Energy 306 (2024) 132539

Contents lists available at ScienceDirect

Energy

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

The impact of taxation, technological innovation and trade openness on renewable energy investment: Evidence from the top renewable energy producing countries

Ebaidalla M. Ebaidalla

Ibn Khaldon Center for Humanities and Social Sciences, Qatar University, Qatar

ARTICLE INFO

Handling Editor: X Zhang

Keywords:
Taxation
Renewable energy investment
Technological innovation
Trade openness

ABSTRACT

In the context of contemporary global warming, transitioning from traditional fossil energy to renewable energy sources emerges as a crucial strategy to reduce carbon emissions and achieve the 7th sustainable development goal (SDG). Tax policy significantly shapes the investment landscape, influencing all factors concerning the transition to renewable energy, such as technological innovation and trade openness. However, no empirical studies have examined the direct and moderating role of taxation on renewable energy investment, mainly due to the scarcity of tax data. Therefore, this paper utilizes the recently released Government Revenue Dataset (2023) to explore the complex link between taxation, technological innovation, trade openness, and renewable energy investment for a sample of the top 37 renewable energy-producing countries during the period (1996–2021). The results of the cross-section ARDL (CS-ARDL) and the pooled mean group ARDL (PMG-ARDL) models indicate that taxation has a negative and significant influence on renewable energy investment across all model specifications, both in the short and long run. Conversely, innovation and trade openness exhibit a positive and significant influence on clean energy investment. Regarding the moderating influence of taxation, the results revealed that tax revenues depress the positive impact exerted by technological innovation and international trade. Furthermore, the fully modified ordinary least square (FMOLS) and dynamic ordinary least square (DOLS) models affirm the robustness of the long-run results obtained from CS-ARDL and PMG-ARDL models. The study’s findings offer significant insights into how countries engaged in renewable energy production can enhance their taxation framework to leverage trade and innovation to promote renewable energy investment.

List of the abbreviations

Abbreviation	Definition
ARDL	Autoregressive Distributed Lag
BRI	Belt and Road Initiative
CADF	Cross-sectional Augmented Dickey-Fuller
CIPS	Cross-sectional Im-Pesaran-Shin
CO2	Carbon Dioxide Emissions
CS-ARDL	Cross-section Autoregressive Distributed Lag
CSD	Cross-sectional Dependence
DH	Dumitrescu and Hurlin
DOLS	Dynamic Ordinary Least Square
EKC	Environmental Kuznets Curve
EIA	Energy Information Administration
EU	European Union
FMOLS	Fully Modified Ordinary Least Square
GDP	Gross Domestic Product
GLS	Generalized Least Square
GRD	Government Revenue Dataset
PMG-ARDL	Pooled Mean Group Autoregressive Distributed Lag
RECAI	Renewable Energy Country Attractiveness Index
REI	Renewable Energy Investment
SDG	Sustainable Development Goal
TAX	Taxation
TIN	Technology Innovation
TRD	Trade Openness
UK	United Kingdom
UNU-WIDER	United Nations University-World Institute for Development Economics Research
USA	United States of America
VIF	Variance Inflation Factor
WDI	World Development Indicators

E-mail address: ebaidalla@qu.edu.qa.

https://doi.org/10.1016/j.energy.2024.132539
Received 26 February 2024; Received in revised form 19 July 2024; Accepted 20 July 2024

1. Introduction

In response to the substantial carbon emissions associated with fossil fuels, transitioning to clean energy has emerged as a crucial coping mechanism in recent decades. Renewable energy contributes significantly to environmental quality and sustainable energy supply. For instance, renewable energy sources, such as bioenergy, solar, and wind produce little to no GHG emissions during energy generation, reducing air pollution and contributing to environmental quality [1,2]. Additionally, by diversifying energy sources, countries can enhance their energy security and reduce vulnerability to supply disruptions and price instability in the global energy market [3–5]. Moreover, renewable energy enables the decentralization of energy production, allowing local communities to generate power, reduce transmission losses and maintain control over energy supply [6–8]. Furthermore, transition to clean energy fosters renewable energy production, contributing to achieve the 7th sustainable development goal (SDG) that aims to "*Ensure access to affordable, reliable, sustainable and modern energy for all by 2023*".

The literature documents numerous fiscal instruments that stimulate investment in renewable energy sources, including subsidies, tradable emission rights, and tax incentives [9,10]. Among these, taxation exerts a key role in promoting the development and deployment of green energy technologies [11–13]. Tax incentives provided by the government on machinery, equipment and materials related to renewable energy production can reduce project cost, thereby encouraging renewable energy investment [12,14,15]. In addition, taxes can increase the prices of non-renewable energy products, thus supporting the shift to renewable energy [16,17]. Moreover, specialized taxes, such as carbon taxes, place a greater financial burden on the demand for fossil fuels, creating an incentive for investments in green energy projects [15,18,19].

It is worth mentioning that industrialized and emerging countries, particularly the top renewable energy producing countries, suffer from several environmental problems, including high energy consumption and pollutant emissions [20,21]. Consequently, they are compelled to prioritize investments in clean energy sources and transition towards renewable energy systems as an essential strategy to mitigate environmental degradation. Simultaneously, most of the top renewable energy producing countries collect substantially higher tax revenues, accounting for more than 30 % of their government budgets [22,23]. Despite the theoretical linkage between taxation and renewable energy investment (REI), as far as we know there are no studies exploring this relationship, mainly in the context of the top renewable energy-producing countries, primarily due to the scarcity of taxation datasets. Therefore, this study fills this gap utilizing the recent tax dataset, compiled by the United Nations University, World Institute for Development Economics Research (UNU-WIDER).

Moreover, beyond its direct effect, taxation can indirectly influence renewable energy investment through various channels, a matter that has not been sufficiently studied. Considering the advanced levels of technology and trade openness in the leading renewable energy producing countries, we believe that taxation moderates the influence of innovation and trade on green energy investment. Numerous empirical studies have argued that taxation can provide more resources for public spending on technological innovation related to green energy [24,25]. Furthermore, offering tax credits or deductions for firms that invest in research and development can stimulate technological innovation across various industries, including renewable energy [26,27]. Similarly, taxation can encourage investment in green energy through international trade and capital movements. For instance, tax exemption on clean energy-related technologies may facilitate trade in technology and encourage the transfer of clean energy technology between nations [10,28,29]. Furthermore, reducing trade tariffs enhances the overall international trade of goods and services, particularly renewable energy technologies [30]. Despite the significant interaction between taxation, innovation, international trade and renewable energy investment (REI), this issue remains largely unexplored in existing research. Therefore, the present study aims to investigate the role of taxation, technological innovation, and international trade in encouraging REI in the top renewable energy producing countries. The study also examines whether taxation enhances or weakens the effect of innovation and trade openness on renewable energy investment.

The study has numerous contributions to extant literature. First, to our knowledge, this is the sole study examines the combined effect of taxation, innovation, and trade openness on renewable energy investment in the top renewable energy producing countries, which are currently undergoing an energy transition characterized by high taxes along with advanced levels of trade and technological innovation. Second, although the factors influencing renewable energy consumption have gained sizable attention, there are quite fewer studies examining the drivers of green energy production. Third, the study ensures the robustness of the empirical results by adopting several estimation methods, including the cross-section autoregressive distributed lag (CS-ARDL), pooled mean group-autoregressive distributed lag (PMG-ARDL), fully modified ordinary least squares (FMOLS), and the dynamic ordinary least square (DOLS) models. Finally, this study employs the latest version of the Government Revenue Dataset , making it the first attempt to incorporate this dataset into the renewable energy literature.

The rest of this paper is structured as follows: Section two outlines the theoretical and empirical literature on the nexus between taxation, technological innovation, trade, and investment in renewable energy. Section three details the data and techniques used for estimation. Section four presents the empirical findings and their discussion. Lastly, section five concludes with recommendations and avenues for future research.

2. Literature review

This section reviews the theoretical and empirical literature on the interaction between taxation, trade openness, innovation, and renewable energy investment. The section is structured into four subsections. The first subsection explores theoretical and empirical perspectives on how taxation influences renewable energy investment (REI). The second subsection discusses the association between technological innovation and REI. The third subsection examines the influence of trade openness on REI. Lastly, the fourth subsection identifies and discusses the existing research gap that this study aims to address.

