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Impact of technological innovation and formal institutions in renewable energy transition

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ABSTRACT

The shift to a low-carbon economy is advanced by renewable energy, which is also an effective means of ensuring energy sustainability. Technological innovation and formal institutions are considered to be some of the main enablers of the renewable energy transition. This study examines the effect of formal institutions and technological innovation on renewable energy across 91 countries from 2002 to 2022 using the dynamic system GMM method. Subsample analysis is performed to consider differences in the dataset in terms of technology infrastructure, formal institutions, economic development and energy systems. A panel threshold model is used to examine the potential asymmetry of formal institutions on the impact of technological innovation on renewable energy. The result reveals that for the aggregate country sample, technological innovation and formal institutions promote renewable energy. However, subsample estimates reveal that the impact of technological innovation and formal institution contrast in developing and developed country samples. Further, depending on the level of institutional quality, the impact of technological innovation varies significantly and exerts asymmetric relationships.

1. Introduction

The global energy structure is undergoing a significant alteration as countries confront the dual challenges of securing energy and moderating climate change. Every year, governments gather at the United Nations Climate Change Conference (UNCCC) to stock take and pledge targets for net zero emissions. The yearly gathering of countries at UNCCC shows the determination of authorities to curb climate change and the resulting environmental catastrophe (Shahbaz et al., 2022). However, many countries around the world still rely on fossil fuels (coal and oil) to provide their energy supply (IRENA, 2024). These energy sources are not only nonrenewable but also cause greenhouse gas emissions (Brini et al., 2017).

Given the existential threat driven by climate change facing many economies in the world, the rate of carbon reduction needs to be significantly improved in the coming years to meet global net zero targets and carbon neutrality by 20250. As a result, renewable energy sources are becoming an increasingly essential source of alternative energy. In 2023, worldwide new investment in renewable energy reached US$735 billion, with countries like China, Europe, and the US heavily investing in solar and wind energy (IEA, 2024). This clean energy transition is driven by several factors, including financing, investment, affordability, and various energy mixes of economies with different strategies. As countries pledge sustainable practices and international norms such as the SDGs and climate accords, understanding the factors influencing renewable energy use and production is essential.

Consequently, a number of studies in literature have examined the determinants of renewable energy from various perspectives, including financial market (Li, 2023; Kim and Park, 2018), international trade (Wang and Zhang, 2021; Zeren and Akkuş, 2020), energy prices (Brini et al., 2017; Apergis and Payne, 2014), environmental degradation (Long et al., 2024; Sadorsky, 2009), and government policies (Mo and Jeon, 2022), etc. In the era of fast technological development and the need for better governance and management, technological innovation and institutional quality to increase efficiency and reduce market distortions is becoming a vital aspect of economic activities in modern economies. Yet studies investigating the effect of technological innovation and the quality of institutions on renewable energy remain relatively scarce. This study attempts to address this gap by empirically scrutinizing how technology innovation and formal institutions impact renewable energy in global economies.

Technological innovation (Coccia, 2021) is the widespread application of information and communication technologies in economic activities, with data being a production input beside traditional factors of

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labour and capital (Dian et al., 2024). The network technologies help transfer data, and ICTs are the primary conduit to foster consumption and production efficiency and improve economic structure (Wang et al., 2023). Specifically, in the context of renewable energy consumption, the application and integration of technology into the energy structure can be especially useful. For instance, technological innovation can expedite the transition from fossil fuel energies towards a clean, renewable and sustainable energy platform, given the renewable's ICT and knowledge-based nature relative to fossil fuels (Wang et al., 2024). Renewable energy advancement, accompanied by technological innovation, can ease in reducing carbon emissions and building environment sustainability by improving energy efficiency and ultimately improving energy consumption (IEA, 2017).

The integration of advanced technology into energy systems, especially in pollution intensive industries, can decentralize power systems and bring improvements in the production processes. This will bring more transparent monitoring of carbon footprints and energy consumption throughout the production chain (Cepal, 2022). Industrial Revolution 4.0, accompanied by digital technologies, can facilitate the incorporation of renewable energy into production factories using advanced technologies, hence significantly enhancing energy sustainability (Scharl and Praktiknjo, 2019). Further, renewable energy technologies driven innovations can minimize operating and repair costs, reduce energy losses and dependence on fossil fuels and optimize energy structure. Technology advancements are transforming energy use by making it more flexible and adaptable, leading to effective demand management. With smart grids and meters with analytics capabilities, it is possible to accurately monitor and optimize consumption, thereby reducing wastage (Padmanaban et al., 2024). Furthermore, technological innovation also encourages consumers to produce their own energy, and surplus can be contributed back into the national power grid by investing in solar panel technologies (Parag and Sovacool, 2016).

Moreover, advancement in technology and renewable energy systems is often complemented by policy and institutional challenges, hindering the transition to low-carbon environment. Thus, the quality of institutions and governance is also crucial in fostering renewable energy consumption. Institutions can play a significant part in effectively monitoring and incentivizing policies impacting energy transition at local and national levels. Their ability to condition market environmental activities that lead to improved investment and optimal distribution of resources, where renewable energy sources can compete (Nguyen et al., 2018). Conversely, a lack of effective institutions can be an obstacle to renewable energy development (Sweidan, 2021). The obstacles are commonly present in the form of corruption, breakdown of the rule of law and lack of government effectiveness (Hwang and Venter, 2025).

Several studies highlight the vital role of formal institutions in environmental issues and renewable energy development. According to Mukherjee and Chakraborty (2013), governments may not be as worried about environmental issues or may not enforce legislation in countries where there are no formal democratic institutions. Similarly, factors influencing the quantity of climate change laws were investigated by Fankhauser et al. (2015). They discovered that, in comparison to non-democratic nations, democratic nations typically enact more laws addressing climate change. Additionally, it has been argued that NGOs and civil organizations play a crucial role in helping achieve international goals (Fransen, 2013) like SDG 7, and their involvement can be more successful in countries where institutional principles are maintained (Fredriksson et al., 2005; Fankhauser et al., 2015).

Moreover, renewable energy development is capital-intensive and sensitive to various risks, including policy and regulatory frameworks. Thus, the quality of institutions plays an important role in reducing perceived investment risk and attracting potential investors. Stable policy commitments and proper contract enforcement can lower capital cost and attract investment into renewables energy sector (Polzin et al., 2019). Cross-country investigation shows that countries with credible institutions manage to draw higher levels of investment in renewables (Keeley and Ikeda, 2017). Further, national governments can mobilize institutions as vital tools and mediators in the technology and energy transition (Shahbaz et al., 2022). Also, Aghion et al. (2016) contend that well-established institutions can effectively direct technological transition towards cleaner energy pathways at a wide scale.

Considering the potential influence of technological innovation and the formal institutions on renewable energy consumption, this study attempts to comprehensively analyze their impact. This study contributes to the body of existing literature in a number of ways. First, we empirically investigate the influence of technological innovation and formal institutional quality on renewable energy consumption across 91 countries around the globe, offering valuable insight into whether technological innovation and well-established institutions and governance can assist in advancing renewable energy, hence, contributing to the goal of low-carbon emission transition. Distinct from previous studies, this study considers a large panel of countries at the global level and uses multiple indicators of technological innovation and institutional quality, allowing to find robust implications on renewable energy. Furthermore, while few studies have examined the impact of institutions and technology on renewable energy demand, there is no study to our knowledge that looked at the mutual impact of the two factors on renewable energy. To this end, an interaction variable is developed and examined in the analysis, which is an additional contribution to this study.

Secondly, the review of literature relates to an important implication within the framework of the present study. The extant literature mostly focused on the implications of technology and renewable energy sources on enhancing energy efficiency and intensity, and the implications of institutional quality on sustainable development. These studies have mainly overlooked the actual impact of technological advancements and institutions on renewable energy consumption and the development of renewable energy itself. Therefore, this study lengthens the current literature by empirically investigating the impact of technology innovation and institutions on renewable energy use and development. Specifically, in this study, we focus on the impact of technology on two renewable energy variables (i) renewable energy consumption and (ii) electricity production from renewable sources, including solar and wind.

Third, the transition to low-carbon power and renewable energy sources can be challenging for some countries, especially those that still depend on a large proportion of fossil fuels. Many of these countries are developing economies and are in the early to mid-stage of industrialization and face important decisions about sustainability and economic development. In addition to this, there could be significant differences in the level of technological innovation and institutional quality between countries. For instance, our preliminary analysis shows that technology and the quality of institutions vary in developing and developed countries. As a result, this study also performs empirical estimation on a separate set of samples: developed countries (categorized by high and upper middle income) and developing countries (categorized by low and lower middle income). Given this, the analysis then explores how the differential impact of technology and institutions on renewable energy in two different groups of countries.

Lastly, on methodological grounds, some existing research employs panel unit roots that presume cross-sectional independence. However, as argued by Pesaran (2015), most economic variables are likely to deviate from the independence assumption. Thus, in this study, we employ second-generation econometric techniques and enrich the extant methodological framework in the context of renewable energy. These include the Breusch-Pagan and Pesaran-based cross-section dependence test, the cross-sectionally augmented IPS panel unit root test, the Westerlund cointegration test, and the two-step system GMM method, which considers path dependency and addresses endogeneity issues to evaluate the impact of renewable energy factors. Furthermore, given a large data set of sample countries, which include samples with heterogenous economic growth, technological progress, energy combination and formal institutional systems, the impact of institutional quality and technology can exert a nonlinear effect on renewable energy. In the event of any asymmetric relations, the impacts of technology and institutions might not be accurately examined by linear models. In this respect, the panel threshold method of Seo and Shin (2016) is employed to address potential nonlinearity and provide threshold effects.

