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Bridging innovation, sustainability, and equity: how green technology drives inclusive green economy in developed economies

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Achieving an inclusive green economy (IGE) is an urgent global imperative that integrates environmental sustainability with human well-being and equitable opportunities. Developed economies that have experienced environmental degradation and income inequality are now committed to advancing IGE. This study examines the impact of green technology innovation (GTI) on IGE across 31 developed countries over the period 2000–2021. Specifically, it explores the mediating role of renewable energy consumption (REC) and the threshold effect of environmental tax. The Panel-Corrected Standard Error (PCSE) method, the Panel Threshold Model, the Modified Sobel Test, and the System Generalized Method of Moments (System GMM) are employed to conduct this study. The findings are as follows: (1) GTI has been proven to enhance IGE in developed countries; (2) the link between green technology innovation and IGE is positively mediated by REC, which accounts for 34.65% of the total effect; and (3) environmental tax has an optimal threshold effect on the impact of green technology innovation on IGE; when it is lower than 2%, green technology innovation exhibits a stronger contribution to IGE, while the boosting effect will decrease by 23% when exceeding 2%. This study also gives practical recommendations for developed countries as well as emerging nations. For instance, developed countries should set a reasonable level of environmental tax, whereas emerging nations should increase environmental tax due to the early stages of environmental regulations.

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Introduction

Balancing social inclusiveness, environmental sustainability, and economic prosperity has become a vital global objective for modern societies. The inclusive green economy (IGE) is a critical pathway to achieve the United Nations Sustainable Development Goals (SDGs), particularly SDG 7 (Affordable and Clean Energy), SDG 10 (Reduced Inequalities), and SDG 13 (Climate Action) (Behera, Behera, and Sethi, 2024; Lily and Sharma, 2025; South and Alpay, 2025). Recent international conferences, such as COP27 in 2022 and COP28 in 2023, have underscored the essential need for a fair and just transition toward inclusive development (Behera, Behera, and Sethi, 2024). These agendas advocate for improved green innovation, renewable energy investment, and fiscal reforms to achieve low-carbon, socially equitable growth.

Nevertheless, traditional economic growth neglects equitable public access to resources, opportunities, and benefits (Chaikin and Usiuk, 2019). Moreover, climate change resulting from rapid economic expansion poses significant threats to both the human living environment and long-term sustainable development. In response, international organizations have convened global forums aimed at enhancing cooperation on climate action, including the Kyoto Protocol (2005) and the Paris Agreement (2015). These agreements underscore a collective commitment to lowering pollution and promoting sustainable development. They also call for continued leadership by developed countries in emissions reduction, along with enhanced financial and technological assistance to support developing nations (Shirmohammadi et al., 2020). Thus, there is a growing need to implement an inclusive model of economic development that considers the carrying capacity of environmental and natural resources while promoting domestic sustainability and equitable improvements in societal well-being (Gupta and Vegelin, 2016; Saher et al., 2024).

In this context, the concept of IGE came to light. As part of a broader shift toward equitable and environmentally conscious development, IGE has gained prominence in global agendas, notably the 2030 Agenda (Kwilinski et al., 2023). IGE extends the idea of sustainable development by focusing on integrated progress throughout society and the environment (Angulo-Bustinza et al., 2022; Ren et al., 2022). Unlike traditional green growth paradigms that emphasize intergenerational equity, IGE places particular importance on present-day welfare and the fair distribution of its benefits (Bouma and Berkhout, 2015; Kwilinski et al., 2023). Specifically, IGE prioritizes social justice, human development, environmental preservation, and economic progress through mechanisms such as reducing wealth inequality, expanding access to opportunities, and strengthening economic resilience (Aluko et al., 2024; Dörffel and Schuhmann, 2022). Many countries and institutions have embraced the concept of IGE (Hay et al., 2022) and implemented supporting policies, including technological innovation, clean energy, and environmental tax.

Green technology innovation (GTI) is essential for nations globally to attain economic and environmental benefits through improved energy effectiveness and productivity. GTI supports sustainable expansion while offering viable solutions for reducing CO_2 through the integration of environmental technologies into existing industrial and social systems (Nikzad and Sedigh, 2017). Through the generation of clean energy and advancements in technologies, GTI causes significantly less environmental harm compared to fossil fuels (Wen et al., 2021). Evidence shows GTI has significantly enhanced carbon reduction in Australia (Zakari et al., 2023) and supported sustainable growth in developed economies (Deng et al., 2024; Saqib et al., 2024).

In addition, GTI can improve social equity by enabling inclusive technologies and expanding access to development opportunities across diverse population groups. For instance, GTI has improved the affordability and accessibility of energy in remote rural regions, where communities often face limited access to clean energy (Calvert et al., 2019; Gasser et al., 2022; Hosan et al., 2023). Hosan et al. (2024) further demonstrate that investments in energy innovation significantly enhance social equity, based on samples from 23 developed nations spanning the period from 1995 to 2020.

Renewable energy consumption (REC) has become a crucial measurement to combat climate change, mainly in wealthy economies (Ullah et al., 2021). Despite ongoing efforts, approximately 80% of energy use in OECD countries still comes from fossil fuels (Kafeel et al., 2024), making it a major contributor to global carbon emissions. Hence, the widespread adoption of renewable energy is thus vital to the transition toward a low-carbon global economy (Saleem et al., 2022). And clean energy sources are projected to expand rapidly in the coming decades (Li et al., 2020; Su et al., 2021). GTI has been shown to accelerate the adoption of REC and lessen reliance on conventional energy in both China and other developed nations (Jafri and Liu, 2023; Khan and Su, 2023).

Environmental tax is increasingly recognized as an effective policy instrument to achieve both carbon reduction and inclusive development goals. It is a targeted form of government regulation that aims to protect the environment by imposing taxes on polluting behavior. As environmental taxes raise additional expenditures for businesses, they will tend to boost their efforts with green technology to reduce pollution (Zhang et al., 2023). In Nordic nations, environmental tax is found to lower CO_2 emissions using the ARDL approach (Sharif et al., 2023). Furthermore, by internalizing the external costs of pollution, environmental taxes encourage eco-friendly investments and innovations. Empirical evidence from OECD countries confirms that environmental regulation facilitated green transformation among industrial firms in OECD countries from 1998 to 2018 (Behera and Sethi, 2022).

