



Does technology innovation complement the renewable energy transition?

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Abstract

The study assesses the relationship between technology innovation and renewable energy in the G10 countries. According to the findings, technology innovation has a significant impact on renewable energy in various countries, including Germany, the Netherlands, Sweden, the UK, and the USA. It argues that technological innovation is one of the most important elements in renewable energy in these countries because of their strong innovative base and huge spending on research and development. However, the results for the remaining countries show no causation from technology innovation to renewable energy, implying that variables other than technology innovation drive renewable energy development. On the other hand, renewable energy does Granger cause technology innovation in Germany, the Netherlands, and the USA. These countries need to invest in implementation instead of spending on the existing infrastructure. Furthermore, the increased dependence on fossil fuels and nuclear energy may leave renewables undeveloped, with less emphasis on renewable-technology diffusion.

Keywords Technology innovation · Renewable energy · Patent · Energy transition · Environmental issue

Introduction

The problem of climate change and energy security entails pursuing solutions to reduce greenhouse gas emissions while ensuring energy supply security (Geng and Ji 2016). The transition process is helpful to implement, which reduces the negative environmental effects of production and consumption. Renewable energy (REN) has the potential to achieve environmentally sustainable development, reduce reliance on imported resources, and meet the energy demand with economic growth (Dalby et al. 2018; Rechsteiner 2021). The rising cost of fossil fuels and the depletion of energy resources are propelling factors for REN development. Meanwhile, technological innovation (TI) can serve as the

technical foundation for REN and an essential element of development (Khan et al. 2022a). The leading technology ensures the best use of REN sources to meet the energy demand (Khan and Su 2022). Technology integration with renewables can help to achieve long-term economic growth while addressing environmental concerns (Sherif et al. 2022). TI has digitalized, allowing for REN integration and output optimization using analytic and artificial intelligence. Renewable energy technologies (RETs) substantially contribute by improving plant efficiency and maintaining consistent production (Park 2005). However, RETs are more expensive than fossil energy and commercialization is lower, which may undermine REN (Palage et al. 2019). A rising trend of low carbon technologies has been observed recently and represents most of all patents in environmental technologies. Thus, TI will profoundly impact REN development and vice versa and the global energy pattern (Geng and Ji 2016).

The study is conducted with the purpose of evaluating the causal nexus between TI and REN in the Group of Ten (G10) countries. The group comprises eleven industrial countries: “Belgium, Canada, France, Germany, Italy, Japan, the Netherlands, Sweden, Switzerland, the UK, and the USA” which consult and collaborate on economic, monetary, and financial matters. These are the most innovative countries with economic strength and leaders in the energy

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transition to meet environmental targets (Su et al. 2022). Meanwhile, G10 countries are world leaders in REN and produce enough electricity to power their economies and household. Similarly, the countries have set ambitious targets to get most of their electricity from renewables by 2030 and looking forward to a bright future with REN. These countries have placed to fully decarbonize their electricity supply by 2035, which will accelerate technological advances and infrastructure. Meanwhile, countries strive hard to follow the energy transition process because they are the largest energy consumers and carbon emitters. Also, innovation is critical to achieving environmental sustainability by introducing energy-efficient technologies to preserve economic growth without harming the environment (Sherif et al. 2022). Furthermore, the innovation process generates a movement toward green technologies that protect the environment and increase market efficiency through government laws that lead to a transition to low-carbon technology in these countries. Figure 1 illustrates that more spending on research and development (R&D) and innovation have been noted in these countries, making REN more competitive and appealing. Rapid growth in green patents, particularly since 2005, may cause the impetus for renewables. This rising trend in low-carbon technology innovations is supported by public policies, environmental regulation, and higher energy prices. However, patent registration slowed following the financial crisis in 2008 and even declined in specific technological sectors. Furthermore, the crisis has hampered the expansion of the REN through the flow of debt from banks to renewable developers. Moreover, the crisis results in slashing subsidies for innovative renewable projects due to investors' uncertainty (Shivakumar et al. 2019).