The rest of the sections are structured in the following way. Section 2 examines the literature on renewable energy with respect to technology and formal institutions. Section 3 outlines research data and methodology employed in the study. Section 4 presents the estimation results and discussions. Finally, section 5 provides the conclusion and offers economic policy implications.

2. Literature review

In this section, we provide germane literature to this study. It is structured in two parts, consisting of a theoretical background with a conceptual framework and empirical literature on renewable energy consumption.

2.1. Theoretical background

2.1.1. Technological innovation and renewable energy

The effect of technological advancement on economic output has been documented in the mainstream economic growth models and theories. Starting with the Neoclassical growth theory of Solow (1956), productivity modelled with technological innovation, in association with usual labour and capital accumulation, has been considered as a critical input of economic growth. This model was further augmented with other growth enhancing variable, such as institutions and R&D, by new (endogenous) growth theories of Romer (1994) and Mankiw et al. (1992). However, main economic growth theories pay less attention to energy use in the growth process until empirical support is provided by the energy economist that shows the vital role of energy in economic output growth (Ayres et al., 2013; Sharma, 2010). As energy is being recognized as a critical growth-enhancing input, research interest in examining the impact of technology on renewable energy demand is gaining attention.

Integration of technology and clean energy into the energy system, considering green and renewable energy sources, can promote significant change in the real energy system. Such change and development can have a profound impact on various aspects of the energy system, including access, affordability, security and sustainability and can bring substantial changes in energy production and consumption patterns (Hwang and Venter, 2025). Not long ago, renewable energy used to be less commercialized relative to fossil fuel-based energy due to the cost (Yang et al., 2019); however, technological innovation is promoting investment in renewable energy (Popp et al., 2011). As renewable energy technology grows, the cost of energy is decreasing, and the share of renewable energy in the total energy market is accelerating (Geng and Ji, 2016). Solar and wind technologies are becoming important clean energy source options, as well as making energy affordable and accessible. The confluence of the development of new technology and climate change forms the imperative to study the relationship between technological innovation and energy development. Chen and Lei (2018) note that technological advancement is a significant factor in renewable energy development and improves the energy structure. Technology has the unique characteristics of low reproduction cost and rapid transmission, allowing economies to upgrade their production and consumption methods (Hanelt et al., 2020). From the energy use perspective, the effect of such upgrades is deeply captured in the optimization of energy demand and production output (Reichardt et al., 2025). According to the theory of optimal allocation, technology allows overcoming information barriers in allocating production factors, which intuitively allows businesses to efficiently allocate energy, providing an opportunity to improve energy intensity (Jiang and Li, 2024). Some theoretical research also argues that the technology sector is energy-intensive and the production and processing of innovative technologies amplify energy consumption (Gyamfi et al., 2023). Usman et al. (2021) also identified that ICT development substantially boosts electricity consumption and energy demand.

Hypothesis 1. Technological innovation fosters renewable energy investment, improves efficiency, lowers cost and enhances adoption. Thus, technology can promote renewable energy consumption.

2.1.2. Formal institutions and renewable energy

Institutional theory postulates that the effectiveness of institutions have substantial influence on the governance of resources and how policies are developed and implemented (North, 1990; Hoffman, 1999). Countries with effective formal institutions are in a better position to implement policies and initiatives aimed at enhancing renewable energy consumption (Bhattacharya et al., 2017). The quality of a formal institution also fosters investment in clean energy infrastructure and a higher adoption rate (Uzar, 2020). Thus, the quality of formal institutions is an essential factor in renewable energy consumption function. Further, a business-friendly environment with robust institutions has the potential to attract foreign investment in the real sector (J. Wang et al., 2022). These investment inflows would not only generate economic activity and jobs but also greater use of renewable energy to stay competitive in a environmentally friendly business (Wu et al., 2022).

Theoretical literature also contends the role of international trade in renewable energy adoption. Trade openness serves as an effective proxy for assessing the extent of countries' involvement with one another via the exchange of goods and services, thereby facilitating access to renewable technologies and, subsequently, increased utilization of renewable energy (Chen et al., 2021). Trade openness, however, may also result in increased environmental deterioration (see, for example, Le et al., 2016). Thus, the impact of trade openness or any other factors on renewable energy may vary depending on the institutional quality of democratic and non-democratic nations. For instance, democratic countries with strong public and private institutions have stronger environmental and ecological obligations (Neumayer, 2002) and are more inclined to enact policies regarding climate change and the environment (Fankhauser et al., 2015). On the other hand, a less democratic country with no or laxer environmental concerns (Fankhauser et al., 2015) could turn into a ‘pollution port’ for high-volume industrial manufacturing. In other words, international trade may enhance FDI inflows (Hakimi and Hamdi, 2016) into countries, and the lack of environmental protection policies may also increase FDI in these countries. Khan et al. (2021) demonstrate that conducive government legislation is essential to the progression of renewable sources of energy. Moreover, institutional quality can also moderate the effect of technological factors in fostering renewable energy consumption, thus institutions and technology can have mutual influence on renewable energy (Hwang and Venter, 2025).

Hypothesis 2. The quality of formal institutions plays a significant role in renewable energy consumption.

The theoretical literature above provides the groundwork for the development of the conceptual model in Fig. 1.

2.2. Empirical literature

2.2.1. Technological innovation and renewable energy

Some of the initial studies in this stream of literature include research by Popp (2002) in the case of the US, using the data from 1970 to 1994 to examine the impact of energy prices on energy-efficient innovation. Considering both the demand and supply side factors, the study shows that the existing body of knowledge and energy prices have a strong

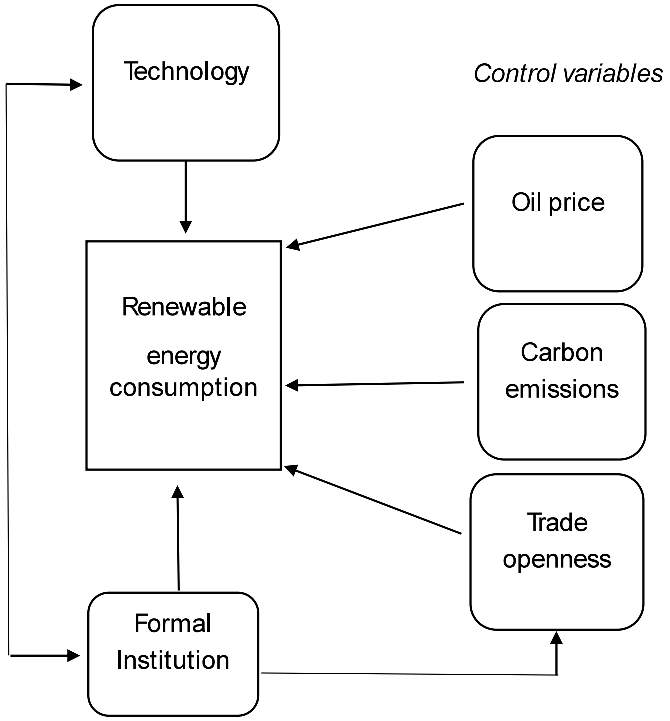

Fig. 1. Conceptual framework. Source: The authors construct following the theoretical literature.

favourourable effect on innovation. Similarly, to enhance the energy system, Fri (2003) highlights the role of knowledge acquisition in fostering technological innovation, whereas Herring and Roy (2007) analysed the bounce back effect of technology on energy efficiency.

Recent studies continue to add to this stream of work. For example, Jin et al. (2018) examine the energy use – innovation nexus for China using the panel method and show a positive and bilateral link between the variables. The findings conclude that technology could help countries to improve energy efficiency and structure. In their study, Pan et al. (2019a,b) model the connection between environmental policies, technological innovation and energy efficiency for China. The findings show that environmental regulations contribute to energy efficiency through innovation, while innovation itself show a significant evidence in enhancing energy efficiency.

Saudi et al. (2019) examined the effect of different metrics of innovation on energy inefficiency. They found that R&D, patents and high-tech exports negatively impact energy inefficiency in Indonesia. Pan et al. (2019), using annual data (1976-2014) for Bangladesh, studying the factors influencing energy intensity, show that technological innovation impacts energy intensity. Chen et al. (2021) investigate the issue of the technology and energy efficiency nexus in the context of Arab countries for the period 1990 to 2016. They found that while the shadow economy unfavourable impact on energy efficiency, technological advancement improves energy efficiency.

Wang et al. (2022) explored the association between the digital economy and high-quality energy generation in China using provincial data from 2007 to 2017. Their results indicate a significant positive influence of the digital economy on high-quality renewable development. The authors contend that the positive effect of the digital economy is facilitated through economic growth, innovation and application. Huang and Lin (2023) investigated the effect of digital technology in electricity production using panel fixed effects for 93 countries. According to the authors, by improving energy structure, digitalization help reduce carbon intensity and at the same time contributes to renewable energy promotion. In particular, the adoption of digital technologies enables integration of renewable sources in the total energy mix by enabling grid modernization.

Yi et al. (2024) studied the effect of digital innovation on clean energy innovation using generalize method of moments system in 65 countries from 2002 to 2019. The authors examined the effect of digital innovation on aggregate renewable energy as well as on specific renewable energy sources. Their findings reveal that digital innovation significantly increases renewable energy both at aggregate and specific renewable energy sources (Solar and wind). By accounting for heterogeneity, the authors also show that in highly developed and large manufacturing economies, the influence of digital innovation is relatively stronger. Similarly, Wang et al. (2023) examine the heterogeneous effect of digitalization in Asian economies during 2003-2019. The estimates show that the effect of digitalization on renewable energy development was relatively stronger in high-income economies. Further, their regional differences indicate that technology is being impactful in East and South Asian regions. Dian et al. (2024) and Guan et al. (2025) explored whether digitalization influences green technology innovation and energy efficiency, respectively. Using data for some selected Chinese cities, they show that digitalization positively contributes to green technology innovation and energy efficiency. This relationship is further facilitated by government policies, financial markets and human capital development.