Despite the growing literature, existing research has centered on the transformation of economic models and the environmental and economic outcomes of GTI, with increasing but still limited attention to its implications for human development and social equity. As the concept of the inclusive green economy (IGE) is both relatively novel and comprehensive, there are limited studies on the influence of GTI on IGE, especially the role of GTI in improving welfare and social equity. Furthermore, research on the underlying mechanisms of GTI for IGE is largely insufficient. Specifically, GTI may indirectly promote IGE through REC by influencing energy consumption patterns and generating economic, environmental, and social benefits. Additionally, the relationship between GTI and IGE may not be linear; environmental tax may exert a threshold effect. While moderate environmental tax could incentivize GTI, excessively high taxes may constrain corporate R&D investment, thereby diminishing GTI's contribution to IGE.

To address these research gaps, this study employs 31 developed economies from 2000 to 2021 that have undergone periods of environmental degradation and income inequality and are now committed to achieving IGE development. The objectives of this study are as follows: (1) to investigate the impact of GTI on IGE in developed nations; (2) to explore the mediation effect of REC; and (3) to examine the threshold effect of environmental tax.

This study makes the following contributions: (1) It provides a more nuanced understanding of how GTI affects IGE, thereby extending current research frameworks neglecting human development and social equity; (2) by constructing a theoretical framework including the mediating effect of REC and the threshold effect of environmental tax, it further investigate the mechanisms of the relationship between GTI and IGE; (3) it constructs a new comprehensive index of IGE encompassing four dimension (economic development, human development and well-being, social equity, and ecological environment), representing an expansion of existing research; (4) the findings offer policy recommendations for both developed and emerging economies concerning GTI, REC, and environmental tax to promote IGE.

These are the remaining components: Section "Literature review and hypotheses" is the literature review and hypotheses, followed by the methodology and data in Section "Methodology and data". Section "Results and discussion" covers results and discussion. The conclusion is provided in Section "Conclusion and policy implications".

Literature review and hypotheses

Green technology innovation (GTI) and inclusive green economy (IGE). The impact of GTI on the IGE has been explored from multiple perspectives. First, the productivity-enhancing role of technology. Technological progress has been found to boost China's sustainable growth from 2005 to 2020 (Qian and Ji, 2022), as well as support long-term development in developed countries more broadly (Mensah et al., 2019). Second, given GTI's integration of technological advancement with environmental objectives, it gained plenty of scholarly interest in the context of carbon reduction and environmental conservation. For instance, environmental innovation in 23 OECD countries greatly lowers CO_2 emissions by promoting clean technologies and utilization (Costantini et al., 2017). Using the ARDL model, GTI reduces carbon emissions in developing nations (Behera, Behera, Sucharita, et al., 2024), while economic expansion does the opposite (Amin et al., 2023).

Third, a new perspective has emerged, suggesting that GTI is a critical driver of well-being and social equity by making technological advancements more inclusive and generating development opportunities across all segments of society. GTI not only benefits pollution control and resource conservation but also integrates social and economic benefits (UNCTAD, 2018), aligning closely with the principles of IGE. In the USA, digital technologies have been shown to significantly improve social equality, with technological progress alone accounting for approximately 30% of the variation in social equity (Skare and Porada-Rochoń, 2022). While guaranteeing accessibility and justice in the distribution of resources, GTI has become a vital means of attaining inclusive development globally (Antonyraj, 2025). Hence, GTI contributes to an IGE by promoting the economy, environment, welfare, and equity, thereby forming the basis for Hypothesis 1.

H1. GTI favorably influences the inclusive green economy.

GTI, renewable energy consumption (REC), and IGE. In addition to focusing on GTI, scholars have also explored the impact of REC on carbon emissions. Some hold positive opinions. For instance, Haldar and Sethi (2021) demonstrate, using a GMM model, that CO_2 emissions have decreased as a result of the development of REC in developing nations between 1995 and 2017. Similarly, Zhang et al. (2024) find that REC strengthens the BRICS economies' environmental conditions from 2016 to 2023. These results stem from substitutes of fossil energy with REC, which lowers greenhouse gas emissions and supports cleaner production structures. Additionally, as a low-carbon energy source, REC stimulates economic growth while advancing IGE by enhancing the energy blend and pollution reduction (Cui et al., 2022). Conflicting results do exist, though. In the USA, renewable energy credits have a short-term increase in CO_2 emissions but a long-term decrease (Kartal, 2023). REC greatly decreases CO_2 emissions in MENA and OECD nations but is negligible in SAARC nations (Rahman and Ferdaous, 2024). Such short-term negative or insignificant results are often attributed to transitional inefficiencies, which commonly arise before the long-run environmental gains of renewable energy are fully realized (Adeyinka et al., 2024; Behera, Sucharita, et al., 2024; Reutter and Lehmann, 2024). Typical constraints include high initial infrastructure investment, insufficient grid capacity, or immature technological systems.

Furthermore, REC could contribute to well-being and enhance social equity by providing clean, affordable, and reliable energy. From a well-being perspective, REC supports long-term energy price stability, reducing household energy costs and shielding vulnerable populations from the volatility of fossil fuel markets (Burlinson et al., 2024). In terms of social equity, REC can significantly reduce energy poverty by expanding access to electricity in remote and underserved regions (Chandratreya, 2025; Jiao and Tan, 2024). By improving access to energy, REC facilitates greater opportunities for education, healthcare, and economic activities, thereby narrowing socio-economic gaps (Tansuchat et al., 2025). Taken together, REC is likely to exert a beneficial influence on IGE.

As renewable energy must be collected, stored, and transformed, it represents a synergistic integration of technology and environmental principles. Technological advancement is essential for expanding renewable energy to fulfill national energy needs and achieve IGE. Empirical evidence shows that environment-related innovations help OECD economies move towards REC (J. Li et al., 2020). In Canada, green energy technology has the potential to maintain GHG emissions from REC within acceptable limits (Janzen et al., 2020). Furthermore, by switching from the existing heavy-energy manufacturing techniques to less energy-intensive ones, green technology can decrease dependency on fossil fuels and boost reliance on REC (Jafri and Liu, 2023).

In summary, GTI serves as a strong driver of REC expansion. In turn, increased adoption of REC decreases environmental pollution while enhancing well-being and social equity, contributing to the achievement of IGE. Therefore, REC is expected to mediate the relationship between GTI and IGE, leading to the formulation of Hypothesis 2.

H2. REC positively mediates the relationship between GTI and the inclusive green economy.