Following the nuclear disaster in 2011, the energy policy in these countries witnessed a sudden change to phase out nuclear power and develop RETs to fill the electricity supply gap (Shivakumar et al. 2019; Su et al. 2022). The collapse of oil prices in 2014 lowered the value of future energy savings or fossil fuels and the motivation for green energy. Similarly, the growth has been slowed since 2014 because of REN production's inability to create enough energy while avoiding environmental dangers. TI triggers changes in the energy system and enables a multi-directional and highly-integrated energy system. The energy sector has developed smart electricity grids to integrate decentralized REN generation into the system. However, these countries' economic activities are adversely affected by coronavirus disease (COVID-19), suppressing environmental issues and slowing the energy transition process. This uncertainty results in the decline of investment in renewable energy, and some of these countries have revealed a decreasing movement of REN. Moreover, shutting down renewable energy manufacturing factories due to the pandemic might have a detrimental impact on REN (Su et al. 2022). Hence, the discussion about the causality between TI and REN in G10 countries is critical due to their position in the global economy, technological development, and environmental issues.

The research makes a substantial contribution to the current body of knowledge. It offers a fresh viewpoint on country association as compared to earlier research. As a result, this article applies panel causality to the causation association between TI and REN in G10 nations, adding a new aspect to the causality link. Furthermore, the study looks at precise outlines of the causal relation between TI and REN and how the relationship differs between G10

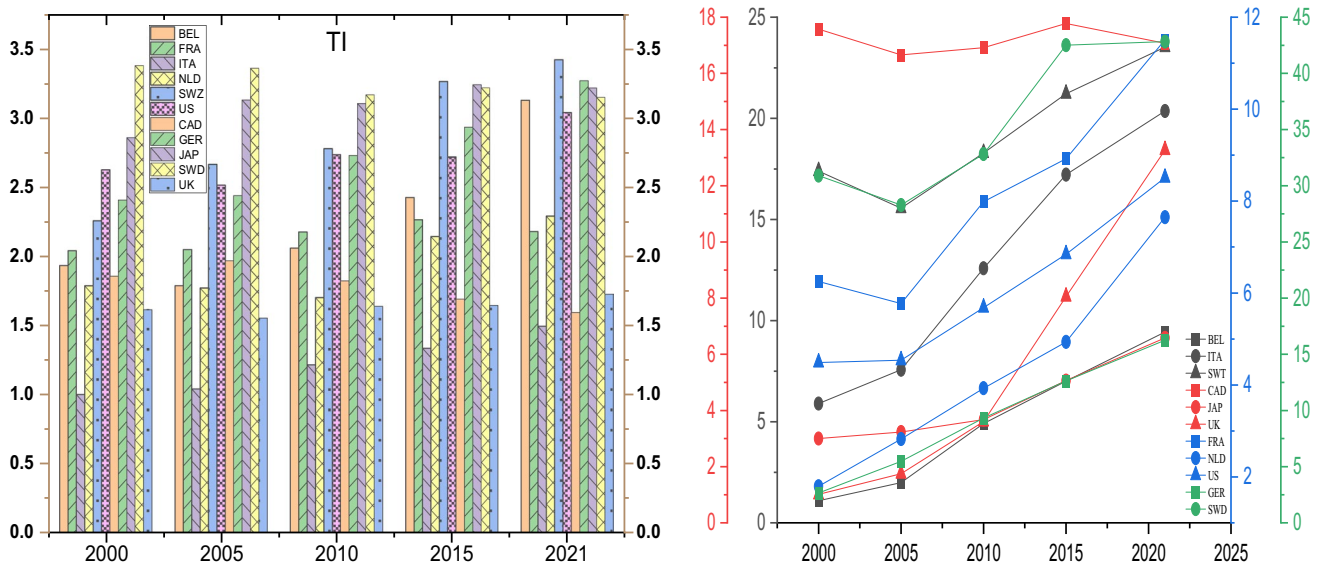


Fig. 1 Behaviour of TI and REN

countries. The result has meaningful policy recommendations for G10 countries and recognizes the essential causal elements of TI and REN. Similarly, REN is described by its strong innovative base, huge spending on research and development, rising fossil fuel prices, and environmental issues. The findings show that TI has a significant effect on REN in various countries, including Germany, the Netherlands, Sweden, the UK, and the USA. It argues that TI is one of the essential elements in REN in these countries because of their strong innovative base and huge spending on research and development. However, the results for the remaining countries show no causation from TI to REN, implying that other variables other than TI drive REN development. REN does Granger cause TI in Germany, the Netherlands, and the USA. These countries need to invest in implementation instead of spending on the existing infrastructure.

The paper consists of a literature review in Section "Review of literature". The methodology is outlined in Section "Panel bootstrap Granger causality", while the data summary is illustrated in Section "Data". The most important analysis of the results is demonstrated in Section "Empirical analysis", followed by the Conclusion in last Section".