2.1. Link between taxation and renewable energy investment

The impact of taxation on renewable energy investment (REI) can be explained through various investment theories. According to the accelerator theory of investment [31,32], an increase in output or sales encourages firms to expand their investment in equipment and machinery to meet rising demand. However, higher taxes, such as corporate and income taxes, reduce firms' sales and profitability, which in turn increases the effective cost of capital and lowers expected returns. In the same vein, the neoclassical theory of investment developed by Hall and Jorgenson [33], Jorgenson [34] and Boadway [35], suggests that taxation influence investment decisions by affecting the cost of capital. Specifically, taxes on investment returns, like corporate income or capital gains taxes, raise the cost of capital, thereby diminishing firms' incentive to invest in new projects. Similarly, Tobin's Q theory of investment [36] argues that higher taxes increase the cost of capital, discouraging investment when Tobin's Q ("the ratio of market value to replacement cost") is high. Consequently, all mainstream investment theories emphasize that taxation reduces firms' profitability, ultimately negatively affecting investment decisions.

Drawing on the aforementioned theories, taxation can significantly influence investment in renewable energy sources through various channels [12]. For example, offering tax credits for green energy projects can make renewable energy investment more attractive to businesses and investors [14,37]. On the other hand, imposing taxes on carbon emissions or fossil fuel consumption can create economic incentives for transitioning to sustainable energy sources [13]. Moreover, a stable and predictable tax policy environment is crucial for enhancing investor confidence and certainty that is needed to implement long-term renewable energy projects. Overall, tax policy can significantly affect the economic feasibility and investment climate, thereby substantially contributing to renewable energy investment.

Several studies have investigated the association between tax policy and renewable energy investment (REI) using different data samples and estimation techniques. However, most previous studies focused on the influence of special taxes, such as carbon tax and energy tax, yielding inconclusive results. For instance, Abbas et al. [13] scrutinized the association between environmental tax and investment in clean energy investment using data for China over the period between 2012 and 2021. Employing the quantile regression as well as the Probit and Tobit methods, the results showed that environmental tax has a positive effect on investment in clean energy sources. By contrast, Dogan et al. [19] examined the influence of energy and environmental taxes on renewable energy for 25 European Union (EU) states. Using the FMOLS and DOLS models over the period between 1995 and 2019, the study demonstrated that both energy and environmental taxes have a significant negative effect on REI.

2.2. Relationship between technological innovation and renewable energy investment

Technological innovation is a key factor in stimulating investment in clean energy. Indeed, innovations in various renewable technologies, such as solar panels, storage systems and smart grid technologies allow clean energy to be more efficient, affordable and accessible [1,38]. These technological innovations lessen the overall costs of energy projects, making them more appealing to investors [39,40]. Moreover, breakthroughs in research and innovation lead to the discovery of new and improved methods for harnessing renewable energy, further incentivizing investments in sustainable and environmentally friendly energy solutions [41].

Empirically, the influence of technological innovation on REI has gained substantial consideration in energy economics literature. For example, Zheng et al. [1] examined the impact of technological innovation on renewable energy investment across 30 Chinese provinces from 2005 to 2017. Employing both spatial and non-spatial panel models, the study indicated that higher levels of technological innovation are linked to greater renewable energy investment in all provinces. Similarly, Khan et al. [40] explored the causal link between innovation and REI in Germany from 2000 to 2021. Using causality tests, the study revealed a positive and significant influence of technological innovation on REI.

Using a cross-country dataset, Bamati and Raoofi [42] explored the influence of innovation on green energy investment across 25 developing and developed countries from 1990 to 2015. Utilizing the Generalized Least Square (GLS) panel data estimation method, the study revealed that the factors influencing renewable energy sources differ based on the level of development. For instance, in developed countries, the results indicated that investing in green energy is significantly affected by high technology exports, whereas in developing countries, technology exports do not have a notable impact on renewable energy sources. Similarly, Vural [10] examined the association between technological innovation and renewable energy investment in Latin America during the period between 1991 and 2014. The study employed the FMOLS estimation technique and found that innovation exerts a positive and significant influence on REI. Ahmed et al. [38] inspected the effect of technological innovation on renewable energy investment in G7 over the period 1985–2018. Their empirical results revealed that technological innovation encourages renewable energy production in G7 countries. Likewise, Su et al. [43] used a quantile regression approach and found that technological innovation exerts a positive and significant effect on REI in G7 countries. Lately, Khan and Su [41] investigated the association between technological innovation and renewable energy in the Group of Ten (G10). Their findings pointed out a noteworthy influence of technology innovation on REI in certain nations like Germany, Sweden, the Netherlands, the UK, and the USA. Conversely, for other countries, the results revealed an absence of a direct relationship between technology innovation and REI, implying that factors beyond innovation are responsible for the advancement of clean energy in such countries.

2.3. Link between trade openness and renewable energy investment

Trade has been considered a crucial driver of renewable energy investment. It facilitates the flow of goods and services, including advanced technologies, hence allowing countries to access and adopt new renewable energy technologies. This, in turn, promotes investments in renewable energy projects [44,45]. International trade also contributes to cost reduction in the renewable energy sector, as importing components and materials from countries with lower production costs can make renewable energy plans more economically feasible and attractive to businesses [46,47]. In addition, renewable energy projects often rely on global supply chains, hence trade openness facilitates the flow of components and equipment across borders, reducing costs and increasing the efficiency of supply chains for renewable energy projects [29,30].

Empirically, there has been insufficient research attention devoted to the association between trade openness and investment in clean energy. Nevertheless, the available research yields inconclusive evidence. For instance, Chen et al. [48] adopted the autoregressive distributed lag (ARDL) and the Granger causality test to study the association between CO_2 emissions, GDP, international trade and REI in China during the period (1980–2014). The findings indicated a bidirectional causality between trade openness and REI. Hussain et al. [29] scrutinized the link between international trade and renewable energy investment for a sample of 51 Belt and Road Initiative (BRI) states spanning the period between 1996 and 2017. Employing the random-effects and two-stage estimation methods, their results revealed that trade openness moderates the influence of institutional indicators on investment in green energy sources.

2.4. Research gap

While numerous studies have investigated the factors influencing renewable energy investment (REI), there are still existing research gaps that require further exploration. First, the nexus between taxation, technological innovation, trade openness and REI has not received adequate research attention. Given the importance of green energy in the country's strategy toward sustainable and clean energy, this study fills a crucial gap in the literature, focusing on the moderating impact of taxes on REI. Second, while some empirical studies have studied the effect of taxation on clean energy and the environment, the majority have concentrated on specific taxes, such as carbon and environmental taxes. Conversely, the influence of tax revenues on REI has not yet been explored in existing research. Third, since tax policy affects trade openness, innovation and the overall production landscape, analyzing both the direct and moderating impacts of taxation would provide an important contribution to existing literature. Moreover, this study focuses on the top renewable energy-producing countries as a case study because these economies invest more in renewable energy technology while experiencing high tax rates and CO_2 emissions. Therefore, this study contributes significantly to existing literature and offers valuable policy recommendations aimed at enhancing investments in clean energy sources.

3. Methods and data

3.1. Conceptual framework and model specification

Based on the above theoretical and empirical literature, we hypothesize that renewable energy investment (REI) relies on taxation (TAX), technological innovation (TIN), and international trade (TRD). Besides the core explanatory variables, the study uses carbon emissions (CO_2) and GDP per capita (GDP) as control variables. According to the available literature, an improvement in economic growth is likely to stimulate clean energy investment [49,50]. In contrast, CO_2 emission is expected to negatively influence renewable energy investment, as indicated by previous research (e.g. Ref. [29,50,51]). Fig. 1 displays the conceptual framework of the relationships between variables of the study.

Based on the conceptual model, the study addresses the impact of core independent variables on renewable energy investment using four models, with a focus on taxation as a moderator for both technological innovation and trade openness impacts. Each model is designed to capture specific aspects of how these variables interact and influence renewable energy investment.

The first model examines the direct effects of GDP growth (GDP), emissions (CO2), technological innovation (TIN), and taxation (TAX) on renewable energy investment (REI).

$$\mathrm{REI}_{\mathrm{it}} = \alpha_0 + \alpha_1 \mathrm{GDP}_{\mathrm{it}} + \alpha_2 \mathrm{CO}_{2\mathrm{it}} + \alpha_3 \mathrm{TIN}_{\mathrm{it}} + \alpha_4 \mathrm{TAX}_{\mathrm{it}} + \varepsilon_{\mathrm{it}} \tag{1}$$

Where REI_{it} is the outcome variable denoting the level of renewable energy investment and ε_{it} is the disturbance term. Equation (1) shows that REI depends on GDP, CO_2, TAX, and TIN.