GTI, environmental tax, and IGE. As a regulatory penalty imposed on business polluting activities, environmental tax incentivizes enterprises to engage in green-oriented practices, such as developing green innovation. By adopting GTI, firms seek to reduce pollution-related fines, thereby enhancing environmental performance while also realizing economic and social benefits. Consequently, prior studies have explored the impact of environmental tax on GTI, yet the findings remain mixed. Some support the positive views. It has been found that environmental regulation has a strong correlation with GTI and promotes its adoption in the OECD economy (Ahmed, 2020; Nchofoung et al., 2023). Environmental tax has double rewards, including lowering pollution and promoting the development of GTI (Fan et al., 2018). These positive outcomes are primarily attributable to the fact that sound tax policies can internalize environmental costs and incentivize businesses to invest in clean technologies to avoid taxation. However, some academics hold contrary opinions. By compelling enterprises to increase expenditures on pollution control and diverting substantial amounts of corporate capital, environmental regulations may hinder technological innovation within firms (Li et al., 2021). Environmental tax hinders GTI among Chinese firms by decreasing corporate cash flow and financing, which is particularly detrimental to non-state-owned businesses (Wang et al., 2023). Moreover, while environmental tax may promote GTI in developed economies, it may have adverse effects in poor countries (Nchofoung et al., 2023). Negative effects generally occur because excessive tax burdens crowd out R&D investment, particularly in economies with weak innovation capabilities or limited fiscal support.

An emerging viewpoint reveals a U-shaped or inverted U-shaped nonlinear relationship between environmental tax and GTI. Proponents of a U-shaped relationship argue that enterprises lack sufficient incentive to pursue GTI if pollution penalties are less than those for R&D expenditures. In such cases, environmental tax can crowd out liquidity, thereby exerting a suppressive effect. However, once pollution-related costs surpass R&D, an "innovation compensation" effect is triggered that enhances GTI (Dhekra and Qiao, 2023; Li et al., 2021; Zhang et al., 2019). Zhang et al. (2019) further note that the inhibitory effect tends to occur in the early stages of environmental regulation, where standards are still low and incentives for innovation remain weak. Conversely, dissenting scholars have identified an inverted U-shaped effect of environmental tax on GTI in China's manufacturing sector, indicating that current tax levels have not yet reached the inflection point for maximizing innovation (Wei et al., 2023).

Several studies have further examined the triadic relationship between GTI, environmental tax, and IGE. Eco-innovation has been shown to promote sustainable growth in Africa (Dhekra and Qiao, 2023). Another study finds that environmental regulation positively moderates the impact of GTI on carbon reduction in China (Chang et al., 2023). Notably, environmental tax may exert a threshold effect on the GTI–IGE relationship. According to the Porter Hypothesis, well-designed environmental regulation can signal inefficiencies in resource use and pollution, encouraging firms to innovate and achieve "innovation compensation" that offsets regulatory costs (Porter, 1991). This implies that moderate levels of environmental tax can strengthen the role of GTI in enhancing environmental outcomes. However, the effectiveness of such tax measures depends on their intensity; overly high tax rates may stifle innovation by crowding out firms' financial resources (Wang and Yu, 2021). This threshold effect is particularly relevant in developed countries, where environmental tax systems were implemented earlier and generally operate at higher rates. While moderate taxation can motivate firms to invest in GTI and amplify its contribution to IGE, excessively high environmental taxes may reduce firms' capacity to innovate, thereby weakening the positive effect of GTI on IGE. In contrast, many poor markets may not have yet reached the optimal threshold for taxation, often prioritizing economic growth over environmental protection. Therefore, this study formulates Hypothesis 3.

H3. Environmental tax has a threshold effect on the relationship between GTI and the inclusive green economy.

Overall, the theoretical framework of this study is shown in Fig. 1. First, CTI enhances productivity and reduces environmental pollution, both of which are beneficial for IGE. In particular, the reduction in pollution, in particular, has direct benefits for public health, especially in densely populated or marginalized communities. In addition, GTI fosters social equity by enabling inclusive technologies and expanding access to development opportunities across diverse demographic groups. Second, GTI provides crucial technical support for the collection, storage, and conversion of renewable energy, primarily by upgrading conventional, energy-intensive manufacturing technologies into low-energy alternatives. By reducing dependency on fossil fuels and increasing the proportion of REC, this shift advances IGE significantly. This mechanism suggests that REC may serve as a positive mediator in the relationship between GTI and IGE. Third, a well-calibrated environmental tax not only imposes penalties but also creates incentives for firms to pursue environmental improvements. Consequently, the effectiveness of GTI in promoting IGE might rely on the current tax rate. Specifically, when the environmental tax is set below an optimal threshold, firms are highly motivated to invest in GTI to avoid financial penalties, thereby accelerating its positive impact on IGE. Conversely, if the tax exceeds the optimal level, the excessive financial burden might displace funds intended for green R&D, ultimately weakening the contribution of GTI to IGE.

Methodology and data

Econometric models

Baseline model. The baseline model is adopted to explore the impact of GTI on IGE, addressing Hypothesis 1. The panel data in this research may suffer from the cross-sectional dependence (CD) issue. Consequently, it may generate misleading conclusions by directly applying traditional ordinary least squares (OLS), fixed-effect, and random-effect models. To address these concerns, Driscoll and Kraay (1998) proposed the Panel-Corrected Standard Error (PCSE) method to provide more robust and reliable estimates through essentially modifying the standard error of traditional methods (Zidi and Hamdi, 2024). Compared with conventional estimators, the PCSE method possesses remarkable advantages because it assumes that the structure of the error variance is constant within panels but varies across panels (Ayuba and Adekoya, 2023). In addition, it accounts for contemporaneous correlation, meaning that error terms are correlated across panels within the same time period but remain uncorrelated over time. However, it also has a limitation in that it cannot address endogeneity issues. Therefore, the subsequent sections of this paper will conduct the endogeneity test.