Studies have also shown that information and communications technologies enable the development of renewable energy. For example, Alsaleh and Wang (2023) empirically investigate the effect of ICT on renewable energy development in developed and developing European Union economies. Their results show that in developed countries, ICT's effect on geothermal-based energy production was greater than in developing EU countries. On the other hand, the authors found that the impact of geothermal on carbon emission was relatively higher in developing economies. Similarly, Wang et al. (2024) and Alsaleh and Abdul-Rahim (2023) examined the ICT's influence on bioenergy and hydro energy generation in EU countries. The findings show positive and significant effects of ICT in bioenergy and hydro energy development.

Existing literature also shows mixed findings. For instance, according to empirical data from China and South Asia, technological growth has increased the proportion of renewable energy consumption in the country's energy consumption (Chowdhury et al., 2022). This phenomenon is dynamic, though. The economy and climate can suffer because of excessive energy use brought on by development in ICT adoption (Zhao et al., 2023). He et al. (2017) examined the impact of technological innovation on renewable energy using the Chinese provincial data. The findings demonstrate that research and development in ICT influence renewable energy development. Similarly, the question of whether the creation of new technology progresses renewable energy is examined by Xie et al. (2020). While the findings show that new innovative technologies positively influence renewable energy, existing technologies cannot significantly impact renewable energy.

2.2.2. Formal institutions and renewable energy

Several studies in empirical literature have also explored the effect of institutions on renewable energy demand. Cadoret and Padovano (2016), in one of the first studies on this, provide evidence to show the influence of governance quality and political dogma on renewable energy. Their study focused on European countries and revealed that lobbying activity in the manufacturing sector adversely impacts renewable energy. Though Arminen and Menegaki (2019) demonstrated that the quality of institutions proxied by corruption levels has minimal impact on energy consumption in middle and high-income countries. Similarly, Uzar (2020) also attempted to estimate the impact of institutions on the consumption of renewable energy in a panel of 38 countries. The author indicated that in the long run, institutions support renewable energy consumption.

Apergis and Pinar (2021) examined the influence of party polarization on renewable energy in 25 European countries during 2003-2017. They show the negative effect of party polarization on renewable energy. Chen et al. (2021), using the democracy index for 97 countries around the world during 1995- 2017, show that institutions positively influence renewable energy use. Rahman and Sultana (2022) also examine the effect of institutional quality on renewable energy consumption. They found that controlling institutional corruption and improving government efficiency have a positive effect on renewable energy. Cadoret and Padovano (2016) show very similar outcomes regarding corruption control in the deployment of renewable energy. The author used corruption perception and index to measure the quality of institutions. Saidi and Omri (2020), while examining the link between growth and renewable energy, accounting for institutions. They observed that quality institutions matter for both growth and renewable energy.

Formal institutions can also play import role in safeguarding environmental issues through regulatory agencies and policy design, such as curbing fossil fuel subsidies and carbon tax, leading to and implementing measures that enhance renewable energy (Abban et al., 2023; Liu et al., 2022). Opeyemi et al. (2019) explored the role of institutions in energy and trade relations for sub-Saharan African economies. They show that renewable energy inverse relationship with trade and manufacturing. However, a formal institution with better corruption control and regulatory quality can improve this relationship. Amiri et al. (2019) investigated how formal institutions affect natural resource trade and its effect on economic growth in different resource-endowed economies. The results show a resource curse in countries with poorly managed institutions, while the opposite for countries with good institutions. Shahbaz et al. (2022) investigated the effect of governance in the digital technology and energy transition nexus for 72 countries during 2003-2019 in a panel model system. The study indicates that improvement in governance competencies enables digital technologies to positive influence on renewable transition. Further, the heterogeneous analysis shows different effects in middle and high-income countries. Specifically, in middle-income countries, digital technology reduces renewable energy transition, while in high-income countries, digital technology was found to have a positive impact on energy transition. Table 1 provides recent findings on related literature.

3. Data and estimation methodology

3.1. Data

The data for this study have been drawn from multiple publicly available sources to create a panel data set comprising 91 countries globally over the period 2002 to 2022. The number of countries and the period are based on the availability of data on the key variables of interest utilized in the study. These variables are discussed next, and Table 2 provides the variable definition and data sources.

3.1.1. Variables

3.1.1.1. Dependent variable. In this study, renewable energy (REW) is the dependent variable. Specifically, renewable energy is measured by renewable energy consumption as a percentage of total final energy consumption and electricity production from renewable sources, including solar and wind. The data on these series are obtained from the World Development Indicators (WDI) of the World Bank. Including both the aggregate and specific modern renewables can provide a more robust analysis of the present transition to renewable energy sources. It also considers the substantial potential of modern renewables to improve energy affordability, environmental sustainability and economic development. Further, compared to traditional energy sources (hydro), modern renewables can substantially benefit from ongoing technological improvement and appropriate institutional and governance design.

Table 1
Recent literature findings.

Authors	Time	Countries	Methods	Findings
Guan et al. (2025)	1998-2013	China	Difference in difference	Digital technologies enable firms to reduce energy intensity, however, there is a regional difference.
Yi et al. (2024)	2002-2019	65 countries	Generalize method of Moments	Digital innovation improves renewable energy with bigger countries have stronger impact.
Wang et al. (2024)	2007-2017	China	SYS-GMM	AI positively influences high quality energy development.
Pan et al. (2019)	1976-2014	Bangladesh	DAG and SVAR	Innovation is important in energy intensity where it is also influenced by finance and trade
Huang and Lin (2023)	2010-2019	93 countries	Two-way fixed model	technology improves carbon intensity and optimizing energy system improves carbon reduction effect.
Abban et al. (2023)	1990-2019	29 European	Spatial model	Renewable energy reduces carbon emissions and agencies must act to reduce carbon pollution with cooperation.
Rahman and Sultana (2022)	2002-2019	19 emerging	PMG-ARDL model	Institutional quality enhances renewable energy.
Apergis and Pinar (2021)	2003-2017	25 European	Panel estimation	Inverse relationship with party polarization and renewable energy.
Chen et al. (2021)	1995-2017	97 countries	Panel threshold model	Institutions positively influence renewable energy outcomes.
Shahbaz et al. (2022)	2003-2019	72 countries	Panel estimation	The digital economy positively influences energy transition, however, the impact is asymmetric.

3.1.1.2. Independent variable. There are two main independent variables of interest in this study: technological innovation and formal institutions. Given the multiple dimensions of technology, a technology index (TEI) is developed for the purpose of this study. The commonly used PC factor method is applied to develop the TEI, which consists of a total of 5 indicators: fixed broadband subscription, mobile cellular subscription, internet use, ICT goods export and ICT goods import. With respect to institutions, various dimensions and numbers of indicators have been mentioned in the literature to proxy institution quality. But there is no agreement among studies on standard indicators to be used, as organizations are still developing measures that reflect the actual picture of different countries. In this study, the Worldwide Governance Indicator (WGI) data measuring institutional quality are used. There are six indicators reflecting separate aspects of institutions: Corruption control, governance, political stability, regulatory quality, rule of law and voice and accountability. Governance score rank is used to assess the institutional effect, which ranges from 0 to 100, with 0 indicating countries with the lowest rank and 100 the highest. Based on this, an institutional index (INS) is constructed using the PC factor method. Recent studies have also employed PC methods (see, for e.g. Sun et al., 2025; Dosso, 2023).

3.1.1.3. Control variables. There are also sets of control variables used

Table 2
Variable definition and data source.

Variable	Indicators/description	Source
Renewable energy (REW)	Renewable energy consumption (% of total final energy consumption)	World Bank
	Electricity production (renewable sources, % of total)	World Bank
Technological Innovation (TEI)	Fixed broadband subscription (per 100 people)	World Bank
	Mobile cellular subscription (per 100 people)	World Bank
	Internet use (% of population)	World Bank
	ICT goods export (% of total goods)	World Bank
	ICT good import (% of total goods)	World Bank
Formal Institutions (INS)	Corruption control	WGI
	Governance	WGI
	Political stability	WGI
	Regulatory quality	WGI
	Rule of law	WGI
	Voice and accountability	WGI
Per capita GDP (GDPPC)	Per capita GDP in constant 2015 US$	WDI
Trade openness (TOP)	Share of exports and imports in GDP	WDI
Oil price (OIP)	Spot crude price (US$/bbl) (West-Texas Intermediate)	SRWED
Carbon emission (COE)	CO2 emission (metric tons per capita)	WDI

Note: WGI – Worldwide Governance Indicator, WDI – World Development Indicators and SRWED - Statistical Review of World Energy Database.

in this study. The consideration of the controls is based on the literature: Per capita GDP (GDPP) in constant 2015 US$ is a measure of income and economic development. High per capita income countries are expected to have more inclination towards renewable energy (Chen et al., 2021). Trade openness (TOP) is the share of exports and imports in GDP and is often used to consider the nature of economic policy and activity as well as the mechanism of technology transfer (Chen et al., 2021). Oil price (OIP) is the spot crude price (US$/bbl) (West-Texas Intermediate) from the Statistical Review of World Energy Database, which is used to proxy energy cost. Carbon emission (COE), which measures environmental degradation, is proxied by CO2 emission (metric tons per capita) (Belaïd et al., 2021).