The second mode scrutinizes the direct impact of GDP, CO2 emissions, international trade (TRD) and TAX on REI.

$$\mathrm{REI}_{\mathrm{it}} = \beta_0 + \beta_1 \mathrm{GDP}_{\mathrm{it}} + \beta_2 \mathrm{CO}_{2\mathrm{it}} + \beta_3 \mathrm{TRD}_{\mathrm{it}} + \beta_4 \mathrm{TAX}_{\mathrm{it}} + \mathrm{v}_{\mathrm{it}} \tag{2}$$

The above two models serve as a baseline to understand the direct effect of taxation without considering interaction effects.

In the third model, we assess the interaction between technological innovation and taxation as the main effect.

$$\mathrm{REI}_{\mathrm{it}} = \gamma_0 + \gamma_1 \mathrm{GDP}_{\mathrm{it}} + \gamma_2 \mathrm{CO}_{2\mathrm{it}} + \gamma_3 \mathrm{TIN}_{\mathrm{it}} + \gamma_4 \mathrm{TAX}_{\mathrm{it}} + \gamma_5 \mathrm{TIN}_{it} * \mathrm{TAX}_{\mathrm{it}} + \epsilon_{\mathrm{it}} \tag{3}$$

The inclusion of the interaction term (TIN $*$ TAX) allows us to explore whether taxation enhances or weakens the influence of technological innovation on REI.

Finally, the fourth model examines the impact interaction between trade openness and taxation as the main effect.

$$\mathrm{REI}_{\mathrm{it}} = \delta_0 + \delta_1 \mathrm{GDP}_{\mathrm{it}} + \delta_2 \mathrm{CO}_{2\mathrm{it}} + \delta_3 \mathrm{TRD}_{\mathrm{it}} + \delta_4 \mathrm{TAX}_{\mathrm{it}} + \delta_5 \mathrm{TRD}_{it} * \mathrm{TAX}_{\mathrm{it}} + \mu_{\mathrm{it}} \tag{4}$$

The main function of this model is to evaluate the moderating role of taxation on the effect of international trade on REI, captured by the interaction term (TRD*TAX). The interaction coefficient (δ_5) in equations (3) and (4) denotes our key coefficient that assesses the moderating impact of taxation.

The definition and summary statistics of the variables are displayed

Table 1
Definition and summary statistics.

Variable	Definition	Mean	S.D	Skewness	Kurtosis
REI	Investment in renewable energy, represented by total energy generated from renewables (quad Btu)	1.620	3.311	3.953	20.170
TAX	Tax revenues (% of GDP)	22.576	7.121	0.865	4.511
TIN	Technological innovation (Total number of patents)	49455.05	157546.6	3.064	19.133
TRD	Trade (% of GDP)	68.763	31.112	0.994	3.949
GDP	GDP per capita (constant in US$)	30925.8	17420.5	0.045	1.856
CO_2	Greenhouse gas emissions (metric tons per capita)	1.620	3.311	2.282	3.22

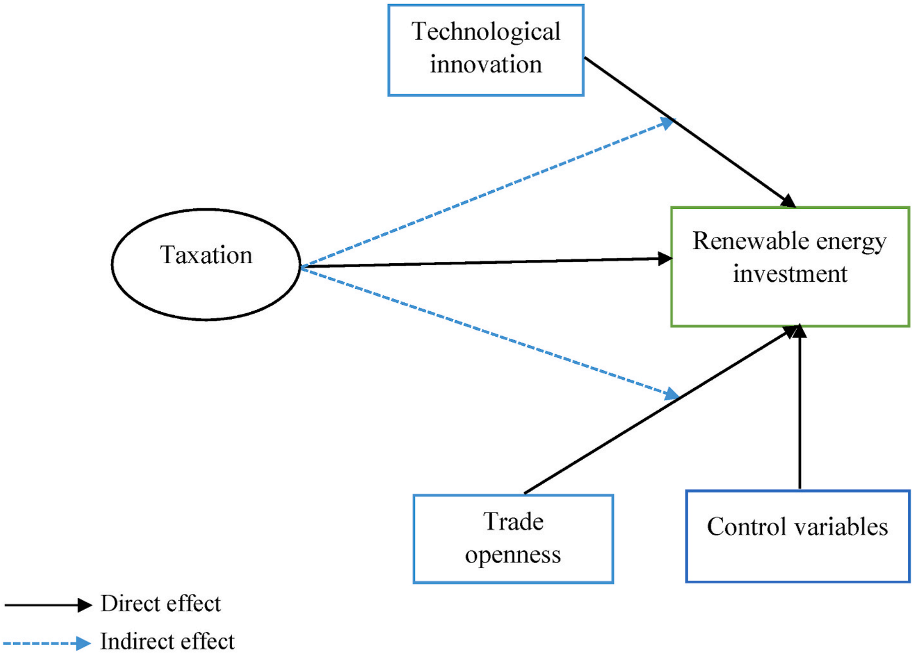

Fig. 1. Conceptual model.

in Table 1. As can be seen from the table, the averages of taxes, trade openness, and technological innovation are relatively high in the sample countries, reflecting the context of these countries. We use all variables in the logarithm form to account for linearizing relationships, stabilizing variance, and improving interpretability.

3.2. Analytical techniques

3.2.1. Testing cross-sectional dependence and slope heterogeneity

Dealing with panel data requires ensuring that the model is free of cross-sectional dependence (CSD) and slope heterogeneity. Examining these issues is crucial for testing the unit root and cointegration characteristics of the variables, and helps in identifying the appropriate estimation methods. Failure to address the CSD and slope heterogeneity may lead to biased results [52,53]. The existence of CSD is a common problem in the studies use panel datasets, as indicated by many preceding researchers (e.g. Ref. [54,55]). The cross-sectional dependence (CSD) arises from interrelated fluctuations and undisclosed factors that collectively boost "error term, spatial dependence, and idiosyncratic pairwise dependency" without a predetermined structure of common fundamentals or spatial interdependence [10,56]. This situation may be explained by the increasing financial and economic connection among nations and financial institutions in recent decades [52,57]. Therefore, to examine the CSD, we adopt three tests, namely, Breusch-Pagan, Pesaran CD, and Pesaran scaled LM.

Regarding slope heterogeneity, the study employs the Pesaran and Yamagata [58] test to evaluate the presence of slope consistency among cross-section units. This test is commonly used in panel data studies because of its capability to address the issue of cross-sectional dependency [2,52].

3.2.2. Testing unit root and cointegration

Following inspecting CSD, we examine the stationarity of the variables to identify the integration order of our variables. Given that we aim to adopt the CS-ARDL and ARDL-PMG models, the stationarity test is a pre-condition to ensure that the variables are not stationary at second differences. The outcomes of CSD examination help to select the suitable unit root test. If the CSD test indicates the existence of a cross-sectional dependence issue, we adopt the second-generation unit root tests, like Cross-sectional Augmented Dickey-Fuller (CADF) and Cross-sectional Im-Pesaran-Shin (CIPS) tests. These tests are more appropriate to deal with the issue of CDS [10,38].

After inspecting the unit root properties of our variables, we test the cointegration to examine the long-run association between the variables under study. The study employs the Westerlund [59] test, which is an appropriate second-generation cointegration test used in literature to overcome cross-sectional dependence (CSD) and slope variability [10, 60].

3.2.3. Estimation techniques

To estimate our models presented in equation (1) through 4, we adopt the Cross-section ARDL (CS-ARDL) and the Pooled Mean Group ARDL (PMG-ARDL) models. The CS-ARDL model, established by Chudik and Pesaran [61], extends the ARDL framework by incorporating cross-sectional averages and lagged values of variables. The CS-ARDL has several advantages over other panel cointegration methods, such as the FMOLS and DOLS. First, the CS-ARDL technique allows us to address the issue of slope variability and endogeneity [2,62]. Second, this method can be adopted regardless of the order of integration, accommodating variables with mixed orders such as stationary I(0) and non-stationary I(1) processes. Third, the CS-ARDL method yields consistent outcomes in the presence of CSD. In recent decades, a vast body of studies has adopted this approach to explore diverse issues related to energy economics and environmental quality, particularly in the realm of panel data, where CSD is widespread (e.g. Ref. [45,62,63]). Therefore, the CS-ARDL model for equations (1)–(4) can be described as follows:

$$\mathrm{REI}_{\mathrm{it}} = \sum_{\mathrm{j=1}}^{\mathrm{p}} \delta_{\mathrm{ij}} \mathrm{REI}_{\mathrm{it-j}} + \sum_{\mathrm{j=0}}^{\mathrm{q}} \phi'_{\mathrm{ij}} \mathrm{X}_{\mathrm{it-j}} + \sum_{\mathrm{j=0}}^{\mathrm{r}} \vartheta'_{\mathrm{ij}} \overline{\mathrm{Z}}_{\mathrm{\ t-j}} + \omega_{\mathrm{t}} + \mu_{\mathrm{it}} \tag{5}$$

where, $\overline{\mathrm{Z}}_{\mathrm{\ t-j}} = (\overline{\mathrm{REI}}_{\mathrm{i,t-j}}, \overline{\mathrm{X}}_{\mathrm{i,t-j}})$ represents the means of cross-sections for dependent and explanatory variables, thereby addressing cross-section dependence [2,45]. X_{it} is the vector of predictors, which includes control variables (i.e. GDP and CO2) beside the core regressors (TAX, TIN, TRD, TIN*TAX, TRD*TAX). Since equation (5) applies to different specifications (i.e., equations (1)–(4)), the vector of X_{it} varies accordingly. The symbols p and q denote the lags for the response and regressors, respectively. Moreover, the term ω_t denotes the fixed effects. δ_{ij} is the parameter of the lagged outcome variable; ϕ'_{ij} are coefficients vector of lagged regressors; and μ_{it} is a disturbance term.