Accordingly, this paper employs the PCSE model to correct traditional models that neglect the above issues. Following Le and Nguyen (2019) and Xu et al. (2023), this study elucidates the impact by adopting the PCSE model, corresponding to Hypothesis 1. As presented in Eq. (1), IGE_{it} refers to the independent variable of IGE, GTI_{it} denotes the dependent variable of GTI, and CV_{it} represents the selected control variables.

$$IGE_{it} = \alpha_0 + \beta_0 GTI_{it} + \sum \beta_j CV_{it} + \varepsilon_{it} \tag{1}$$

Dynamic model. Considering that the PCSE model does not account for endogeneity, this study additionally employs a dynamic approach of the System GMM to mitigate potential endogeneity concerns and obtain more robust and reliable estimates. Traditional fixed effects models may lead to downward bias in fixed effect estimates and upward bias in OLS estimates (Nickell, 1981). Consequently, various econometric issues (endogeneity and overidentification) inherent in the fixed effect model are commonly addressed using the System GMM estimator. This method leverages the lagged values of explanatory variables as instrumental variables to mitigate endogeneity (Ullah et al., 2018). Hence, the approach is preferred over static models. IGE_{it-1} represents the lagged independent variable in Eq. (2).

$$IGE_{it} = \alpha_0 + \beta_0 IGE_{it-1} + \beta_1 GTI_{it} + \sum \beta_j CV_{it} + \varepsilon_{it} \tag{2}$$

Mediation model. This study follows prior research (Baron and Kenny, 1986) and uses the stepwise regression method to test the mediating effect of REC. Its advantage lies in its interpretability and compatibility with panel data, whereas its limitation is that it assumes linear and sequential relationships and may not fully capture complex feedbacks. Equations (3) and (4) are constructed, combined with Eq. (1), to confirm whether REC mediates the relationship between GTI and IGE, which responds to Hypothesis 2.

$$REC_{it} = \alpha_0 + \beta_0 GTI_{it} + \sum\beta_j CV_{it} + \varepsilon_{it} \quad (3)$$

$$IGE_{it} = \alpha_0 + \beta_0 GTI_{it} + \beta_1 REC_{it} + \sum\beta_j CV_{it} + \varepsilon_{it} \quad (4)$$

Additionally, the Modified Sobel Test, which fully accounts for individual effects, is employed to complement the stepwise mediation analysis. The Sobel test is specifically designed to evaluate the significance of the mediating effect and provides precise estimates of the mediating effect (Sobel, 1982). Its z-value and significance are utilized to evaluate the validity of the mediator.

Threshold model. This paper employs the Panel Threshold Model to the threshold effect of environmental tax. Compared with linear models, this threshold model recognizes changes in the structure of economic activity and effectively handles nonlinear problems (Jahanger et al., 2022). However, the model's effectiveness requires sufficient data variation around the threshold. Therefore, the study adopts the approach to investigate the nonlinear effect. As shown in Eq. (5), I(.) is an indicator function, Tax_{it} refers to environmental tax, and τ is the threshold value (turning point).

$$IGE_{it} = \alpha_0 + \beta_o GTI_{it} I\left(Tax_{it} < \tau\right) + \beta_1 GTI_{it} I(Tax_{it} > \tau) + \sum\beta_j CV_{it} + \varepsilon_{it} \quad (5)$$

Variables

Dependent variable. IGE: While scholars have explored the construction of indicators for the green economy and the inclusive economy (Hao et al., 2023; Kwilinski et al., 2023), there remains a notable gap in the development and measurement of indicators specifically tailored to IGE. Therefore, this study aims to construct a comprehensive IGE index for countries worldwide.

First, given that the concept of IGE emphasizes the economy, humans, welfare, and environment, alongside emphasizing equitable distribution (Bouma & Berkhout, 2015; Ren et al., 2022; Saher et al., 2024), the IGE index in this study is structured around four key dimensions: economic development, human development and well-being, social equity, and ecological environment. Second, appropriate indicators are selected for each dimension. A 4-dimensional and 11-indicator IGE index is constructed based on the relevant studies (Engelmann et al., 2019; Fan et al., 2023; Krysovatyy et al., 2023; OECD, 2017) as well as the accessibility and reliability of global data, as shown in Table 1. Finally, the entropy-weighted TOPSIS method is employed to

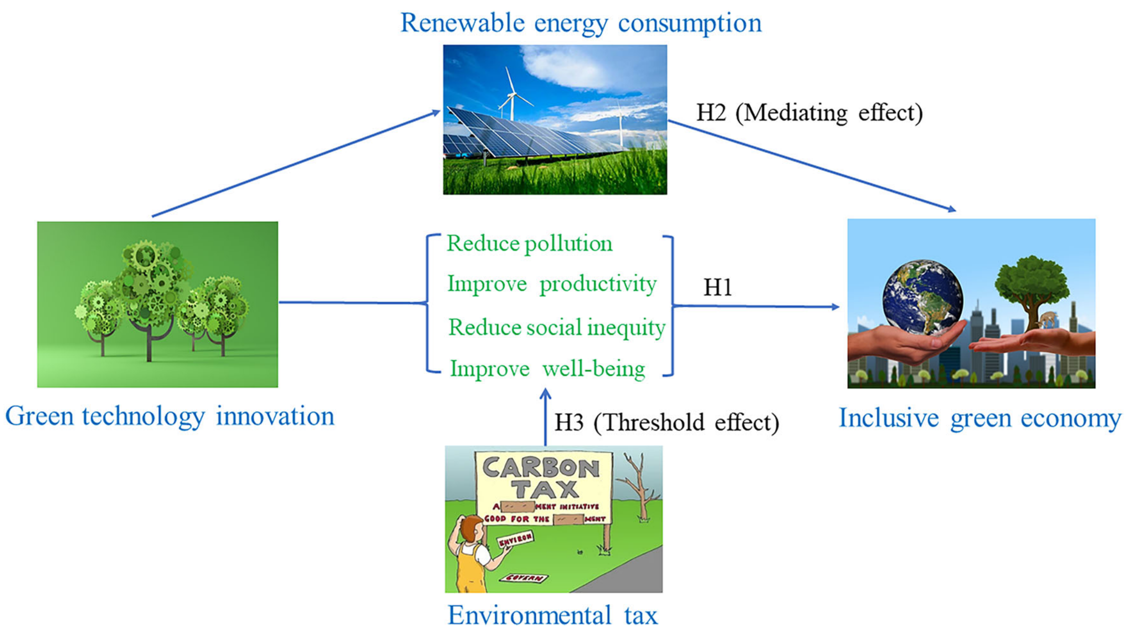

Fig. 1 Theoretical framework of this study. This figure displays the hypothesized relationships among green technology innovation, renewable energy consumption, environmental tax, and inclusive green economy, including direct effect (H1), mediating effect (H2), and threshold effect (H3).