Table 3 provides the summary statistics for the sample countries. The panel of 91 countries was further categorized into two panels: 23 developing countries and 68 advanced countries.[1] Given the sample of countries, in the mean, developing countries use more renewable energy relative to advanced economies. Advanced countries emit more carbon emissions. On the other hand, advanced countries have greater output, trade, technological innovation and improved formal institutions, in contrast to developing countries. Oil prices are almost similar for both developing and advanced economies in the sample.

3.2. *Estimation methodology*

3.2.1. *Model*

Following the theoretical and empirical literature (Bourcet, 2020) on renewable energy determinants, the following model is postulated, which shows the link between renewable energy use and its explanatory variables:

$$REW_{it} = f(TEI_{it}, INS_{it}, GDPPC_{it}, TOP_{it}, OIP_{it}, COE_{it}) \tag{1}$$

Table 3
Descriptive analysis.

	Variables	Mean	Maximum	Minimum	Std. Dev.	Observations
All						
	LREW	1.223	1.980	0.100	0.499	1820
	LTEI	1.887	2.263	−0.111	0.362	1820
	LINS	1.745	1.984	1.299	0.141	1820
	LGDPPC	3.925	5.051	2.609	0.572	1820
	LOIP	1.780	2.000	1.418	0.165	1820
	LCO2	0.500	1.416	−1.193	0.527	1820
	LTOP	1.813	3.346	0.547	0.300	1820
Developing						
	LREW	1.529	1.980	0.230	0.415	460
	LTEI	1.627	2.179	−0.111	0.506	460
	LINS	1.622	1.796	1.299	0.090	460
	LGDPPC	3.244	3.952	2.609	0.306	460
	LOIP	1.780	2.000	1.418	0.165	460
	LCO2	−0.150	0.677	−1.193	0.463	460
	LTOP	1.716	2.689	0.674	0.322	460
Developed						
	LREW	1.120	1.919	0.100	0.483	1360
	LTEI	1.975	2.263	0.152	0.242	1360
	LINS	1.787	1.984	1.375	0.131	1360
	LGDPPC	4.156	5.051	3.186	0.443	1360
	LOIP	1.780	2.000	1.418	0.165	1360
	LCO2	0.720	1.416	−0.154	0.329	1360
	LTOP	1.846	3.346	0.547	0.285	1360

Note: LREW, LTEI, LINS, LGDPPC, LOIP, LCO2, and LTOP are logs of renewable energy consumption, technology innovation, formal institution, per-capita income, oil price, carbon emissions per-capita and trade-openness, respectively.

Where *REW* is the renewable energy. *TEI* and *INS* denote technological innovation and formal institutions, respectively. *GDPPC* is income per capita; *COE* is carbon secretions per capita; *OIP* is the oil price; *TOP* is trade openness. The variables' definition and measurement are provided in the data section. *t* is the time and *i* is the cross-section of countries. Equation (1) is further transformed into a logarithmic form to control for possible outliers and heteroskedasticity effects. The logarithmic form also shows the elasticity parameter of independent variables to the dependent variable (Rahman and Sultana, 2022):

$$lnREW_{it} = \vartheta_{io} + \tau_{1i}\, ln\, TEI_{it} + \rho_{2i}\, ln\, INS_{it} + \beta_{3i} lnGDPPC_{it} + \gamma_{4i} lnCOE_{it} + \delta_{5i}\, ln\, OIP_{it} + \pi_{6i}\, ln\, TOP_{it} + \epsilon_{it} \tag{2}$$

Where ϑ_o is the intercept term and the characters $\beta_1, \gamma_2, \delta_3, \pi_4, \tau_5, and\ \rho_6$ represent the parameter estimates of the explanatory series. $\in_{it}$ is the assumed normal error term.

3.2.2. *Cross-sectional dependence*

First, a cross-sectional dependence test of the variables is conducted to ascertain the presence of any dependence. Ali et al. (2020) argue that in the panel analysis, it is necessary to check for cross-sectional dependency. Due to cross-country linkages and economic integration as a result of globalization, the shocks in just one nation can easily be shifted to other nations (Destek and Aslan, 2017), and econometrically, this can adversely impact the test statistics and efficiency. The Breusch-Pagan (BP) (Breusch and Pagan, 1980) and Pesaran (2004) cross-sectional dependence tests are used in this study. The null hypothesis ($Cov(\gamma_{kt}, \gamma_{vt}) = 0$) indicates the absence of cross section dependence in the panel. The BP test is suitable for panels with modest cross sections (N) and relatively longer periods (T). The Breusch-Pagan test is built on LM statistics:

$$CD_{LM} = T \sum_{k=1}^{N-1} \sum_{v=k+1}^{N} \widetilde{\varphi_{kv}}^{2} \tag{3}$$

Where $\widetilde{\varphi_{kv}}^{2}$ is the correlation between residuals (pair-wise), which is as follows:

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[1] Groups are based on World Bank's (2023) classification of countries based on income – GNI per capita.

$$\widetilde{\varphi_{kv}} = \widetilde{\varphi_{vk}} = \frac{\sum_{t=1}^{T} \varepsilon_{kt}\varepsilon_{vt}}{\left(\sum_{t=1}^{T} \varepsilon_{kt}^2\right)^{1/2} \left(\sum_{t=1}^{T} \varepsilon_{vt}^2\right)^{1/2}} \tag{4}$$

Where ε_{kt} is the OLS estimate of γ_{kt}. It is defined as: $\varepsilon_{kt} = y_{kt} - \widetilde{\delta_k} x_{kt}$. Where $\widetilde{\delta_k}$ is the OLS estimator of δ_k obtained using the auxiliary regression of y_{kt} on x_{kt} for individual k, independently.

3.2.3. *Panel unit root*

Any regression analysis requires the proper order of integration. Even when a significant *t*-test or F-test is present, non-stationary variables can have negative effects, like making the forecast useless, making it difficult to choose the right model, and producing erroneous results (Ali et al., 2020). In the manifestation of cross dependency, Banerjee et al. (2001) showed poor properties with over-rejection power. As a result, standard unit root tests are not applicable. Thus, a second generational test, which is cross-sectionally augmented and designed by Pesaran (2007), is used. In cross-section dependence, Pesaran (2007) provides cross cross-sectionally augmented test by developing Im et al. (2003) (IPS) unit root analysis. The rejection of the nonstationary null premise for all *k* suggests series are stationary. The augmented IPS is based on ADF estimation, which is adjusted with the difference of each series and lagged values of cross-sectional averages. It is in the form:

$$CIPS = \frac{1}{N} \sum_{k=1}^{N} \widetilde{t_k} \tag{5}$$

3.2.4. *Westerlund panel cointegration*

Cointegration among variables is necessary to prevent illegitimate regression estimation. The long-run association involving two or more variables implies cointegration (Ali et al., 2020). Two variables that are non-stationary separately and whose linear process becomes stationary have cointegration of order (1,1) (Yaseen et al., 2018). To confirm the cointegration, Westerlund (2005), which is a second-generation cointegration analysis, is applied. Its better accuracy (Zhu et al., 2018) makes it superior to residual-based cointegration tests (Pedroni, 2004). According to Wang and Dong (2019), Westerlund cointegration constitutes a panel-specific AR as well as the same-AR test statistics. These tests can be examined using Equations (6) and (7):

$$AR = \sum_{k=1}^{N} \sum_{v=1}^{T} \widehat{\varphi_{kt}}^2 \widehat{\phi_k}^{-1} \tag{6}$$

$$AR = \sum_{k=1}^{N} \sum_{v=1}^{T} \widehat{\varphi_{kt}}^2 \left(\sum_{k=1}^{N} \widehat{\phi_k} \right)^{-1} \tag{7}$$

Where AR is the average group variance-ratio test statistic, $\widehat{\varphi_{kt}}^2 = \sum_{j=1}^{v} \widehat{\mu_{kj}}$, $\widehat{\phi_k} = \sum_{v=1}^{T} \widehat{\mu_{kv}}^2$ and $\widehat{\mu_{kv}}^2$ are the panel regression residuals. The test statistics examine the null assumption of no cointegration between the variables.

3.2.5. *Static panel long-run regression*

After the preliminary analysis and tests, for a benchmark estimation, the fixed effect model is employed to investigate the long-run impact of the key explanatory variables on renewable energy. Specifically, a static two-way fixed effect linear model with Driscoll-Kraay robust standard errors is used. This approach is robust in the case of cross-sectional dependence, heteroskedasticity and autocorrelation as observed in the initial analysis. Further, the country and time fixed effect considers unobserved country difference which are relevant when examining a wide group of countries with diverse features, as present in this study. The two-way fixed (static) model has the following form:

$$\begin{aligned} lnREW_{it} = {} & \vartheta_{io} + \beta_{1i} \ln TEI_{it} + \beta_{2i} \ln INS_{it} + \beta_{3i} lnGDPPC_{it} + \beta_{4i} lnCOE_{it} \\ & + \beta_{5i} \ln OIP_{it} + \beta_{6i} \ln TOP_{it} + \theta_i + \pi_t + \epsilon_{it} \end{aligned} \tag{8}$$

Where ϑ_o is the constant, β_{1i} to β_{6i} are variable parameters. θ_i and π_t are fixed country and time effects and ϵ_{it} is an independent error variable. The consideration of both country and time effects, provides more robust estimates relative to conventional OLS when the dataset has such heterogeneity present.