The long-term parameters of the CS-ARDL can be measured through the following equation:

$$\widehat{\gamma}_{\mathrm{CS-ADL,ij}} = \frac{\sum_{\mathrm{j=0}}^{\mathrm{q}} \widehat{\phi}_{\mathrm{ij}}}{1 - \sum_{\mathrm{j=1}}^{\mathrm{p}} \widehat{\delta}_{\mathrm{ij}}} \tag{6}$$

Moreover, the error correction form can be described as below:

$$\begin{aligned}\Delta\mathrm{REI}_{\mathrm{it}} &= \lambda_{\mathrm{i}}\left[\mathrm{REI}_{\mathrm{it-j}} - \gamma_{\mathrm{ij}}\mathrm{X}_{\mathrm{it}}\right] \\ &- \sum_{\mathrm{j=1}}^{\mathrm{p-1}} \delta_{\mathrm{ij}} \Delta\mathrm{REI}_{\mathrm{it-j}} + \sum_{\mathrm{j=0}}^{\mathrm{q}} \phi'_{\mathrm{ij}} \Delta\mathrm{X}_{\mathrm{it-j}} + \sum_{\mathrm{j=0}}^{\mathrm{r}} \vartheta'_{\mathrm{ij}} \overline{\mathrm{Z}}_{\mathrm{\ t-j}} + \omega_{\mathrm{t}} + \mu_{\mathrm{it}}\end{aligned} \tag{7}$$

In equation (7), λ_i represents the error correction term (ECT), which quantifies the rate at which renewable energy investment (REI) adjusts toward long-term equilibrium. The ECT coefficient is expected to be negative, falling between 0 and 1. Δ indicates the first difference operator, while the remaining terms are defined as in equation (5).

In addition to the CS-ARDL model, the analysis adopts the pooled mean group-autoregressive distributed lag (PMG-ARDL) model. The PMG-ARDL is similar to CS-ARDL model, as both are based on an autoregressive distributed lag process, consequently being more appropriate for comparing results. The PMG-ARDL model also provides short and long-term coefficients comparable to those of the CS-ARDL method. In addition, PMG-ARDL resolves concerns related to cross-section dependence, slope heterogeneity, and endogeneity, hence providing reliable estimators. Furthermore, the PMG-ARDL is formulated to reflect dynamic associations by accommodating lagged dependent and explanatory variables. Finally, adopting both PMG-ARDL and CS-ARDL for comparison purposes is supported by several empirical studies (e.g., Ref. [56,64]). Following the ARDL framework, we specify the PMG-ARDL model of short and long-term estimators, as follows.

$$\Delta\mathrm{REI}_{\mathrm{it}} = \theta_{\mathrm{i}}\left(\mathrm{REI}_{\mathrm{it-j}} + \alpha_{\mathrm{ij}}\mathrm{X}_{\mathrm{it}}\right) + \sum_{\mathrm{j=1}}^{\mathrm{p-1}} \pi_{\mathrm{ij}} \Delta\mathrm{REI}_{\mathrm{it-j}} + \sum_{\mathrm{j=0}}^{\mathrm{q}} \rho_{\mathrm{ij}} \Delta\mathrm{X}_{\mathrm{it-j}} + \omega_{\mathrm{t}} + \mu_{\mathrm{it}} \tag{8}$$

In Equation (8), θ_{i} denotes the error correction term, π_{ij} and ρ_{ij} capture the short-term parameters, while α_{ij} represents the long-term parameters of the model. Furthermore, X_{it} represents the vector of explanatory variables, as defined earlier.

Moreover, to verify the robustness of the long-term findings of the CS-ARDL and PMG-ARDL models, the study employs the panel Fully Modified OLS (FMOLS) and panel Dynamic OLS (DOLS) models. These methods are widely employed in literature to estimate the long-run coefficients. Both DOLS and FMOLS possess the capability to mitigate problems of small sample bias, autocorrelation and endogeneity associated with the OLS estimator [56,65,66].

Finally, to investigate the causal association between the variables, we utilize the Dumitrescu and Hurlin [67] panel Granger causality test. Here is the DH causality test specification:

$$Y_{it} = \gamma_i + \sum_{k=1}^{K} \theta_i^k Y_{it-k} + \sum_{k=1}^{K} \epsilon_i^k Z_{it-k} + \mu_{it} \tag{9}$$

Here, K denotes the optimal lag length. The null hypothesis in the HD test suggests no causal effect from Z to Y, while the alternative hypothesis suggests causality from Z to Y. We use the DH causality test because it is suitable for cases involving heterogeneity across countries and cross-sectional dependence [54,60].

3.3. Data and data sources

The study employs annual data from 1996 to 2021, covering the top 37 renewable energy-producing countries. These countries, selected based on the Renewable Energy Country Attractiveness Index (RECAI) by Ernst & Young Global Limited, include Argentina, Austria, Australia, Belgium, Brazil, Canada, China, Chile, Denmark, Egypt, France, Finland, Greece, Germany, Italy, India, Israel, Japan, Kazakhstan, Morocco, Mexico, Norway, Netherlands, Poland, Philippines, Portugal, Romania, South Korea, South Africa, Spain, Switzerland, Sweden, Turkey, Thailand, UK, USA, and Vietnam.

Data were sourced from various outlets, such as the Energy Information Administration (EIA), the Government Revenue Dataset (GRD), and the World Bank' World Development Indicators (WDI). In the literature, there are several measurements have been used to quantify the renewable energy investment (REI), such as the portion of renewable energy in total energy production [29]. However, following the recent studies on renewable energy investment (e.g. Ref. [49,51]), we measure REI using the production of total renewable energy from all renewable sources. The data on renewable energy investment is sourced from the EIA. Data on GDP, carbon emissions, trade, and technological innovation are gathered from the WDI.

Importantly, data on tax revenues are sourced from the Government Revenue Dataset (GRD), compiled by the UNU-WIDER. The GRD provides a comprehensive and detailed compilation of government revenue data for 200 countries and territories from 1980 onwards. It encompasses various types of revenues, including tax and non-tax revenues, and provides a breakdown of tax types such as direct taxes, indirect taxes, and taxes on international trade. This dataset offers valuable insights into government fiscal behavior, enabling researchers to analyze trends, compare fiscal policies, and assess the economic impact of different revenue sources [23].

Tables 2 and 3 present the correlation matrix and the outcomes of the variance inflation factor (VIF) examination, respectively. The VIF terms for all variables are below 5, implying the absence of multicollinearity among the variables.

4. Results and discussion

4.1. Pre-requisite tests

Table 2
Correlation matrix.

	REI	TAX	TIN	TRD	GDP	CO_2
REI	1.000					
TAX	−0.050	1.000				
TIN	0.790	−0.140	1.000			
TRD	−0.333	0.173	−0.316	1.000		
GDP	0.173	0.619	0.149	0.241	1.000	
CO_2	0.065	−0.188	0.120	−0.197	−0.359	1.000

Table 3
Multicollinearity test: Inflation factor analysis.

	VIF	1/VIF
TAX	2.200	0.455
TIN	1.810	0.552
TRD	1.350	0.741
GDP	1.240	0.807
CO_2	1.210	0.829
VIF Mean	1.56	

Table 4
Results of cross-sectional dependence.