Table 1 Construction of the IGE index.

Dimensions	Basic indicator	Attribute
Economic development	GDP per capita	+
	Percentage of GDP from import and export	+
Human development and well-being	Education spending as a percentage of GDP	+
	Rate of enrollment in postsecondary education	+
	Life expectancy	+
Social equity	Proportion of women in the workforce	+
	Gini coefficient	-
Ecological environment	Rate of forest cover	+
	GDP per unit of energy use	+
	Electric power consumption per capita	-
	Greenhouse gas emissions per capita	-

Table 2 List of sample countries.

Number	Countries	Number	Countries	Number	Countries
1	Australia	11	Greece	21	Netherlands
2	Austria	12	Iceland	22	New Zealand
3	Belgium	13	Ireland	23	Norway
4	Canada	14	Israel	24	Portugal
5	Czechia	15	Italy	25	Slovak Republic
6	Denmark	16	Japan	26	Slovenia
7	Estonia	17	Korea	27	Spain
8	Finland	18	Latvia	28	Sweden
9	France	19	Lithuania	29	Switzerland
10	Germany	20	Luxembourg	30	United Kingdom
				31	United States

determine indicator weights and compute the IGE index in a more objective and data-driven manner (Yu et al., 2020). Specifically, the weights of indicators are first determined using the entropy-weighted approach in this study, and then the TOPSIS method is applied for the final evaluation. The entropy-weighted approach allocates weights by considering the variety of indices, therefore reducing the impact of subjective elements (Lin and Zhou, 2022). The TOPSIS approach then identifies the best alternative by decreasing the distance to the positive ideal solution and maximizing the distance from the negative ideal solution (Kumar and Kaur, 2019).

Independent variable. GTI: The assessment of GTI is typically approached through input and output measures. From the input perspective, R&D expenditure is commonly used to quantify innovation input (Lee and Min, 2015); however, such investments do not necessarily guarantee successful outcomes and provide limited insight into actual innovation outputs. Nevertheless, as a form of measuring the output of technical innovation, patent data offers a more precise and accessible means of evaluation and allows for classification of innovations (Gorodnichenko and Schnitzer, 2013). Accordingly, this study adopts the number of green patents as a proxy for GTI output, in line with previous research (Shao et al., 2021).

Mediating variable. REC: as a replacement for fossil energy, it fulfills the demand for eco-friendly and efficient energy. The share of clean energy in overall consumption is utilized to evaluate REC (Nuță et al., 2024).

Threshold variable. Environmental tax (Tax) is a hybrid of environmental regulation and tax for environmental preservation, which is measured by environmental tax revenue of GDP (Jahanger et al., 2024).

Control variables. Control variables: government intervention (GOV), urbanization (URB), and foreign direct investment (FDI), as they could have an effect on the economy, society, and environment (Hazem et al., 2024; Pata et al., 2023; Uche et al., 2023), which have a link with IGE.

Sample and data sources. A panel sample of 31 developed countries from 2000 to 2021 is adopted to explore the role of GTI in enhancing IGE as well as the mediating effect of REC and the threshold effect of environmental tax. These countries are listed in Table 2. As indicated in Table 3, the OECD and World Bank databases served as the main sources of data for this investigation.

Table 3 Variables and data sources.

Variables	Measurement	Data sources
IGE	IGE index	World Bank
GTI	Natural logarithm of 100*(the number of green patents)	OECD database
REC	Share of clean energy in overall consumption	World Bank
TAX	Environmental tax revenue (% of GDP)	OECD database
GOV	Government expenditure (% of GDP)	World Bank
URB	Percentage of urban population	World Bank
FDI	FDI, net inflows (% of GDP)	World Bank

Table 4 Statistical analysis.

Variable	Obs	Mean	SD	Min	Max
IGE	682	0.326	0.083	0.182	0.614
GTI	682	9.358	2.380	2.665	13.708
REC	682	0.199	0.170	0.007	0.840
TAX	682	0.024	0.008	0.006	0.051
GOV	682	0.198	0.034	0.104	0.282
URB	682	0.773	0.115	0.508	0.981
FDI	682	0.050	0.094	-0.326	0.614

Results and discussion

Descriptive statistical analysis. In Table 4, IGE exhibits a relatively balanced distribution, having an average value of 0.326 and a range of 0.182–0.641. In contrast, GTI shows greater variability (SD = 2.38). With an average of 0.199 along with a spread of 0.007–0.840, REC shows that most wealthy nations continue to consume a relatively small percentage of clean energy. TAX, GOV, and URB exhibit a smooth distribution, and their SDs are much less than 1. The net flow of FDI in developed nations varies widely, from a negative minimum of −0.326 to a maximum of 0.614.

Cross-sectional dependence test. Cross-sectional dependence (CD) often arises as a result of shared factors that simultaneously affect all individuals. This issue can result in inaccuracies in analysis caused by inefficiencies, inconsistencies, lack of credibility, and biases (De Hoyos and Sarafidis, 2006). To tackle the issue, Pesaran (2004) introduced a test for error CD that relied on averaging paired correlation coefficients, which could be applied to both fixed-effect and random-effect models. Compared with the Frees test, the CD test is particularly advantageous due to its ability to handle both balanced and unbalanced panel data, making it highly flexible for practical applications (Muhammad et al., 2021). When panel data is highly imbalanced or the sample size is small, the reliability of the test diminishes; however, neither of these conditions applies to this study. Therefore, this research adopts it to test the presence of CD.

Table 5 displays the outcomes of the CD test, which strongly rejects the null hypothesis of no CD ($P < 0.01$), indicating the presence of residual cross-sectional connectivity issues in the panel data. This suggests that individual cross-sections exhibit dependency due to the influence of common factors. Such dependency may result in inconsistent findings and therefore, requires appropriate methodological adjustments of the PCSE model.

Table 5 Results of the CD test.

Variables	CD-test	*P* value
IGE	93.609	0.000***
GTI	57.847	0.005***
REC	77.1	0.000***
TAX	20.405	0.000***
GOV	34.42	0.000***
URB	60.534	0.000***
FDI	14.506	0.000***

***$p < 0.01$.

Table 6 The results of the unit root test.