3.2.6. *Dynamic system GMM*

Next, the study employs dynamic panel regression analysis to investigate the impact of technology and formal institutions on renewable energy. Compared to static regression, dynamic regression allows for path dependence emanating from its dependent variable. Second, the dynamic models do not adopt complete exogeneity, especially in explanatory variables and the disturbance term. Rather, they consider the possibility of endogenous variables, which results in more robust outcomes in the case of endogeneity and reverse causality. Specifically, the two-step system GMM (Arellano and Bover, 1995; Blundell and Bond, 1998) is employed in this study. The two-way system GMM is more suitable in a smaller time period (T) relative to the number of cross-sections (N) in panel data analysis, as present in this study. In such panel data settings, the systems GMM approach not only gives robust estimates but also performs efficiently, unlike the difference GMM. Moreover, compared to the different GMMs, the system GMM employs both lagged-levels and lagged-differences as moment conditions in instruments for difference and level regressions, respectively (López, 2022). The dynamic panel regression for this study is expressed as follows:

$$\begin{aligned} lnREW_{it} = {} & \vartheta_{io} + \beta_0 lnREW_{it-1} + \beta_{1i} \ln TEI_{it} + \beta_{2i} \ln INS_{it} + \beta_{3i} lnGDPPC_{it} \\ & + \beta_{4i} lnCOE_{it} + \beta_{5i} \ln OIP_{it} + \beta_{6i} \ln TOP_{it} + \theta_i + \pi_t + \epsilon_{it} \end{aligned} \tag{9}$$

Where $lnREW_{it-1}$ is the period lagged term of renewable energy (dependent variable), and is employed on left hand side to consider the path dependence of the regressand.

To analyze the moderation effect of institutions on technology from the viewpoint of enhancing renewable energy use, an interaction variable between the technology and institutions is formulated and introduced in the regression equation:

$$\begin{aligned} lnREW_{it} = {} & \vartheta_{io} + \tau_{1i} \ln TEI_{it} + \rho_{2i} \ln INS_{it} + \sigma_{3i} \ln TEI\_INS_{it} + \beta_{4i} lnGDPPC_{it} \\ & + \gamma_{5i} lnCOE_{it} + \delta_{6i} \ln OIP_{it} + \pi_{7i} \ln TOP_{it} + \theta_i + \pi_t + \epsilon_{it} \end{aligned} \tag{10}$$

Where *TEI_INS* is a variable denoting the interaction between technology and institutions.

3.2.7. *Panel threshold model*

Furthermore, given the presence of possible nonlinearity in explanatory variables and renewable energy, a threshold panel model designed by Seo and Shin (2016) is utilized to investigate such nonlinearity. Equation (9) is split into a sample form based on the value of the candidate threshold. According to Seo and Shin (2016), the dynamic threshold model is based on a first difference GMM approach, effectively accounting for endogeneity by treating both the threshold variable and other regressors endogenous. Compared to the static threshold model, the dynamic threshold model applied here does not necessitate full exogenous covariates to get consistent outcomes. Moreover, the dynamic threshold approach gives an asymptotic normal outcome and is appropriate when the country cross-section (N) is greater than the yearly observation (T). Following Seo and Shin (2016) and Seo et al. (2019) the panel dynamic threshold can be expressed as follows:

$$Y_{it} = (1, Z_{it})\varphi_1 {}^* I\{q_{it} \le \gamma\} + (1, Z_{it})\varphi_2 {}^* I\{q_{it} \ge \gamma\} + \mu_{it} + \varepsilon_{it} \tag{11}$$

Where $i = 1, \ldots..n$ and $t = 1, \ldots.T$. Y_{it} is the dependent variable, Z_{it} is time varying set of explanatory variables, q_{it} is the threshold variable, which is the formal institution in this study, φ represent the coefficient for two different regimes and γ denotes the candidate threshold value.

4. Results and discussion

4.1. Preliminary results

4.1.1. Cross-sectional dependence and stationary properties

Assessing stationarity is a crucial initial step in econometric analysis of time series data. The contemporary economist generally utilizes panel data analysis rather than being confined to univariate time series. Numerous panels possess abbreviated temporal dimensions yet are examined across multiple cross-sections. Conventional panel unit root tests, commonly known as first-generation panel unit root tests, utilize pooled panel data. According to Im et al. (2003), this approach frequently makes strong assumptions about cross-sectional independence and inter-cross-sectional homogeneity. Some extant literature (Apergis and Payne, 2014) has used first-generation tests and as a result, could suffer from size distortions. Recent literature takes into account the cross-section dependence (Belaïd and Zrelli, 2019). To allow for cross-sectional dependence, one can argue for an integrated panel model with a fractional model structure. Unit root tests based on this factor augmented structures are termed cross sectionally dependent unit root tests. Thus, we first establish the second-generation test by employing Pesaran's (2004) cross-section dependence test. We examine this with a panel structure consisting of 91 renewable energy-producing countries for the period of 2002 to 2022, as well as for a subsample of developing and developed countries.

The findings of Pesaran's cross-section dependence analysis are provided in Table 4. Based on the findings, the null hypothesis (cross-sectional independence) is firmly discarded for all three groups of samples (full, developing, and advanced countries) at the 1% significance level. This outcome applies to all the variables (LREW, LTEI, LINS, LGDPPC, LCO2, LOIP, and LTOP). As a result, regardless of the sample of nations used, we discover that every variable has a cross-sectional correlation.

4.1.2. Panel unit root

Since the variables are cross sectional dependent, we employ cross sectionally augmented unit root test of Pesaran (2007), that is, cross sectionally augmented Im, Pesaran, and Shin (CIPS) test. Table 5 provides the CIPS test results. At log levels, for all variables and all samples used, we are unable to reject the unit root hypothesis at any level of significance. However, the non-stationary process is eliminated at the respective significance level when the first difference of the variables is employed. This is also true regardless of the sample used. Hence, according to the result, the variables are stationary in first differences.

4.1.3. Panel cointegration

In the following phase, we examine the long-run cointegration using the Westerlund cointegration (Westerlund, 2005). The results are reported in Table 6. The statistical impact of the tests eliminates the null of no cointegration, which implies there is confirmation of long-run cointegration between renewable energy and technology innovation and formal institutions as well as the control variables. Thus, the investigation of the effects of explanatory variables in the model can be further examined. We also applied for Pedroni's (2004) panel test.[2]

Table 4
Test for cross-sectional dependence.

Variables	Full sample		Developing		Developed	
	Test stats	Prob-value	Test stats	Prob-value	Test stats	Prob-value
LREW	5.73	0.000*	38.16	0.000*	37.08	0.000*
LTEI	59.52	0.000*	68.53	0.000*	19.58	0.000*
LINS	39.47	0.000*	24.17	0.000*	22.49	0.000*
LGDPPC	10.21	0.000*	49.64	0.000*	16.78	0.000*
LOIP	68.18	0.000*	71.13	0.000*	23.45	0.000*
LCO2	15.91	0.000*	36.47	0.000*	17.88	0.000*
LTOP	27.83	0.000*	56.73	0.000*	19.92	0.000*

Note: * and ** denote 1% and 5% significance levels.

4.2. Main empirical findings

4.2.1. Panel static regression

After preliminary tests and ascertaining the long-run cointegration between the independent variables and the dependent variable (renewable energy), it is of economic interest to trace the long-run effect of the independent variables. The Driscoll-Kraay-based two-way fixed static model is used to investigate the effect of technology and formal institutions on renewable energy consumption. The Discroll-Kraay based two-way estimator provides robust standard errors and addresses empirical issues like heteroskedasticity and autocorrelation arising from the data generation process (Fuinhas and Marques, 2019).

Table 7 presents the findings from the two-way fixed effect estimator. Four variants of Equation (8) are estimated. The results indicate that technological innovation has a significant (1%) and positive impact on renewable energy consumption in the first and fourth variants. In variants 2 and 3, it is also positive but lacks significance. With respect to the formal institution, its effect on renewable energy consumption is negative and significant at 1% in the third and fourth variants.

4.2.2. Dynamic system GMM regression

Given that static panel estimators do not consider the long-run path dependency of the dependent variable and endogeneity issues, a dynamic panel estimator is employed. For the purpose of this, the two-step system GMM is used to address this.

As reported in Table 8, the Arellano-Bond test for AR (1) – first order autocorrelation was found to be significant, indicating rejection of autocorrelation in the error term. Similarly, for the AR (2)-second order autocorrelation, probability values are higher than 10%, suggesting that there is no second order autocorrelation in all the specifications. In the last panel, the Sargen-Hansen test for the validity of instruments chosen in the models indicates that they are valid, as the null hypothesis cannot be rejected in all the regression models.

From the coefficient estimate using system GMM, the technological innovation is found to be positive and statistically significant impact on renewable energy consumption at 1% level, except in model four when the time effect is introduced, however the coefficient remains positive. The effect of formal institutions on renewable energy is also positive and significant, except in model four with the time effect. Compared to the static model, where the effect of institution is negative, in the dynamic model, when the path dependency and endogeneity issue is appropriately considered, the sign of the LINS coefficient becomes positive and empirically significant.

To investigate the moderation effect of formal institutions on technological innovation in fostering renewable energy, an interaction variable of lnTEI_INS is constructed and included in the regression equation (10). Table 9 reports the results based on the interaction effects. As shown, the impact of technological innovation on renewable energy is positive when the interaction variable (LTEI_INS) is included, which is consistent with earlier estimates with no interaction term. With respect to the institution (LINS) variable, it is also found to be positive and statistically significant in all the 5 models. The effect of the interaction variable (LTEI_INS) is positive and significant on renewable energy in all specifications, indicating a mutual positive contribution of technology and institutions.

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[2] Result is not report to conserve space; however, it is available upon request.

Table 5
CIPS panel test.