Variable	Breusch-Pagan test	Pesaran CD test	Pesaran scaled LM test
REI	115.271[a]	7.327[a]	41.267[a]
TAX	63.446[a]	6.672[a]	13.446[a]
TIN	52.255[a]	8.921[a]	8.255[a]
TRD	106.364[a]	7.887[a]	36.838[a]
GDP	89.562[a]	9.432[a]	21.364[a]
CO2	71.723[a]	10.623[a]	19.271[a]
TAX*TIN	83.214[a]	9.832[a]	17.921[a]
TAX*TRD	92.234[a]	6.502[a]	28.210[a]

[a] Denotes 1 % significance.

As outlined in the methodology, our analysis commences by assessing cross-sectional dependence (CSD) and slope heterogeneity. The results of CSD in Table 4 indicate that all test statistics for the three CSD tests are statistically significant at the 1 % level for all variables, indicating the incidence of cross-sectional dependence. This implies that the countries under study are connected and any economic or financial shocks in one country may affect other nations. Moreover, the statistics of Pesaran and Yamagata's [58] test of slope heterogeneity in Table 5 are significant in all four models, implying slope heterogeneity among the estimated models.

After conducting cross-sectional dependence (CSD) and slope variability tests, the second phase is inspecting the unit root of the variables under study. Nevertheless, in the incidence of CSD and slope heterogeneity, the first-generation unit root testing techniques may lead to biased results. Therefore, our analysis used the second-generation unit root test, namely CIPS and CADF, as outlined in the methodology. The results of both Cross-sectional Im-Pesaran-Shin (CIPS) and Cross-sectional Augmented Dickey-Fuller (CADF) tests in Table 6 point out that all variables are integrated at the first difference, except the REI and CO_2 variables are stationary at the level. Therefore, in the presence of different orders of integration amongst the variables, using CS-ARDL and PMG-ARDL models becomes a suitable approach for estimation.

Moreover, to test the long-run relationship between the variables, we adopted the Westerlund [59] test, which is a suitable method when dealing with cross-sectional dependence and variability in slopes. The results of cointegration in Table 7 indicate that most statistics of the Westerlund are statistically significant in all models, implying the occurrence of cointegration between the variables. Upon identifying a long-run relationship between the variables, CS-ARDL and PMG-ARDL models would be appropriate techniques to investigate the long-run coefficients.

4.2. Results of CS-ARDL and PMG-ARDL models

Table 8 presents the estimation results of our models using the CS-ARDL and PMG-ARDL methods. Starting with the control variables, the Table reveals that GDP is significant and bears its expected sign in

Table 5
Slope heterogeneity.

	Model 1	Model 2	Model 3	Model 4
Delta tilde	23.933[a]	23.669[a]	20.541[a]	20.277[a]
Delta tilde adjusted	27.488[a]	27.185[a]	24.252[a]	23.940[a]

[a] Denotes 1 % significance.

Table 6
Results of unit root test.

Variable	CADF		CIPS	
	Level	First difference	Level	First difference
REI	-2.779^{b}	-3.030^{a}	-2.695^{a}	-5.226^{a}
TAX	-1.920	-4.634^{a}	-2.008	-4.441^{a}
TIN	-2.169	-4.816^{a}	-2.009	-4.603^{a}
TRD	-2.251	-4.209^{a}	-1.560	-4.143^{a}
GDP	-1.676	-3.221^{a}	-1.811	-3.171^{a}
CO_2	-2.609^{b}	-5.007^{a}	-2.377^{a}	-4.865^{a}

[a] $p < 0.01$.
[b] $p < 0.05$.

Table 7
Westerlund Bootstrap test results (Z-value).

	Model 1	Model 2	Model 3	Model 4
G_t	-3.01^{a}	-2.193^{a}	-2.729^{b}	-1.211
G_a	-2.12	-2.608	-3.291^{a}	-4.353^{c}
P_t	-4.18^{a}	-3.879^{a}	-0.087	-1.339^{c}
P_a	2.36^{a}	-1.344^{c}	-2.826^{b}	-2.508^{c}

[a] $p < 0.01$.
[b] $p < 0.05$.
[c] $p < 0.1$.

both the short and long-term, whereas CO_2 emissions are negative and significant only in the long-term. Precisely, the short-run and long-run results reveal that GDP growth exerts a positive impact on REI in all four models, using both CS-ARDL and PMG-ARDL methods. This finding aligns with many prior studies (e.g. Ref. [1,39,42]).

The results of long-run model point out that the effect of CO_2 emissions on REI is negative and significant in all estimated models. This result implies that GHG emissions discourage green energy production in the long-run. Serval studies, such as Silva et al. [50], Bellakhal et al. [49], Hussain et al. [29], and Alsagr [51] revealed a similar impact for CO_2 emissions on REI. By contrast, the outcomes of the short-run for both PMG-ARDL and the CS-ARDL models point out that the coefficients of CO_2 emissions are insignificant in all four models, implying that GHG emissions have no significant impact on REI in the short-term, supporting the results of Alsagr [51].

Regarding our core explanatory variables, the results of CS-ARDL and PMG-ARDL estimators indicate that taxation exerts an adverse and significant impact on REI in all models, across both the short and long-term. This result implies that taxation reduces green energy investment in the top renewable energy-producing nations. This can be justified by the fact that an increase in tax rate discourages investors from innovating and investing in environmental-related technology, hence depressing energy transition. This finding corroborates many previous studies, which argued that taxation discourages investment in environmental technology and clean energy (e.g. Ref. [12,17]). Furthermore, this result supports mainstream investment theories, such as the accelerator principle and the neoclassical model, which argue that taxation reduces firms' profitability and, subsequently their investment decisions. Nevertheless, this result contradicts the impact of environmental taxation on green energy technologies, as several empirical studies like Nchofoung et al. [68] and Dogan et al. [19] found that environmental taxes enhance renewable energy production. Therefore, our study highlights the importance of taxation in renewable energy investment and offers valuable contributions to the theoretical connections between these variables.

Moreover, the results demonstrate that the impact of technological innovation is positive and significant on REI in most long-term models, nevertheless, the short-run impact of innovation on REI is insignificant in models 2 and 4. This result suggests that technological innovation exerts a significant role in stimulating energy transition in the top clean energy-producing countries, particularly in the long-term. This also suggests that advanced energy technology concerning energy generation and storage would enhance renewable energy investment, as innovation offers cheap technologies infrastructure, hence attracting investors to renewable energy [69,70]. Moreover, Khan et al. [40] and Adebayo et al. [2] argued that advanced energy technology has the potential to contribute to improving renewable energy generation capabilities, hence promoting the shift toward renewable energy sources.

In addition, the findings of long-term for both PMG-ARDL and CS-ARDL estimators revealed that trade openness positively and significantly influences renewable energy investment across most model specifications. However, the results of the short-run revealed that the effect of international trade is positive and significant in models 2 and 4 according to the CS-ARDL method, while it is significant in model 2 under the PMG-ARDL method. The short-run results of trade openness imply that a country with a high level of international trade has the potential to produce more clean energy sources. This finding supports many previous empirical research (e.g., Ref. [10,49]).

Furthermore, to understand whether taxation enhances or depresses the effect of technological innovation and trade on renewable energy investment, we estimated our model using two interaction terms (i.e., TIN*TAX and TRD*TAX), as outlined in models 3 and 4. The results of the long-run reveal that the interaction effect of TAX with TIN is positive and significant in both CS-ARDL and PMG-ARDL models. However, the coefficient of the interaction term is lower in comparison to the direct effect of technological innovation, suggesting that taxation weakens the positive influence of innovation on green energy investment. This result can be clarified by the fact that taxation discourages investment in innovation, hence reducing its impact on REI. Conversely, the impact of TIN*TAX in the short-run is found insignificant under the two estimation methods.

Regarding the moderation impact of taxation on trade openness, the results reveal that the effect of interaction between taxation and trade openness (TRD*TAX) is negative and significant in both the short and long-term. This result implies that taxes undermine the positive impact of trade openness. This finding can be attributed to the fact that an increase in tax rates reduces the volume of international trade, hence negatively affecting the REI. This result also means that taxes on international trade depresses investment in renewable energy sources. Furthermore, this finding aligns with the real-world context in the countries under examination, where high tax rates are prevalent.

Finally, the parameters of the error correction term are consistently negative and significant across all estimated models using various estimation methods. The relatively high values of error terms suggest a substantial degree of adjustment between our variables toward equilibrium over one year.