Variable	CIPS (t-bar)	
	I(0)	I(1)
IGE	−1.414	−3.263***
GTI	−2.899***	
REC	−2.371	−4.698***
TAX	−2.851***	
GOV	−1.516	−3.575***
URB	−2.597*	
FDI	−3.872***	

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

Unit root test. When cross-sectional correlation exists in panel data, first-generation unit root tests are inadequate because they assume independence across cross-sections. Therefore, this paper employs the second-generation CIPS proposed by Pesaran (2007), which accounts for the (CD). This method is more appropriate than the second-generation CADF because it evaluates the unit root of the entire panel rather than examining each cross-section individually (Pesaran, 2007; Westerlund et al., 2016), making it better suited for macroeconomic data. This method exhibits a significant decline in statistical power when dealing with small samples, but this study does not encounter such circumstances. As shown in Table 6, GTI, TAX, URB, and FDI contradict the null hypothesis of a unit root. In contrast, the remaining variables exhibit non-stationary characteristics. However, further analysis confirms that these non-stationary variables become stationary after first-differencing. The result displays that the panel data in this study exhibit a mixed I(0) and I(1) structure.

Direct effect. To examine the link between GTI and IGE, both the traditional OLS, fixed-effect, random-effect, and PCSE models are used in this study for comparative analysis. As previously discussed, conventional statistical methods fail to address issues of CD. Therefore, following prior research (Le and Nguyen, 2019; Xu et al., 2023), this study utilizes the PCSE model, which corrects for the CD issue and improves estimation validity, as presented in Table 7.

Initially, the findings from the OLS model suggest that GTI negatively affects IGE, which contradicts Hypothesis 1. To account for individual heterogeneity, the study further applies both random and fixed-effects models. The Hausman test results (Chi^2-statistics = 30.8, $P < 0.01$) indicate that the latter is better suited than the former. Therefore, this research adopts the PCSE model based on the standard error adjustments to the fixed-effect model. According to the PCSE estimation, GTI significantly enhances IGE in wealthy nations, thereby supporting Hypothesis 1. Furthermore, it has been found that IGE is positively impacted by urbanization in developed nations. This can be attributed to the economies of scale brought about by urbanization, particularly in sectors such as energy and technology (Belloumi and Alshehry, 2016), which is shown to increase IGE in this study. Additionally, previous research has shown that urbanization initially facilitates and then hinders environmental pollution in China (Chen et al., 2023). In contrast, government intervention and FDI are found to have a negative effect on IGE in this analysis.

Table 7 Results of direct effect.

Variables	OLS	RE	FE	PCSE model
GTI	−0.002	0.011***	0.012***	0.012***
	(0.001)	(0.002)	(0.002)	(0.003)
GOV	−0.834***	−0.306***	−0.315***	−0.315***
	(0.091)	(0.058)	(0.058)	(0.096)
URB	0.271***	0.545***	0.595***	0.595***
	(0.029)	(0.042)	(0.044)	(0.056)
FDI	0.168	−0.028***	−0.028***	−0.029***
	(0.031)	(0.010)	(0.009)	(0.013)
cons	0.292***	−0.138***	−0.184***	−0.214***
	(0.229)	(0.033)	(0.032)	(0.040)
N	682	682	682	682
Chi^2-statistics			30.8***	

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

The key findings in this study confirm GTI's significant boost in IGE in industrialized nations. From the standpoint of social equity and benefits, earlier research finds that GTI has emerged as a crucial strategy for attaining inclusive development by guaranteeing accessibility and justice in the distribution of resources (Antonyraj, 2025). Similarly, digital technologies have been shown to enhance social equality, with technological progress alone accounting for about 30% of the variation in social equity (Skare and Porada-Rochoń, 2022). These outcomes might result from GTI's contribution to advancing technology in the direction of more inclusion and generating possibilities for growth for people from all socioeconomic backgrounds, thereby significantly enhancing well-being and social equity. From an environmental perspective, there is a similar study showing that green patents improve environmental performance in G7 nations (Anu et al., 2023). It is undeniable that developed countries have realized their damage to the environment while achieving rapid economic growth. Subsequently, they have also actively carried out green measures, such as GTI. A relevant study confirms that technological advances have dramatically minimized pollution, improving environmental quality in industrialized nations (Popp, 2012). According to statistics from the OECD database, a large number of environment-related technologies have emerged in OECD countries, dedicated to environmental management and renewable energy generation (Paramati et al., 2022). Nonetheless, the OECD database also reveals that developing nations, particularly low-income developed nations, have a smaller number of green patents than developed nations. This indicates that the application and transformation of GTI in developing countries is still at a low level, and its role in supporting environmental protection and IGE has not yet been fully utilized. Therefore, developing countries should provide more assistance to enterprises' GTI to realize IGE through the creation of eco-friendly materials and products, as well as the improvement of resource and energy efficiency.

Mediation effect. Table 8 displays the findings of the stepwise regression technique, which is used to determine the mediator of REC. GTI has been proven to accelerate IGE, as established in

Table 8 Results of mediating effect.

Variable	Model (1) IGE	Model (1a) REC	Model (1b) IGE
REC			0.246*** (0.0215)
GTI	0.012*** (0.003)	0.017*** (0.006)	0.008*** (0.002)
GOV	−0.315*** (0.096)	0.173 (0.199)	−0.358*** (0.069)
URB	0.595*** (0.056)	1.125*** (0.145)	0.318*** (0.030)
FDI	−0.029*** (0.013)	−0.068*** (0.024)	−0.012 (0.011)
_cons	−0.214*** (0.040)	−1.079*** (0.112)	0.052** (0.006)
N	682	682	682
Sobel test		Z-value = 4.843***	
Goodman-1 (Aroian)		Z-value = 4.835***	
Goodman-2		Z-value = 4.851***	
Proportion of mediating effect:		34.65%	

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

Section "Direct effect". In Model (1a), GTI also has a facilitating influence on REC (beta = 0.013, $P < 0.01$). In Model (1b), both GTI and REC significantly promote IGE, with respective coefficients of 0.008 ($P < 0.01$) and 0.248 ($P < 0.01$). In conclusion, all results in Models (1), (1a), and (1b) demonstrate that the link between GTI and IGE is facilitated positively by REC.

To further validate the mediator of REC, the modified Sobel test is employed. All three computed Z-values of the Sobel test are significant at the 1% level, suggesting that REC positively mediates the relationship between GTI and IGE. Further information reveals that 34.65% of the total effect is substantially mediated by REC. Therefore, Hypothesis 2 is accepted.