	Full sample				Developing				Developed			
Variables	T-stats	1%	5%	10%	T-stats	1%	5%	10%	T-stats	1%	5%	10%
in (log) levels												
LREW	2.242	−2.70	−2.57	−2.51	−0.618	−2.83	−2.67	−2.58	−0.954	−2.72	−2.59	−2.53
LTEI	2.145	−2.70	−2.57	−2.51	−1.891	−2.83	−2.67	−2.58	−1.354	−2.72	−2.59	−2.53
LINS	−2.054	−2.70	−2.57	−2.51	−1.886	−2.83	−2.67	−2.58	0.171	−2.72	−2.59	−2.53
LGDPPC	0.597	−2.70	−2.57	−2.51	−1.282	−2.83	−2.67	−2.58	0.309	−2.72	−2.59	−2.53
LOIP	0.195	−2.70	−2.57	−2.51	−1.946	−2.83	−2.67	−2.58	−2.491	−2.72	−2.59	−2.53
LCO2	1.651	−2.70	−2.57	−2.51	0.378	−2.83	−2.67	−2.58	−1.160	−2.72	−2.59	−2.53
LTOP	1.652	−2.70	−2.57	−2.51	0.887	−2.83	−2.67	−2.58	1.383	−2.72	−2.59	−2.53
in (first) diff												
LREW	−8.418*	−2.70	−2.57	−2.51	−7.065*	−2.83	−2.67	−2.58	−7.599*	−2.72	−2.59	−2.53
LTEI	−12.153*	−2.70	−2.57	−2.51	−6.713*	−2.83	−2.67	−2.58	−10.929*	−2.72	−2.59	−2.53
LINS	−12.071**	−2.70	−2.57	−2.51	−7.134*	−2.83	−2.67	−2.58	−9.534*	−2.72	−2.59	−2.53
LGDPPC	−8.970**	−2.70	−2.57	−2.51	−2.682**	−2.83	−2.67	−2.58	−7.077*	−2.72	−2.59	−2.53
LOIP	−7.685*	−2.70	−2.57	−2.51	8.946*	−2.83	−2.67	−2.58	−5.086*	−2.72	−2.59	−2.53
LCO2	−6.541*	−2.70	−2.57	−2.51	−2.933**	−2.83	−2.67	−2.58	−7.031*	−2.72	−2.59	−2.53
LTOP	−4.606*	−2.70	−2.57	−2.51	−8.803*	−2.83	−2.67	−2.58	−5.277*	−2.72	−2.59	−2.53

Note: * and ** express 1% and 5% significance levels, in that order. We include constant and trend, and a 1-period lag.

Table 6
Westerlund cointegration test.

Test (without interaction)	With constant		With const & trend	
	Statistic	p-value	Statistic	p-value
Full sample				
Variance-ratio	−12.85	0.002*	−2.736	0.009*
Developing				
Variance-ratio	−1.214	0.001*	−2.470	0.001*
Advanced				
Variance-ratio	−11.635	0.002*	−2.79	0.03**
Test (with interaction term)				
Full sample				
Variance-ratio	−1.972	0.007*	−2.711	0.004*
Developing				
Variance-ratio	−2.218	0.009*	−6.206	0.000*
Advanced				
Variance-ratio	1.889	0.004*	2.684	0.000*

Note: The lag period is based on the automatic Akaike information criterion. * and ** denote levels of significance at 1% and 5%, respectively. Bootstrap (400) p-values are used with panel test statistics.

Table 7
Estimates from two-way fixed effects with Driscoll-Kraay SE.

Dependent variable: LREW				
	(1)	(2)	(3)	(4)
LTEI	0.023 (0.005)*	0.003 (0.015)	0.015(0.016)	0.091(0.011)*
LINS		−0.290 (0.170)	−0.439 (0.079)***	−0.343 (0.061)***
LGDPPC			0.762(0.062)*	0.297(0.081)*
LOIP			0.004(0.030)	0.742(0.171)*
LCO2			1.166(0.041)*	0.900(0.035)*
LTOP			0.149(0.026)*	0.058(0.024)**
Constant	1.268 (0.021)*	1.736 (0.260)	0.668(0.146)*	0.009(0.100)*
Year fixed	No	No	No	Yes
Country fixed	Yes	Yes	Yes	Yes
R-square	0.031	0.083	0.414	0.451
Obs	1820	1820	1820	1820
Countries	91	91	91	91

Note: * and ** denote 1% and 5% significance levels. Values in are Driscoll-Kraay standard errors.

Table 8
Estimates of dynamic system GMM (no interaction).

Dependent variable: LREW				
	(1)	(2)	(3)	(4)
LREW.1	0.941 (0.083)*	0.940 (0.069)*	0.955 (0.015)*	0.953 (0.198)*
LTEI	0.011 (0.006)***	0.031 (0.002)***	0.021 (0.009)**	0.034 (0.021)
LINS		0.090 (0.032)*	0.329 (0.144)**	0.417 (0.217)
LGDPPC			0.004 (0.028)	0.005 (0.043)
LOIP			−0.015 (0.007)**	−0.017 (0.011)
LCO2			0.061 (0.021)**	−0.048 (0.030)
LTOP			0.018 (0.012)	0.011 (0.015)
Constant	0.005(0.021)	0.138 (0.061)**	−0.492 (0.179)*	0.5377 (0.219)
Time effect	No	No	No	Yes
Autocorrelation Arellano-Bond test:				
AR (1)	−3.67*	−3.67*	−3.56*	−3.56*
AR (2)	0.78	0.77	0.61	0.61
Overriding restriction Sargen-Hansen test				
Moment function 2-step weight	2.94	4.36	17.53	11.42
Moment function 3-step weight	5.43	6.95	53.89	67.81

Note: *, **, and *** are significance levels at 1%, 5% and 10%, respectively. Values in are corrected standard errors.

4.2.3. Sub-sample analysis

Once the aggregate (full) sample has been examined, a subsample analysis is carried out. Given the large cross-section in this study, the countries are divided into two sub-samples: developed countries (categorized by high and upper middle income) and developing countries (categorized by low and lower middle income). Many of these countries are in the early to mid-stage of industrialization and face important decisions about sustainability and economic development. In addition to this, there could be significant differences in the level of technological innovation and institutional quality between countries. For instance, our preliminary analysis (Table 3) shows a substantial difference in technological innovation and formal institutions between developing and developed countries, respectively.

The results presented in Tables 10 and 11 reveal that the impact of technological innovation and formal institution contrast in developing and developed country samples. The elasticity coefficient of renewable energy consumption with respect to technology (LTEI) is positive and

Table 9
Estimates of dynamic system GMM (with interaction).

Dependent variable: LREW					
	(1)	(2)	(3)	(4)	(5)
LREW.1	0.941(0.083)*	0.940(0.069)*	0.938(0.010)*	0.974(0.018)*	0.961(0.024)*
LTEI	0.011(0.006)***	0.031(0.002)***	0.413(0.244)***	0.025(0.021)	0.016(0.002)*
LINS		0.090(0.032)*	0.132(0.036)*	0.382(0.172)**	0.505(0.279)***
LTEI_INS			0.256(0.152)***	0.059(0.013)*	0.032(0.018)***
LGDPPC				0.024(0.031)	0.011(0.049)
LOIP				0.001(0.011)	0.018(0.011)
LCO2				0.069(0.024)*	0.055_0.029)**
LTOP				0.017(0.014)	0.008(0.003)**
Constant	0.005(0.021)	0.138(0.061)**	0.163(0.073)**	0.552(0.213)***	0.665(0.294)**
Time effect	No	No	No	No	Yes
Autocorrelation Arellano-Bond test:					
AR (1)	−3.67*	−3.67*	3.68**	3.58**	3.46**
AR (2)	0.78	0.77	0.43	0.58	0.49
Overriding restriction Sargen-Hansen test					
Moment function 2-step weight	2.94	−3.67*	8.22	16.99	5.94
Moment function 3-step weight	5.43	0.77	0.83	86.52	66.96

Note: *, **, and *** are significance levels at 1%, 5% and 10%, respectively. Values in are corrected standard errors.

Table 10
Subsample analysis (Developing countries).

Dependent variable: LREW			
	(1)	(2)	(3)
LREW.1	0.987(0.008)*	0.989(0.013 (*	0.925(0.138)*
LTEI	−0.005 (0.002)**	−0.005 (0.006)	−0.004 (0.001)*
LINS		0.004(0.102)	0.044(0.0163)
LGDPPC			−0.022(0.189)
LOIP			0.029 (0.017)***
LCO2			0.075(0.109)
LTOP			−0.021(0.45)
Constant	0.025(0.016)	0.016(0.170)	0.025(0.560)
Autocorrelation Arellano-Bond test:			
AR (1)	−2.60*	−2.60*	−2.45*
AR (2)	0.60	0.60	0.53
Overriding restriction Sargen-Hansen test			
Moment function 2-step weight	2.68	1.46	1.36
Moment function 3-step weight	4.16	2.91	2.80

Note: *, **, and *** are significance levels at 1%, 5% and 10%, respectively. Values in are corrected standard errors.

Table 11
Subsample analysis (Developed countries).