4.3. *Robustness analysis*

To validate the reliability of the long-term findings, we adopted two alternative single equation estimation techniques, namely the fully modified OLS (FMOLS) and the dynamic OLS (DOLS) models. The outcomes of both FMOLS and DOLS models in Table 9 show that all the estimated coefficients align with the long-term results of CS-ARDL and PMG-ARDL models presented in Table 8. Remarkably, the coefficients of interaction terms are consistent with the results of CS-ARDL and PMG-ARDL methods, confirming the harmful effect of taxation on clean energy investment through technology innovation and trade openness. Therefore, we conclude that our results are robust under different estimation methods, hence lending support to the impact of our core explanatory variables (i.e., TAX, TIN, and TRD).

4.4. *Causality test results*

Finally, to comprehend the causal connections among the variables under study, we employed the Dumitrescu and Hurlin [67] panel Granger causality test. The results of the DH test for the causality

Table 8
Results of CS-ARDL and PMG-ARDL models.

Variable	CS-ARDL				PMG-ARDL			
	Model 1	Model 2	Model 3	Model 4	Model 1	Model 2	Model 3	Model 4
Long-run coefficients								
GDP	0.765[a]	0.793[a]	0.769[a]	0.810[a]	1.220[a]	1.320[a]	0.952[a]	0.879[a]
	(0.105)	(0.106)	(0.105)	(0.106)	(0.222)	(0.224)	(0.233)	(0.229)
CO_2	−0.525[a]	−0.465[a]	−0.522[a]	−0.455[a]	−0.954[a]	−0.887[a]	−0.767[a]	−0.856[a]
	(0.052)	(0.056)	(0.052)	(0.058)	(0.218)	(0.242)	(0.201)	(0.244)
TAX	−0.387[b]	−0.306[c]	−0.473[b]	−0.555[a]	−0.482[a]	−0.389[b]	−0.376[a]	−0.537[a]
	(0.153)	(0.161)	(0.150)	(0.180)	(0.131)	(0.173)	(0.121)	(0.160)
TIN	0.200[a]		0.035		0.067[b]		0.367	
	(0.025)		(0.109)		(0.030)		(0.302)	
TRD		0.051[b]		0.003		0.267[b]		0.021
		(0.025)		(0.004)		(0.115)		(0.047)
TAX*TIN			0.143[a]				0.030[b]	
			(0.023)				(0.011)	
TAX*TRD				−0.198[c]				−0.243[b]
				(0.107)				(0.102)
Short-run coefficients								
D(GDP)	0.369[a]	0.231[b]	0.224[b]	0.076[b]	0.456[a]	0.359[a]	0.483[a]	0.346[a]
	(0.080)	(0.089)	(0.091)	(0.033)	(0.120)	(0.109)	(0.101)	(0.092)
D(GDP(1))	0.213[c]	0.121[a]	0.016[b]	0.089	0.361[c]	0.236	0.398[c]	0.256
	(0.108)	(0.030)	(0.007)	(0.115)	(0.206)	(0.200)	(0.208)	(0.213)
D(CO_2)	−0.313	−0.244	−0.238	−0.334	−0.241	−0.202	−0.262	−0.173
	(0.283)	(0.220)	(0.223)	(0.227)	(0.202)	(0.218)	(0.211)	(0.201)
D(CO_2(1))	−0.234	−0.123	−0.076	−0.134	−0.178	−0.202	−0.223	−0.202
	(0.177)	(0.093)	(0.237)	(0.318)	(0.131)	(0.140)	(0.171)	(0.173)
D(TAX)	−0.299[a]	−0.265[a]	−0.303[a]	−0.161[b]	−0.485[b]	−0.389[b]	−0.461[a]	−0.354[b]
	(0.069)	(0.066)	(0.076)	(0.067)	(0.210)	(0.167)	(0.152)	(0.144)
D(TAX(-1))	−0.179	−0.271	−0.209	−0.223	−0.270	−0.091	−0.291	−0.342
	(0.301)	(0.221)	(0.216)	(0.251)	(0.278)	(0.235)	(0.256)	(0.233)
D(TIN)	0.318[a]		0.421[a]		0.440[a]		0.321[c]	
	(0.050)		(0.127)		(0.165)		(0.162)	
D(TIN(1))	0.102[b]		0.201[c]		0.097[c]		0.222[a]	
	(0.046)		(0.107)		(0.052)		(0.047)	
D(TRD)		0.114[a]		0.132[a]		0.473[b]		0.230
		(0.016)		(0.026)		(0.170)		(0.182)
D(TRD(-1))		0.324		0.289		0.183[c]		0.167[b]
		(0.601)		(0.456)		(0.099)		(0.063)
D(TAX*TIN)			0.191				0.132	
			(0.199)				(0.101)	
D(TAX*TIN(-1))			0.056				0.109	
			(0.091)				(0.079)	
D(TAX*TRD)				−0.127[b]				−0.090[a]
				(0.051)				(0.022)
D(TAX*TRD(-1))				−0.082[a]				−0.218[c]
				(0.033)				(0.125)
Constant					6.222[a]	7.291[a]	4.768[a]	3.145[a]
					(0.123)	(0.129)	(0.117)	(0.096)
ECT(−1)	−0.456[a]	−0.521[a]	−0.501[a]	−0.552[a]	−0.642[a]	−0.626[a]	−0.701[a]	−0.675[a]
	(0.055)	(0.062)	0.044	0.056	(0.043)	(0.060)	0.066	0.054

Standard error between ( ).
[a] $p < 0.01$.
[b] $p < 0.05$.
[c] $p < 0.1$.

between renewable energy investment and the core explanatory variables (Taxes, technological innovation, and trade) are displayed in Table 10. The results indicate that there is bidirectional causality among all the variables under examination. These results show that, on one hand, the main independent variables Granger cause REI, and on the other hand, renewable energy investment causes changes in taxation, innovation, and trade openness. Therefore, these findings confirm the long-term association among renewable energy investment and the key independent variables.

Overall, the results generated from different model specifications using various estimation techniques confirm the negative impact of taxation on REI. That is, taxation exerts a direct negative influence on renewable energy investment, implying that a rise in tax rate discourages investment in green energy among the leading renewable energy-producing countries. Moreover, taxation depresses the effect of innovation and international trade on green energy investment. These outcomes align with investment theories such as the accelerator principle and neoclassical theory, which highlight that increased taxes reduce investment profitability, thereby diminishing anticipated returns and discouraging investment decisions. In conclusion, the study underscores how taxation hinders the shift to cleaner energy sources in the leading renewable energy-producing countries. Fig. 2 shows a summary of the results obtained from the estimation techniques.

5. Conclusion and recommendations

This study investigated the impact of taxation, technological innovation, and trade openness on renewable energy investment, with an emphasis on the moderating impact of taxation in the 37 top renewable energy producing nations. We adopted the Cross-section ARDL (CS-ARDL) and the Pooled Mean Group ARDL (PMG-ARDL) models for panel data during the period of 1996–2021. The results revealed that taxation

Table 9
Results of FMOLS and DOLS (robustness analysis).

Variable	FMOLS				DOLS			
	Model 1	Model 2	Model 3	Model 4	Model 1	Model 2	Model 3	Model 4
GDP	1.445[a]	1.115[a]	1.512[a]	1.031[a]	1.453[a]	1.115[a]	1.522[a]	1.031[a]
	(0.083)	(0.025)	(0.088)	(0.022)	(0.113)	(0.0280)	(0.135)	(0.0266)
CO_2	−0.637[a]	−0.457[a]	−0.634[a]	−0.676[a]	−0.645[a]	−0.456[a]	−0.640[a]	−0.677[a]
	(0.101)	(0.078)	(0.095)	(0.065)	(0.131)	(0.101)	(0.124)	(0.0998)
TAX	−0.288[a]	−0.299[a]	−0.743[a]	−0.613[a]	−0.283[a]	−0.299[a]	−0.964[a]	0.631[a]
	(0.056)	(0.043)	(0.058)	(0.180)	(0.071)	(0.051)	(0.380)	(0.170)
TIN	0.286[a]		0.896[b]		0.290[a]		0.910[c]	
	(0.047)		(0.390)		(0.064)		(0.530)	
TRD		0.425[a]		0.304[a]		0.426[a]		0.312[a]
		(0.051)		(0.072)		(0.055)		(0.070)
TAX*TIN			0.217[a]				0.220[a]	
			(0.038)				(0.062)	
TAX*TRD				−0.469[a]				−0.472[c]
				(0.145)				(0.267)
Constant	−3.45[a]	−3.49[a]	−5.37[a]	−6.49[a]	−2.51[a]	−3.49[a]	−3.36[a]	−4.53[a]
	(0.391)	(0.274)	(1.423)	(1.446)	(0.700)	(0.336)	(0.337)	(0.110)

Standard error between ( ).

[a] $p < 0.01$.

[b] $p < 0.05$.