Overall, all findings of this paper show that REC proactively mediates the enhancing effect of GTI on IGE in developed countries. It suggests that GTI encourages the conversion of consumption behaviors to clean energy, which promotes IGE by effectively enhancing both energy efficiency and environmental conservation through the replacement of fossil fuels. This is primarily because in developed countries, advanced technological capabilities and supportive policy frameworks have facilitated the adoption and integration of REC. GTI not only enhances energy efficiency but also incentivizes the utilization of solar, wind, and hydropower, which reduces environmental degradation. This is consistent with other research demonstrating that in wealthy economies, REC mediates the association between R&D spending and carbon reduction (Lin and Li, 2022). However, there are notable differences between this study and previous research. First, compared with traditional technologies, GTI explicitly targets energy saving and environmental protection, making it more effective in promoting the adoption of cleaner energy. Second, previous research has primarily focused on environmental or economic outcomes, while IGE also emphasizes the importance of human development and social equity.

Although these findings are derived from developed countries, they offer valuable insights for regions with different economic and resource contexts. For developing countries, they have obvious advantages in terms of clean resource endowment. Clean energy is crucial to reducing environmental degradation and carbon emissions in those countries. The findings of this paper will provide some insights into the formulation of clean energy development planning, especially in developing countries.

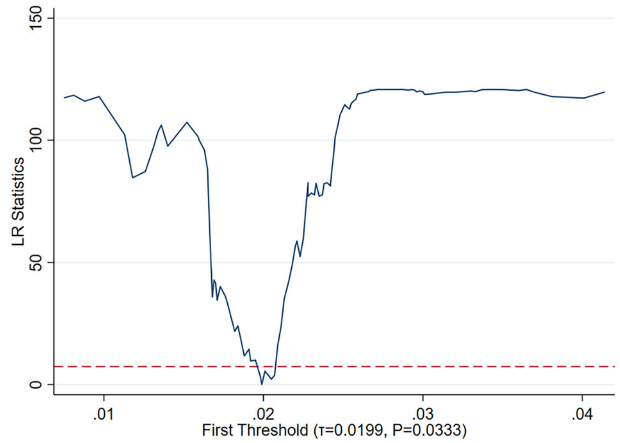

Fig. 2 Threshold estimator. This figure illustrates the nonlinear link between green technology innovation (GTI) and inclusive green economy (IGE), with the 1-threshold effect of environmental tax.

Table 9 Results of threshold effect.

Variables	IGE	IGE
GTI (environmental tax < τ)	0.013**(0.014)	
GTI (environmental tax > τ)		0.010***(0.014)
GOV	−0.343***(0.053)	−0.343***(0.053)
URB	0.536***(0.041)	0.536***(0.041)
FDI	−0.027***(0.009)	−0.027***(0.009)
_cons	−0.120***(0.030)	−0.120***(0.030)
R^2	0.442	0.442

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

Threshold effect. Figure 2 represents a 1-threshold effect of environmental tax in the connection between GTI and IGE, since the value of the 1-threshold is 0.0199 with a significance level of 0.0333.

Furthermore, GTI has been actively contributing to IGE in Table 9. However, the coefficient of GTI is 0.013 when the environmental tax is less than 2% and drops to 0.010 when larger than 2%, representing a 23% reduction. All findings reveal that the link between GTI and IGE in industrialized countries is impacted by environmental tax at a threshold level. Specifically, when the environmental tax is lower than the threshold level of 2%, businesses select to invest more in GTI in order to avoid incurring large tax costs. Therefore, increased GTI in turn effectively promotes IGE. Nevertheless, when it exceeds the threshold level of 2%, businesses are incapable of investing in GTI when burdened with high expenditures of environmental tax, thus weakening the enhancing effect of GTI on IGE. Hence, Hypothesis 3 is supported.

This study demonstrates that environmental tax has a threshold function, and the most appropriate threshold level is 2%. This result indicates an obvious threshold effect, indicating that the facilitating effect of GTI on IGE is not linear but conditional on the level of environmental tax. This finding aligns with other research arguments that a moderate environmental tax can stimulate green innovation by providing sufficient incentives for businesses to reduce pollution through technological upgrades (Liu and Gong, 2018; Wang and Yu, 2021). It is an essential practical guideline for developed countries, which have a long

Table 10 Results of endogeneity test.

Variables	System GMM
IGE_{it-1}	0.972***(0.027)
GTI	0.003*(0.002)
GOV	−0.346***(0.060)
URB	0.009 (0.021)
FDI	0.039***(0.013)
_cons	0.040***(0.011)
Hansen test	0.139
AR(1)	0.003
AR(2)	0.305

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

history of environmental tax systems and high standards. The OECD proposed the "polluter pays" scheme in 1972 to deal with the environmental crisis, which was a typical way of costing pollution. Subsequently, environmental tax has progressively gained acceptance, and many developed countries have established their own environmental tax frameworks (Tan et al., 2022).

However, environmental tax is not the higher the better; there is a suitable level that could be well accepted by enterprises to produce positive incentives to make goods and the environment greener. The 2% level of environmental tax in developed countries is a key turning point in maximizing the incentives for firms to develop GTI that generates high levels of environmental and economic benefits. This interpretation aligns with Wang and Yu (2021), who state that stringent environmental regulations constrain innovation by increasing operational costs for businesses and reducing available resources for research and development. Nonetheless, negative consequences occur when this optimal level is exceeded, as it undermines the facilitating role of GTI for IGE. From a regional perspective, developed countries typically occupy the technological frontier, and overly stringent tax policies may stifle rather than stimulate technological progress. However, this does not extend to developing countries, whose environmental regulations and related tax systems are not yet sophisticated. In order to effectively regulate the promotion of IGE by GTI, developing countries should raise environmental tax standards without concern for the deterrent impact of excessive levels because of the immaturity of environmental regulations.

Endogeneity test. A dynamic panel model is also employed to deal with the endogeneity problem. Table 10 shows that GTI continues to positively affect IGE when estimated using the system GMM model, with a p-value of 0.059. Additionally, the indicators of AR(1), AR(2), and the Hansen test all pass the related tests. Therefore, the empirical results are credible, and endogeneity does not pose a significant concern in this study.