Dependent variable: LREW			
	(1)	(2)	(3)
LREW.1	0.988 (0.011)*	0.988 (0.009)*	0.989(0.014)*
LTEI	0.034 (0.009)*	0.012(0.010)	0.022 (0.015)***
LINS		0.095 (0.033)*	0.103(0.012)*
LGDPPC			0.021(0.033)
LOIP			−0.006 (0.003)*
LCO2			0.029(0.020)
LTOP			0.012(0.005)**
Constant	0.044(0.027)	0.185 (0.061)*	0.237(0.115)**
Autocorrelation Arellano-Bond test:			
AR (1)	−3.29*	−3.30*	−3.27*
AR (2)	0.67	0.64	0.61
Overriding restriction Sargen-Hansen test			
Moment function 2-step weight	2.53	6.52	4.33
Moment function 3-step weight	2.64	6.54	3.56

Note: *, **, and *** are significance levels at 1%, 5% and 10%, respectively. Values in are corrected standard errors.

empirically significant for full and developed country samples. In the developing country sample, the system GMM estimates produce a significant negative impact, except in column 2. The magnitude of the effect also varies between developing and developed samples, with the impact of technology on renewable energy appearing more pronounced in developed countries. This suggests that the current level of technological innovation in developing countries may inhibit or have a very weak impact on renewable energy consumption. Numerous studies have demonstrated that ICT increases total factor productivity and causes structural changes in the economies, which lowers energy consumption and promotes energy efficiency (Xie et al., 2020; Ren et al., 2021). However, this conclusion can be debatable with respect to some developing countries. Economic development and energy use do not entirely decouple as a result of technical innovation (Lange et al., 2020). In fact, energy consumption has increased during the last few decades due to the quick growth of digital technology (Yang and Han, 2023). For developing countries to enhance growth, it is crucial to ensure a sustainable energy supply. However, in the face of increasing environmental concerns, traditional energy use is not sustainable. Our results are consistent with those of Murshed (2020), who shows that the transition to renewable energy is not optimally driven by technology in Asian nations.

The effect of formal institutions (INS) is positive but statistically insignificant for the developing country sample. The average institution index for sampled developing countries is 1.62, compared to 1.78 for advanced country samples. This could possibly indicate that a lack of quality institutions might lead to fewer stringent environmental regulations (Mukherjee and Chakraborty, 2013), and economic growth and trade can lead to lower sustainable energy intake. In contrast, the effect of formal institutions in the developed country sample is positive and statistically significant. Given that developed nations and those that have a huge regard for the environment devote more funds to clean energy, this finding broadly implies that formal institutions are crucial to the adoption of renewable energy. Additionally, greater and better climate change laws in developed and liberal nations, as opposed to the absence of institutions (Fankhauser et al., 2015), may result in spending plans that use more sustainable and renewable sources. Further, it is also established that higher economic growth and trade in developed nations cause a greater consumption of renewables than in developing countries.

4.2.4. Panel threshold estimation

Further, to the heterogeneous impact of technological innovation and institutional factors on renewable energy consumption, the potential asymmetric effect of the institution is investigated using a panel threshold model. The impact of technological innovation and other covariates in the analysis of renewable energy could be different based on the quality of formal institutions. The dynamic panel threshold model (DPTM) proposed by Seo and Shin (2016) is employed in this study. This is because DPTM considers a lagged dependent variable in the threshold model and addresses potential endogeneity issues in the empirical relationship. To derive the threshold candidate for the variable formal institutions, first average annual LINS for each country is obtained. After that, the median figure from the averages of all cross sections in the panel is calculated, which is 1.741.

Table 12 shows the effect of technology on renewable energy depending on whether the country is above or below the threshold value of formal institutions. The impact of technology on renewable energy differs substantially and exerts asymmetric impacts. In particular, for countries above the threshold (countries with high quality institutions), technology has a positive and significant impact on renewable energy. Conversely, in countries below the threshold (countries with low quality institutions), technology have positive impact but is statistically insignificant.

4.3. Robustness analysis

For the benchmark static estimates, the Two-stage Least Squares (TSLS) estimator is utilized to ascertain the robustness of the relationship between technology, institution and renewable energy consumption. The TSLS estimator is useful in addressing potential endogeneity by using instrumental variables. Table 13 provides the coefficient estimates using the TSLS method. Variable technological innovation is found to have a positive and significant effect on renewable energy consumption at 1% level, in line with earlier estimates with two-way fixed effect, hence confirming a robust outcome. Similarly, regarding the institution variable, the robustness estimate show negative and statistically significant impact, as in the two-way fixed impact.

For the robustness test of the dynamic model, additional measures of renewable energy and an updated GMM estimator are used to examine the estimates. Specifically, electricity production from renewable sources and continuously updated GMM (CUE) are employed to test the robustness of dynamic models. The continuously updated GMM is more effective in determinate samples, where the estimates of the ideal matrix may be delicate to the random selection of the original weight matrix (Kripfganz, 2019). The updated GMM addresses this by directly obtaining the ideal weight matrix through a minimization process (Kripfganz, 2019). The results in Table 14 show that both technological innovation and formal institutions have a positive influence on renewable electricity production, except in variant four when times effect is on. In variant four, the impact of technology is positive but not significant. The result from CUE shows that earlier estimates based on system GMM are robust and stable.

Table 12
Panel threshold estimate (with INS as threshold variable).

LREW	Coefficient	Std. err.	z	P-value
Above threshold				
lREW.1	0.975*	0.019	50.06	0.000
LTEI	0.030***	0.016	1.81	0.071
LGDPPC	0.018	0.038	0.48	0.632
LOIP	0.020	0.012	1.60	0.109
LCO2	0.025***	0.015	1.66	0.098
LTOP	0.011**	0.005	2.19	0.029
Below threshold				
lREW.1	0.979*	0.021	45.55	0.000
LTEI	0.019	0.012	1.50	0.135
LGDPPC	0.041	0.046	0.88	0.377
LOIP	0.012	0.008	1.42	0.156
LCO2	0.147***	0.077	1.90	0.057
LTOP	0.003	0.010	0.34	0.734

Note: LTEI is considered endogenous in the model. *, ** and *** refers to significance level at 1%, 5% and 10%, respectively.

Table 13
Two-stage Least Squares (TSLS) estimate for the static model.

Dependent variable: LREW			
LTEI	0.069(0.032)**	0.077(0.006)*	0.152(0.039)*
LINS		−0.385(0.237)*	−0.886(0.151)*
LGDPPC			0.323(0.019)*
LOIP			0.208(0.073)*
LCO2			0.043(0.003)*
LTOP			0.247(0.033)*
Constant	1.344(0.14)*	6.792(0.283)*	2.053(0.170)*
Obvs	1820	1820	1820

Note: *p < 0.01 and **p < 0.05. Values in are cluster errors. LTEI is taken as endogenous, and 1 and 2 lagged terms are used as instruments.

With respect to the moderation effect, that is, the interaction impact of technological innovation and institutions on renewable energy, again, electricity production from renewable sources and continuously updated GMM (CUE) are employed to test robustness. As reported in Table 15, the signs and significance of the estimates of variables LTEI, LINS and LTEI_INS are consistent with earlier estimates based on two-step SGMM. Overall, the technology (LTEI), formal institutions (LINS) and their combined effect (LTEI_INS) significantly induce renewable electricity production. However, the impact of technology and institution is not significant in model 3, although the coefficient estimates are positive.

Lastly, to examine the robustness of the threshold model, components of the formal institution, namely, regulatory quality as an indicator is used. The robustness estimate with regulatory control as threshold variables for institutions is provided in Table 16. As observed, the coefficient sign and significance of LTEI do not vary significantly. Specifically, the technological innovation effect on the above threshold

Table 14
Updated System GMM for dynamic models (with alternative renewable energy measure).

Dependent variable: LREW	(1)	(2)	(3)	(4)
LREW.1	0.918 (0.009)*	0.900 (0.145)*	0.915 (0.012)*	0.882 (0.026)*
LTEI	0.159 (0.034)*	0.112 (0.042)*	0.078 (0.043)***	0.116 (0.269)
LINS		0.351 (0.182)**	0.321 (0.166)**	0.314 (0.098)*
LGDPPC			0.048 (0.029)***	0.140 (0.220)
LOIP			0.078 (0.064)	0.083 (0.093)
LCO2			0.005 (0.305)	0.014 (0.174)
LTOP			0.047 (0.029)***	0.072 (0.034)**
Constant	0.209 (0.065)*	0.726 (0.286)*	0.646 (0.253)*	1.377 (0.312)*
Time effect	No	No	No	Yes
Hansen J-stats (test for all instruments)	2.46	2.51	4.40	4.43

Note: *p < 0.01, **p < 0.05 and ***p < 0.10. Values in are robust errors.

Table 15
Updated System GMM for dynamic models (with interaction and alternative renewable energy measure).

Dependent variable: LREW					
	(1)	(2)	(3)	(4)	(5)
LREW.1	0.918(0.009)*	0.900(0.145)*	0.901(0.015)*	0.918(0.011)*	0.737(0.058)*
LTEI	0.159(0.034)*	0.112(0.042)*	0.938(1.988)	0.433(0.091)*	0.234(0.036)*
LINS		0.351(0.182)**	1.393(2.512)	0.941(0.128)*	0.631(0.318)**
LTEI_INS			0.509(0.225)**	0.573(0.059)*	0.163(0.041)*
LGDPPC				0.052(0.031)***	0.468(0.229)**
LOIP				0.055(0.072)	0.011(0.019)
LCO2				0.022(0.027)	0.394(0.198)
LTOP				0.033(0.021)***	0.056(0.023)**
Constant	0.209(0.065)*	0.726(0.286)*	2.418(0.697)	1.501(0.997)***	7.525(2.452)*
Time effect	No	No	No	No	Yes
Hansen J-stat (test for all instruments)	2.46	2.51	2.86	4.15	21.72

Note: *$p < 0.01$, **$p < 0.05$ and ***$p < 0.10$. Values in are robust errors.

Table 16
Panel threshold estimate (with alternative threshold variable).