[c] $p < 0.1$.

Table 10
Results of DH causality test.

Null hypothesis	W-statistics	P-value
GDP does not cause REI	2.227[a]	0.0000
REI does not cause GDP	18.962[a]	0.0000
CO_2 does not cause REI	12.448[a]	0.0000
REI does not cause CO_2	14.026[a]	0.0000
TAX does not cause REI	12.988[a]	0.0000
REI does not cause TAX	6.826[a]	0.0000
TIN does not cause REI	19.407[a]	0.0000
REI does not cause TIN	8.355[a]	0.0000
TRD does not cause REI	8.759[a]	0.0000
REI does not cause TRD	17.781[a]	0.0000
TAX*TIN does not cause REI	18.144[a]	0.0000
REI does not cause TAX*TIN	15.911[a]	0.0000
TAX*TRD does not cause REI	4.966[a]	0.0000
REI does not cause TAX*TRD	12.484[a]	0.0000

$^{**}p < 0.05$, $^{*}p < 0.1$

The selection of the lag length relies on the Akaike information criterion (AIC).

[a] $p < 0.01$.

exerts an adverse and significant impact on renewable energy investment in both the short and long-run across all estimated models. The impacts of technological innovation and international trade are found to be positive and significant, suggesting that countries with advanced technological innovation and high degree of trade openness are inclined to invest in clean energy projects. However, the results indicate that taxation diminishes the positive influence of both innovation and trade openness on renewable energy investment. Therefore, we conclude that higher tax rates negatively impact renewable energy investment in the top renewable energy producing nations.

The study suggests several policy options to quicken the transition to clean energy sources in the leading renewable energy producing nations. First, policymakers should prioritize tax policy reforms, such as offering tax credits and subsidies for renewable energy investments and reducing overall tax rates. Second, efforts should be intensified to promote technological innovation by incentivizing research and development in advanced green energy technologies, particularly in low-cost energy and clean energy materials. Finally, enhancing trade policies, such as lowering tariffs and streamlining non-tariff barriers, is crucial for fostering trade openness in renewable energy technologies. These measures, along with promoting trade integration and adhering to international standards and certification processes, can facilitate global

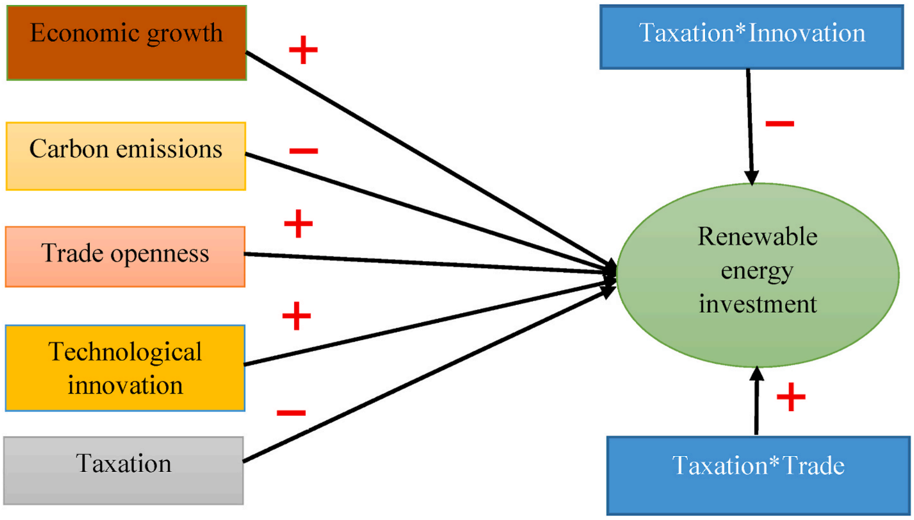

Fig. 2. Summary of estimation results.

cooperation and knowledge exchange, thereby accelerating the transition towards sustainable energy production.

CRediT authorship contribution statement

Ebaidalla M. Ebaidalla: Writing – review & editing, Writing – original draft, Software, Resources, Methodology, Investigation, Formal analysis, Conceptualization.

Declaration of competing interest

The corresponding author declares that he has no financial or non-financial interests that may have influenced the research or the outcomes reported in this paper. The research was conducted with academic rigor and the author was not subject to any external influences that could compromise the objectivity or integrity of the findings. There is no funding or financial support that could potentially introduce bias for this study. The authors affirm their commitment to transparency and declare no conflicts of interest related to the publication of this research in the **Energy** Journal.

Data availability

https://figshare.com/s/4eaa9ded714a05eb9c88

Acknowledgments

Open Access funding provided by the Qatar National Library.