Robust test

Replacing variable. Since environmental degradation is a major obstacle to low-carbon development and IGE, this study replaces the independent variable of IGE with carbon intensity. Carbon intensity reflects the efficiency of economic growth relative to carbon emissions and captures the process of decoupling emissions from output (Lee and Wang, 2022). Lower carbon intensity indicates improved environmental performance, which is an alternative indicator of the ecological environment dimension of IGE. Following this substitution, the expected outcome is negative, as carbon emissions are detrimental to IGE. In Table 11, GTI switching lowers carbon intensity, implying that GTI

Table 11 Results of robust test.

Variables	Replacing variable	Deleting samples	Adding variables	FGLS model
	Carbon intensity	IGE	IGE	IGE
GTI	−0027** (0.013)	0.012*** (0.003)	0.010*** (0.002)	0.002*** (0.001)
GOV	−0.065 (0.354)	−0.365*** (0.097)	−0.338*** (0.095)	−0.273*** (0.007)
URB	−1.085*** (0.177)	0.663*** (0.055)	0.493*** (0.049)	0.316*** (0.003)
FDI	0.049* (0.027)	−0.029** (0.012)	−0.022* (0.011)	0.002* (0.01)
NAT			−0.001 (0.001)	
DEN			0.001*** (0.001)	
_cons	1.531 (0.094)	−0.203 (0.039)	−0.099*** (0.037)	0.062*** (0.003)
N	682	528	682	682

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

sustainability reduces environmental degradation, which facilitates the development of IGE. Hence, the results of this paper have strong stability and feasibility.

Removing samples of G7 countries. The G7 economies represent the most advanced group among developed nations, characterized by significantly higher income levels and a stronger technological foundation. Therefore, this study excludes the G7 sample to test whether the core conclusions remain valid after removing this highly developed subset. The findings in Table 11 demonstrate the consistency of the effect, with no alteration in the results for all variables. Furthermore, it indicates that the conclusions are applicable across a broader set of developed nations and are not dominated by a small subset of G7 countries.

Adding control variables. Additional variables are added to this study: (1) natural resources (NAT), determined as total natural resource rents of GDP (Nathaniel et al., 2021). Countries with higher dependence on natural resources tend to experience stronger environmental pressures due to extraction activities. It has been proved that resource reliance leads to weaker environmental governance and slower green transformation in Sub-Saharan African countries (Erdoğan et al., 2021); (2) population density (DEN), which has been proven to lessen environmental degradation in BRI countries (Chin et al., 2022). Higher population density fosters more efficient land use, reduces per capita energy demand, and thereby enhances environmental quality in South Asian countries (Din et al., 2022). After adding these variables, Table 11 demonstrates the robustness of this research through the consistency of the results.

Model replacement. The Feasible Generalized Least Squares (FGLS) model offers multiple advantages in panel data estimation, including the ability to address cross-sectional dependence, heteroskedasticity, and autocorrelation. This capability allows the study to validate the robustness of the main conclusions even in the presence of cross-sectional correlation. Additionally, it provides supplementary support for the PECE model. The results of the FGLS model in Table 11 provide additional support for the stability and validity of the conclusions presented in this paper.

Conclusion and policy implications

GTI, REC, and environmental tax are all essential measurements towards the target of IGE. By employing samples of 31 wealthy nations from 2000 to 2021, this study examines the link between GTI and IGE, as well as the mediating effect of REC and the threshold effect of environmental tax. The following are the conclusions: (1) Green technologies are an efficient means of attaining balanced economic, human development, social, and ecological advancement, as GTI has been demonstrated to improve IGE in industrialized nations; (2) The link between GTI and IGE is positively mediated by REC, which accounts for 34.65% of the total effect. This mediating function emphasizes the critical importance of GTI and energy transition in accelerating IGE; (3) Environmental tax has an optimal threshold effect in the relationship between GTI and IGE; when it is lower than 2%, GTI exhibits a stronger contribution to IGE, while the boosting effect will decrease by 23% when exceeding 2%. This result suggests that while appropriate environmental tax can encourage innovation incentives, high tax may impair company innovation capacities, which would reduce the efficiency of GTI in boosting IGE.

There are several policy implications that both developed and emerging economies can draw from the empirical research findings. First, as empirical data shows that GTI directly boosts IGE, developed nations should increase GTI subsidies to businesses and encourage them to create eco-friendly goods and increase energy efficiency, both of which would eventually boost IGE. Second, for both developed and underdeveloped countries, they need to recognize that REC is not only a crucial measurement towards IGE but also mediates the link between GTI and IGE. Governments should encourage the use of market processes, advance grid connection technology, and increase the development of renewable energy infrastructure. Third, environmental tax should be strictly regulated by authorities in developed economies. According to threshold analysis, GTI's beneficial contribution to IGE will drastically decrease as environmental tax rates rise above 2%. This implies that although environmental tax is essential for internalizing the costs of pollution, too high rates may put a financial strain on companies and discourage investment in green technologies. However, developing nations should move more quickly to enhance the environmental tax system and boost tax rates without regard to the negative effects of excessive levels. Fourth, emerging nations should offer more funding for enterprises' GTI to achieve the application and transformation of GTI, which will reduce environmental deterioration during rapid development. In addition to speeding up the energy sector's modernization, improving GTI capabilities helps lessen the harm rapid economic growth frequently causes to the environment.

Despite the fact that this paper provides policy recommendations to developed countries as well as emerging nations based on research findings and realities, it has several limitations. First, the empirical research is limited to industrialized nations due to the accessibility and accuracy of environmental tax data. This restricts the findings' applicability to low-income and emerging economies, where environmental tax systems are still in their infancy. Future studies may include developing nations once environmental tax data is more reliable. Another drawback is the lack of empirical data at the firm level. Although this research employs country-level data to examine the impact of GTI on IGE. At the macro level, it is impossible to examine the specific circumstances of enterprises actually adopting green technologies, adjusting investment choices, or responding to environmental tax legislation. Future research should incorporate firm-level data, as such micro-level analysis will provide deeper insights into how policy regulations and environmental changes translate into corporate behavior, ultimately shaping national-level green growth outcomes.

Data availability

The datasets analyzed in this article are available from the corresponding author upon reasonable request.

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Wei Deng and Ye-Gen Ouyang wrote the main manuscript text; Ye-Gen Ouyang and Saira Kharuddin were responsible for the conceptual framework and proofreading; Wei Deng and Mengjie Zhou were responsible for the empirical analysis; All authors reviewed the manuscript.

Competing interests

The authors declare no competing interests.

Ethical approval
Ethical approval was not required as the study did not involve human participants.

Informed consent
This study does not contain studies with human participants.

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