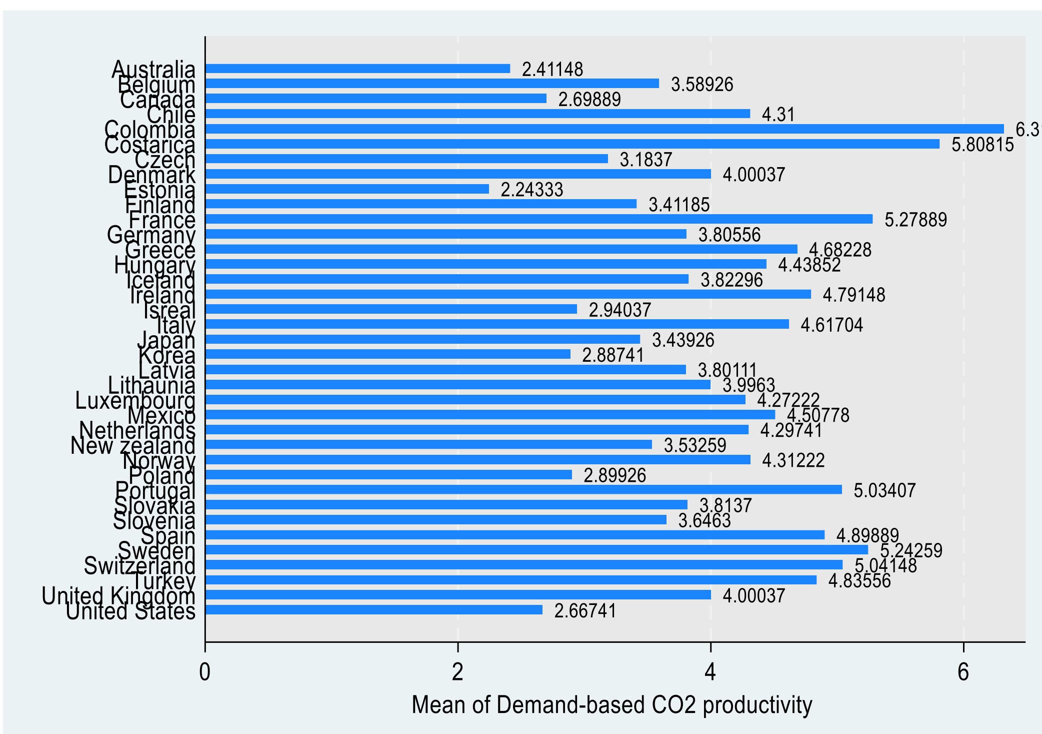
Appendix 2: The quantile plot on the determinants of demand-based CO_2 productivity



Appendix 3. Production-based CO_2 productivity across the OECD countries. Source: Author's computation from OECD database



Appendix 4. Demand-based CO_2 productivity across the OECD countries. Source: Author's computation from OECD database



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