LREW	Coefficient	Std. err.	z	P-value
Above threshold				
lREW.1	0.973*	0.022	44.76	0.000
LTEI	0.024***	0.014	1.67	0.095
LGDPPC	0.043	0.042	1.00	0.316
LOIP	0.011	0.028	0.40	0.686
LCO2	0.017***	0.009	1.90	0.057
LTOP	0.078*	0.008	9.75	0.000
Below threshold				
lREW.1	0.845*	0.03	28.16	0.000
LTEI	0.067	0.145	0.46	0.642
LGDPPC	0.346***	0.194	1.78	0.074
LOIP	0.006	0.055	0.11	0.913
LCO2	0.184*	0.723	2.55	0.011
LTOP	0.035	0.052	0.68	0.499

Note: $N = 91$, $T = 20$. *$p < 0.01$ and ***$p < 0.10$.

countries is positive and statistically significant. However, in the case of below threshold, the effect is positive but not statistically significant, as in earlier estimates.

4.4. *Discussion*

Based on empirical analysis, a number of key findings can be emphasized. The lagged variable of renewable energy favourably and significantly impacted the renewable energy (dependent variable) in all scenarios. This finding suggests that renewable energy has path dependent feature, implying that previous evolution has implications for the present and future position of renewable energy consumption and production.

The impact of technological innovation is found to have a positive impact on renewable energy in agreggate sample, confirming the soundness of hypothesis 1. However, it is observed that in the subsample estimation, technology has a negative impact in developing countries, whereas in developed countries, the result shows that technology has a positive impact on renewable energy. The results foe aggregate level and the developed country sample are similar to Wang et al. (2023), who show that the digital economy enhances renewables in Asian countries. Shahbaz et al. (2022) argue that technological innovation can improve energy transition; thus, it is important to consider technology as an effective instrument for improving energy systems. However, improvements in the energy mix are accompanied by policy and institutional challenges. Formal institution, if appropriately position can be an important instrument for the government to correct market inefficiencies. Formal institutions in this study are found to have a positive impact on renewable energy in the aggregate sample as well as in subsample analysis, thus confirming the validity of hypothesis 2. Institutions paly critical role in shaping government policies which incentivize renewable energy transition (Mahmood et al., 2021).

Furthermore, the effect of technology on enhancing renewable energy can vary in terms of a country's economic development, environmental concerns and trade relations. It is found that economic growth (GDPPC) is positively related to renewable energy in the full sample as well as in the developed country sample. This suggests that the use of renewable energy tends to rise with economic growth. This finding is similar to Sadorsky (2009) and Chang et al. (2009), where developed countries show a positive relationship. However, this connection is inverse for the developing countries sample, where economic growth reduces renewable energy consumption. This finding suggests that while developing countries are transitioning to renewable energy, energy use in these nations still comes from non-renewable resources. For example, Kahia et al. (2016) show green energy and non-renewable energy sources have inverse and bidirectional relations, implying these two sources of energy are substitutes. Similarly, Bhattacharya et al. (2016) showed a negatively charged association between growth and sustainable energy use, signalling that these countries may still use non-renewable energy.

With respect to environmental concern, the impact of carbon emission (COE) is positive irrespective of the sample group, although not statistically significant. The positive impact is more pronounced in developing country samples. An upsurge in per-capita carbon emissions leads to growth in renewable energy use. This finding is consistent with Salim and Rafiq (2012) and Omri and Nguyen (2014). The positive impact can be explained by the fact that high CO2 may initiate greater investment in renewable energy, which often comes as a policy response. Also, countries often respond with environmental concerns and renewable incentives. Analogously, oil prices and renewable energy utilization contrast in the subsample analysis. An increase in oil prices increases renewable energy use in developing countries. However, it decreases renewable energy in developed country samples. The positive association is in line with Apergis and Payne's (2014) findings and theoretical predictions.

The connection between trade and the use of renewable energy shows a differing impact in developing and developed country samples. While full and developed country samples show a positive link between the two variables, in the developing country sample, trade lowers the renewable energy consumption. Although previous studies (Brini et al., 2017; Jebli and Youssef, 2015) found a positive relation between trade and use of renewable energy, we find a negative connection between the two variables in the developing country sample. There are possible explanations for this. The pollution haven theory might come first. There is strong evidence that trade openness and foreign investment (FI) are clearly correlated (Liargovas and Skandalis, 2012). Further, it is discovered that nations with laxer environmental policies were drawing in more foreign direct investment (Tang, 2015; Khan et al., 2021). Since developing nations may have laxer environmental laws (Fankhauser et al., 2015), international trade may possibly draw more foreign investment and reduce investment in green energy in developing nations. For example, Khan et al. (2021) show that foreign investments and renewable energy use are inversely related in about 69 Belt and Road Initiative countries.

5. Conclusion and policy implications

5.1. Conclusions

There has been an increase in interest in considering renewable energy transition for sustainable development over the last couple of decades. Among the other factors, technological innovation and formal institutions play an important role in the renewable energy transition over various stages of a country's development. This study explores the impact of technology and formal institutions on renewable energy consumption and electricity production from renewable sources. Considering the econometric issues in panel data analysis, like autocorrelation and cross-sectional dependency, this analysis utilizes a series of second-generation tests and system GMM techniques to investigate the effect of technological innovation and formal institutions on the renewable energy transition. Given the large heterogenous cross-section in this study, a subsample of developing and developed countries analysis is conducted. Additionally, a panel threshold model is employed to account for the potential nonlinear impact of technology on renewable energy.

The findings from the analysis highlight the following. First, the cross-sectional dependence test shows strong interdependence across the variables used for the sample countries. The coefficient estimates at the aggregate sample reveal that technological innovation has a positive and statistically significant impact on renewable energy transition (renewable energy consumption and renewable electricity production), indicating that technology is crucial in promoting renewable energy. This result is robust and uniform across different specifications and methodologies employed in the analysis. In the subsample of developing countries, the impact of technology is found to be negative. This suggests that developing countries face challenges in integrating technologies to enhance sustainable energy and realize gains from technological innovation and renewable energy sources. Further, these countries are often highly dependent on hard fuels, lack economic diversification and work with low-value production and limited primary exports. They lack technology infrastructure, innovation capacity and specialized workforce to integrate technology and utilize them to produce and use renewable energy.

Secondly, the results indicate that in aggregate sample analysis without path dependency, formal institutions have an adverse impact on renewable energy. However, after considering path dependency features of renewable energy, the analysis shows institutions have a significant positive impact on renewable energy. In the subsample investigation, the impact of formal institutions is positive but statistically insignificant for the developing country sample. This can be due to inherent weaknesses and gaps in institutional arrangements that make them less effective in the renewable energy transition (Shahbaz et al., 2022). In contrast, the effect of formal institutions in the developed country sample is positive and statistically significant. The positive outcome in developed countries can be explained by robust institutions that facilitate strong policy certainty, incentives (high carbon price) to invest and conducive regulations to draw private capital.

Third, the study also explores how the two variables of interest (technology and institution) combine to influence renewable energy. The interaction impact of technological innovation and formal institutions reveals a positive and significant impact on renewable energy. These results indicate that both technological innovation and formal institutions are complementary and can mutually prompt renewable energy transition. Lastly, the panel threshold model reveals that the impacts of technological innovation exhibit asymmetric effects on renewable energy. Specifically, the impact of technology is positive and has a significant impact on renewable energy for countries above the threshold. In contrast, for countries below the threshold, the impact of technology is positive but is statistically insignificant. These results remain consistent when components of the formal institution, namely, regulatory quality is used as a threshold variable.

5.2. Policy implications

In times of globalization and industrialization, technological innovation is reshaping the world's economies and the advent of new technologies is presumed to grow rapidly. In particular, with respect to sustainable development and energy, renewable energy is an unavoidable option, and technology can be a pivotal driver not only in developing clean and cheap renewables sources but also improve energy efficiency and savings through improved technologies. Technological innovation can also make renewable energy sources more accessible and scalable. It is in this respect that the role of policymakers and institutions is critically essential in policy design and implementation to accelerate technology adoption in renewable energy development. Thus, to promote an efficient energy transition, policymakers must concentrate on strengthening governance and institutional frameworks and investing in technology infrastructure. In addition to infrastructure, institutional capacity should be developed so that they can endeavor policies and incentives that are beneficial to supporting renewable energy development. Specifically, this can be implemented by fiscal measures such as subsidies, reducing dividend taxes of renewables and technology infrastructure and strengthening research and development in critical areas of energy and technology through restructuring tax systems.

Furthermore, the implication follows that there needs to concreate long term targets aligning with the country's national and international commitments while progressively crowding out hard fuel supports. This can be accomplished through increasing energy planning openness, providing communities with access to renewable energy information to empower them, and fostering international collaboration to build institutional capacity. Consequently, institutions should shape a stable and encouraging policy environment for the domestic market to attract private and foreign investments and avoid uncertainties as well as minimize the transaction costs. Moreover, through institutional support, barriers can be reduced to increase renewable energy access, for instance, national tariffs on technologies and modern grid infrastructure to transfer renewable energy. Lastly, the findings of the study also relate to a broader implication that countries should re-examine their policy agenda regarding renewable energy consumption and production and work within the framework to remove obstacles regarding renewable development.

5.3. Study limitations and future research

This study thoroughly investigates the impacts of technological innovation and formal institutions on renewable energy for 91 countries globally. However, the author is also of the view that regional and individual country differences exist, and such studies are important for specific insights and identification of unique difficulties and prospects arising from various features, which technological innovation and formal institutions may have for investment and promotion of renewable energy transition. Furthermore, future studies may analyze specific components of technology as well as additional indicators of institutions on renewable energy in a disaggregated method to offer more specific guidelines to policy planners. These investigations can help establish specific aspects of countries and determine specific technology and institutional characteristics that could be beneficial for the renewable energy transition amid the climate and environmental crisis.

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Data availability

The data used in this study can ne accessed from the website outline in the data section of the paper.

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