References

[1] Zheng H, Song M, Shen Z. The evolution of renewable energy and its impact on carbon reduction in China. Energy 2021;237:121639.
[2] Adebayo TS, Ullah S, Kartal MT, Ali K, Pata UK, Ağa M. Endorsing sustainable development in BRICS: the role of technological innovation, renewable energy consumption, and natural resources in limiting carbon emission. Sci Total Environ 2023;859:160181.
[3] Paravantis JA, Kontoulis N. Energy security and renewable energy: a geopolitical perspective. In: Renewable energy-resources, challenges and applications. IntechOpen; 2020.
[4] Cergibozan R. Renewable energy sources as a solution for energy security risk: empirical evidence from OECD countries. Renew Energy 2022;183:617–26.
[5] Khan K, Su CW, Khurshid A, Qin M. Does energy security improve renewable energy? A geopolitical perspective. Energy 2023;282:128824.
[6] Burke MJ, Stephens JC. Political power and renewable energy futures: a critical review. Energy Res Social Sci 2018;35:78–93.
[7] Zhang C, Zhou D, Wang Q, Ding H, Zhao S. Will fiscal decentralization stimulate renewable energy development? Evidence from China. Energy Pol 2022;164:112893.
[8] Sun Y, Gao P, Razzaq A. How does fiscal decentralization lead to renewable energy transition and a sustainable environment? Evidence from highly decentralized economies. Renew Energy 2023;206:1064–74.
[9] Bersalli G, Menanteau P, El-Methni J. Renewable energy policy effectiveness: a panel data analysis across Europe and Latin America. Renew Sustain Energy Rev 2020;133:110351.
[10] Vural G. Analyzing the impacts of economic growth, pollution, technological innovation and trade on renewable energy production in selected Latin American countries. Renew Energy 2021;171:210–6.
[11] Curtin J, McInerney C, Gallachóir BÓ. Financial incentives to mobilise local citizens as investors in low-carbon technologies: a systematic literature review. Renew Sustain Energy Rev 2017;75:534–47.
[12] Qadir SA, Al-Motairi H, Tahir F, Al-Fagih L. Incentives and strategies for financing the renewable energy transition: a review. Energy Rep 2021;7:3590–606.
[13] Abbas J, Wang L, Belgacem SB, Pawar PS, Najam H, Abbas J. Investment in renewable energy and electricity output: role of green finance, environmental tax, and geopolitical risk: empirical evidence from China. Energy 2023;269:126683.
[14] Washburn C, Pablo-Romero M. Measures to promote renewable energies for electricity generation in Latin American countries. Energy Pol 2019;128:212–22.
[15] Onwe JC, Bandyopadhyay A, Hamid I, Rej S, Hossain ME. Environment sustainability through energy transition and globalization in G7 countries: what role does environmental tax play? Renew Energy 2023;218:119302.
[16] Ghazouani A, Xia W, Ben Jebli M, Shahzad U. Exploring the role of carbon taxation policies on CO2 emissions: contextual evidence from tax implementation and non-implementation European Countries. Sustainability 2020;12(20):8680.
[17] Helm C, Mier M. Steering the energy transition in a world of intermittent electricity supply: optimal subsidies and taxes for renewables and storage. J Environ Econ Manag 2021;109:102497.
[18] Yue X, Peng MYP, Anser MK, Nassani AA, Haffar M, Zaman K. The role of carbon taxes, clean fuels, and renewable energy in promoting sustainable development: how green is nuclear energy? Renew Energy 2022;193:167–78.
[19] Dogan E, Hodžić S, Šikić TF. Do energy and environmental taxes stimulate or inhibit renewable energy deployment in the European Union? Renew Energy 2023;202:1138–45.
[20] Saidi K, Omri A. The impact of renewable energy on carbon emissions and economic growth in 15 major renewable energy-consuming countries. Environ Res 2020;186:109567.
[21] Wang JH, Mamkhezri J, Khezri M, Karimi MS, Khan YA. Insights from European nations on the spatial impacts of renewable energy sources on CO2 emissions. Energy Rep 2022;8:5620–30.
[22] OECD. Revenue statistics 2023: tax revenue buoyancy in OECD countries. Paris: OECD Publishing; 2023. https://doi.org/10.1787/9d0453d5-en.
[23] UNU-WIDER. UNU-WIDER government revenue dataset: version 2023'. Helsinki: UNUWIDER; 2023. https://doi.org/10.35188/UNU-WIDER/GRD-2023.
[24] Jiang Y, Qin J, Khan H. The Effect of tax-collection mechanism and management on enterprise technological innovation: evidence from China. Sustainability 2022;14(14):8836.
[25] Sharif A, Kocak S, Khan HHA, Uzuner G, Tiwari S. Demystifying the links between green technology innovation, economic growth, and environmental tax in ASEAN-6 countries: the dynamic role of green energy and green investment. Gondwana Res 2023;115:98–106.
[26] Karmaker SC, Hosan S, Chapman AJ, Saha BB. The role of environmental taxes on technological innovation. Energy 2021;232:121052.
[27] Wei L, Zhang Y, Jia J. How do environmental taxes affect green process innovation? Evidence from the Chinese manufacturing industry. J Manuf Technol Manag 2023;34(5):669–93.
[28] Zeren F, Akkuş HT. The relationship between renewable energy consumption and trade openness: new evidence from emerging economies. Renew Energy 2020;147:322–9.
[29] Hussain J, Zhou K, Muhammad F, Khan D, Khan A, Ali N, Akhtar R. Renewable energy investment and governance in countries along the belt & Road Initiative: does trade openness matter? Renew Energy 2021;180:1278–89.
[30] Mandelman FS, Waddle A. Intellectual property, tariffs, and international trade dynamics. J Monetary Econ 2020;109:86–103.
[31] Harrod RF. An essay in dynamic theory. Econ J 1939;49(193):14–33.
[32] Knox AD. The acceleration principle and the theory of investment: a survey. Economica 1952;19(75):269–97.
[33] Hall RE, Jorgenson DW. Tax policy and investment behavior. Am Econ Rev 1967;57(3):391–414.
[34] Jorgenson DW. Econometric studies of investment behavior: a survey. J Econ Lit 1971;9(4):1111–47.
[35] Boadway R. Corporate taxation and investment: a synthesis of the neo-classical theory. Can J Econ 1980:250–67.
[36] Tobin J. A general equilibrium approach to monetary theory. J Money Credit Bank 1969;1(1):15–29.
[37] Ling-zhi R, Xin-xuan Y, Yu-zhuo Z. Cost-benefit evolution for concentrated solar power in China. J Clean Prod 2018;190:471–82.
[38] Ahmed Z, Ahmad M, Murshed M, Shah MI, Mahmood H, Abbas S. How do green energy technology investments, technological innovation, and trade globalization enhance green energy supply and stimulate environmental sustainability in the G7 countries? Gondwana Res 2022;112:105–15.
[39] Solarin SA, Bello MO, Tiwari AK. The impact of technological innovation on renewable energy production: accounting for the roles of economic and environmental factors using a method of moments quantile regression. Heliyon 2022;8(7):e09913.
[40] Khan K, Su CW, Rehman AU, Ullah R. Is technological innovation a driver of renewable energy? Technol Soc 2022;70:102044.
[41] Khan K, Su CW. Does technology innovation complement the renewable energy transition? Environ Sci Pollut Control Ser 2023;30(11):30144–54.
[42] Bamati N, Raoofi A. Development level and the impact of technological factor on renewable energy production. Renew Energy 2020;151:946–55.
[43] Su CW, Khan K, Umar M, Chang T. Renewable energy in prism of technological innovation and economic uncertainty. Renew Energy 2022;189:467–78.
[44] Murshed M. Are trade liberalization policies aligned with renewable energy transition in low and middle income countries? An instrumental variable approach. Renew Energy 2020;151:1110–23.
[45] Zhongwei H, Liu Y. The role of eco-innovations, trade openness, and human capital in sustainable renewable energy consumption: evidence using CS-ARDL approach. Renew Energy 2022;201:131–40.
[46] Ziesemer T. Renewable electricity supply, infrastructure, and gains from international trade in electric current. Appl Econ Lett 2019;26(17):1439–43.
[47] Hajdukovic I. The impact of international trade on the price of solar photovoltaic modules: empirical evidence. EconomiA 2022;23(1):88–104.
[48] Chen Y, Wang Z, Zhong Z. CO2 emissions, economic growth, renewable and non-renewable energy production and foreign trade in China. Renew Energy 2019;131:208–16.
[49] Bellakhal R, Kheder SB, Haffoudhi H. Governance and renewable energy investment in MENA countries: how does trade matter? Energy Econ 2019;84:104541.
[50] Silva PP, Cerqueira PA, Ogbe W. Determinants of renewable energy growth in Sub-Saharan Africa: evidence from panel ARDL. Energy 2018;156:45–54.
[51] Alsagr N. Financial efficiency and its impact on renewable energy investment: empirical evidence from advanced and emerging economies. J Clean Prod 2023;401:136738.

[52] Ansari MA, Haider S, Masood T. Do renewable energy and globalization enhance ecological footprint: an analysis of top renewable energy countries? Environ Sci Pollut Control Ser 2021;28:6719–32.

[53] Pesaran MH. A simple panel unit root test in the presence of cross-section dependence. J Appl Econometrics 2007;22(2):265–312.

[54] Akram R, Chen F, Khalid F, Huang G, Irfan M. Heterogeneous effects of energy efficiency and renewable energy on economic growth of BRICS countries: a fixed effect panel quantile regression analysis. Energy 2021;215:119019.

[55] Shahzadi I, Yaseen MR, Khan MTI, Makhdum MSA, Ali Q. The nexus between research and development, renewable energy and environmental quality: evidence from developed and developing countries. Renew Energy 2022;190:1089–99.

[56] Luo Y. Does ICT development influence renewable energy investment? Evidence from top-polluted economies. J Clean Prod 2023;428:139271.

[57] Ebaidalla EM, Abusin S. The effect of ICT on CO2 emissions in the GCC countries: does globalization matter? Int J Energy Econ Pol 2022;12(6):56–66.

[58] Pesaran MH, Yamagata T. Testing slope homogeneity in large panels. J Econom 2008;142(1):50–93.

[59] Westerlund J. Panel cointegration tests of the Fisher effect. J Appl Econometrics 2008;23(2):193–233.

[60] Ebaidalla EM. Impact of indirect taxes on CO2 emissions in the presence of institutional quality: evidence from a global panel data analysis. Management of Environmental Quality 2024;35(4):729–50.

[61] Chudik A, Pesaran MH. Common correlated effects estimation of heterogeneous dynamic panel data models with weakly exogenous regressors. J Econometrics 2015;188(2):393–420.

[62] Azam M, Uddin I, Khan S, Tariq M. Are globalization, urbanization, and energy consumption cause carbon emissions in SAARC region? New evidence from CS-ARDL approach. Environ Sci Pollut Control Ser 2022;29(58):87746–63.

[63] Ahmad M, Dai J, Mehmood U, Abou Houran M. Renewable energy transition, resource richness, economic growth, and environmental quality: assessing the role of financial globalization. Renew Energy 2023;216:119000.

[64] Chen R, Ramzan M, Hafeez M, Ullah S. Green innovation-green growth nexus in BRICS: does financial globalization matter? Journal of Innovation & Knowledge 2023;8(1):100286.

[65] Sulaiman C, Abdul-Rahim AS, Ofozor CA. Does wood biomass energy use reduce CO2 emissions in European Union member countries? Evidence from 27 members. J Clean Prod 2020;253:119996.

[66] Ehigiamusoe KU, Dogan E. The role of interaction effect between renewable energy consumption and real income in carbon emissions: evidence from low-income countries. Renew Sustain Energy Rev 2022;154:111883.

[67] Dumitrescu EI, Hurlin C. Testing for Granger non-causality in heterogeneous panels. Econ Model 2012;29(4):1450–60.

[68] Nchofoung TN, Fotio HK, Miamo CW. Green taxation and renewable energy technologies adoption: a global evidence. Renewable Energy Focus 2023;44:334–43.

[69] Luo X, Wang J, Dooner M, Clarke J. Overview of current development in electrical energy storage technologies and the application potential in power system operation. Applied energy 2015;137:511–36.

[70] Tan KM, Babu TS, Ramachandaramurthy VK, Kasinathan P, Solanki SG, Raveendran SK. Empowering smart grid: a comprehensive review of energy storage technology and application with renewable energy integration. J Energy Storage 2021;39:102591.