Review of literature

GENG and Ji (2016) examined the correlation between TI and REN in the six developed countries. According to the results, TI and REN have a long-run relationship and bidirectional causality. He et al. (2018) explored that spending on technologies played an important role in REN development at the provincial level of China. A similar conclusion derived by Palage et al. (2019) stated that developing new technologies effectively impacted REN consumption. Shivakumar et al. (2019) confirmed the nexus between REN and TI as regulation and expansion in the solar system improves renewable generations. Xie et al. (2020) explained that developing new technologies effectively impacted REN consumption. However, the existing technologies can not create a considerable effect on REN. Salvarli and Salvarli (2020) reported that REN had assumed the leading role in future electricity generation that might help to control the environmental hazard. Su et al. (2021) investigated that REN is one of the most important variables in the energy transition, which might aid in resolving environmental challenges. Zheng et al. (2021) examined how TI promotes REN and results indicate that a 1% increase in TI leads to a 0.411% increase in REN in a particular province and has a contagion impact on the neighboring provinces through technology diffusion. Amin et al. (2021) evaluated the association between research spending on REN development and concluded that countries dependent on imported fossil fuels were likely to invest in REN. Khan et al. (2022a, b) concluded that REN

was a leading determining factor in economic and political affairs and is a new battlefield for countries. Khan and Su (2022) showed that REN is driven in G7 countries by government policies and economic support. Su et al. (2022) investigated the nexus between TI, REN, and economic uncertainty in the G7 countries. They conclude that TI and REN go hand in hand, supported by economic stability. Sherif et al. (2022) revealed that innovation significantly impacted REN caused by environmental degradation.

Park (2005) explored that intellectual property rights (IPRs) were a useful instrument for promoting the diffusion of green technology. Johnstone et al. (2010) provided evidence of the role of public policy in promoting RET innovation. IPR systems were important in ensuring that patent contributions were not overlooked. Pop et al. (2011) explained that patenting activity was the potential factor of REN deployment. Furthermore, patenting activity has a major impact on the distribution of REN in Organization for Economic Co-operation and Development (OECD) countries. According to Gattari (2013), patent protection boosted the profitability of green energy-related investments and sped up the advancement of green energy technologies. Rai et al. (2014) explored that weak IPR rules are barriers to the progress of low carbon technologies because the weak rights increase to realization time of investment returns. Gao and Zhai (2018) demonstrated no relationship between IPR rules and the REN industry because of a lack of innovation. Ben Youssef (2020) showed that resident and non-resident patents have a long-term relationship with REN consumption. Sobolieva and Harashchenko (2020) investigated the evolution of technologies and patent activity. The findings showed that solar has the most patents, whereas wind has the fewest. Furthermore, geothermal has the fewest patent. Li et al. (2020) found that IPR protection has no substantial influence on REN usage. This showed that IPRs were not an issue for global energy transition, implying that strong efforts must be made to influence economic inputs to impact REN implementation. Tee et al. (2021) investigate the impact of IPRs on REN development in the panel nations. The findings showed that IPRs were driving REN advancement because increased patent protection rights increased energy production from renewable resources and motivated the development of RETs. Stevens and Rouhollahi (2021) concluded that R&D investment in REN has a long-term, significant, and positive impact on complementary technology innovation.

Panel bootstrap Granger causality

The panel bootstrap Granger approach is utilized in this study to explain the relationship between TI and REN in the G10 countries. There are several advantages to using this strategy. First, it investigates the causal relationship

between each panel member independently, assuming the panel’s heterogeneity, which offers extra information about specific group members. Furthermore, unit root and cointegration testing are not required because the findings of these tests might be inconsistent (Kónya 2004). It can assess if there is unidirectional, bidirectional, or no Granger causation among as many panel members as possible (Khan et al. 2019). Granger causality states that knowledge from a past period of one time series (X) aids in the predicting of a subsequent time series (Y) (Granger 1969). If a country displays both cross-sectional dependency and heterogeneity, the method used to assess causality should account for both qualities. Several panel causality approaches encourage the exploration of such correlations (Kar et al. 2011). In this scenario, Kónya (2006) proposes the bootstrap panel technique, which considers both cross-sectional and heterogeneity components of the causal link. This approach discovers the causal connection using the Seemingly Unrelated Regression (SUR) estimate of the set of equations and Wald tests using country-specific bootstrap critical values. The country-specific critical bootstrap values are useful because they exclude variables from the stationary condition, implying that they are in level form and unaffected by unit root and cointegration characteristics. By adding country-specific limitations, the number of nations having Granger causality is also displayed. The bootstrap panel causality approach may be expressed as follows:

$$\begin{aligned}
 REN_{1,t} &= \alpha_{1,1} + \sum_{i=1}^{lg_1} \vartheta_{1,1,i} REN_{1,t-i} + \sum_{i=1}^{lr_1} \gamma_{1,1,i} TI_{1,t-i} + \sum_{i=1}^{lr_1} \gamma_{1,1,i} GDP_{1,t-i} + \zeta_{1,1,t} \\
 REN_{2,t} &= \alpha_{1,2} + \sum_{i=1}^{lg_1} \vartheta_{1,2,i} REN_{2,t-i} + \sum_{i=1}^{lr_1} \gamma_{1,2,i} TI_{2,t-i} + \sum_{i=1}^{lr_1} \gamma_{1,2,i} GDP_{2,t-i} + \zeta_{1,2,t} \\
 &\dots \\
 &\dots \\
 REN_{N,t} &= \alpha_{1,N} + \sum_{i=1}^{lg_1} \vartheta_{1,N,i} REN_{N,t-i} + \sum_{i=1}^{lr_1} \gamma_{1,N,i} TI_{N,t-i} + \sum_{i=1}^{lr_1} \gamma_{1,N,i} GDP_{N,t-i} + \zeta_{1,N,t}
 \end{aligned}
 \tag{1}$$

And

$$\begin{aligned}
 TI_{1,t} &= \alpha_{1,1} + \sum_{i=1}^{lg_2} \vartheta_{2,1,i} TI_{1,t-i} + \sum_{i=1}^{lr_2} \gamma_{2,1,i} REN_{1,t-i} + \sum_{i=1}^{lr_2} \gamma_{2,1,i} GDP_{1,t-i} + \zeta_{2,1,t} \\
 TI_{2,t} &= \alpha_{1,2} + \sum_{i=1}^{lg_2} \vartheta_{2,2,i} TI_{2,t-i} + \sum_{i=1}^{lr_2} \gamma_{2,2,i} REN_{2,t-i} + \sum_{i=1}^{lr_2} \gamma_{2,2,i} GDP_{2,t-i} + \zeta_{2,2,t} \\
 &\dots \\
 &\dots \\
 TI_{N,t} &= \alpha_{1,N} + \sum_{i=1}^{lg_2} \vartheta_{2,N,i} TI_{N,t-i} + \sum_{i=1}^{lr_2} \gamma_{2,N,i} REN_{N,t-i} + \sum_{i=1}^{lr_2} \gamma_{2,N,i} GDP_{N,t-i} + \zeta_{2,N,t}
 \end{aligned}
 \tag{2}$$

where l is the lag length. GDP is used as a control variable. In a country, the causality may be found in four different forms: (i) There will be unidirectional Granger causation from TI to REN if not all $\gamma_{1,i}$ are zero but all $\vartheta_{2,i}$ are zero. (ii) When all $\gamma_{1,i}$ are zero but not all $\vartheta_{2,i}$ are zero, the unidirectional Granger causality from REN to TI will happen. (iii) When neither $\gamma_{1,i}$ nor $\vartheta_{2,i}$ is zero, REN and TI will exhibit bidirectional Granger causality. (iv) When all $\gamma_{1,i}$ and $\vartheta_{2,i}$ all are zero, REN and TI will have no Granger causality. The lag structure is critical since it will affect the causality test findings. The estimated load will vary depending on the lag structure and number of variables. The problem is handled by Kónya (2006), who permits maximum lags to vary between variables while being constant across equations. For each possible pair of $l_{g1}, lr_1, l_{g2}, lr_2, l_{s2}$, and l_{s2} , we compute the system with 1 to 4 lags and then pick the group that minimizes the Schwarz Bayesian Criterion.

Data

The link between REN and TI is investigated in the G10 countries using the annual data from 2000 to 2021. In the early 2000s, there was an increase in investment in renewable technology, which shows a significant improvement in REN. Meanwhile, the energy shift is accelerating due to environmental concerns, rising oil prices, and technological advancement (Su et al. 2022). Similarly, concerns

Table 1 Descriptive statistics

Country	Variables	Mean	Std. Dev.	Skewness	Kurtosis	J–B
Belgium	TI	2.271	0.451	0.785	2.340	2.656
	REN	4.837	2.799	0.058	1.634	1.722
Canada	TI	1.813	0.134	–0.005	1.705	1.538
	REN	16.984	0.603	–0.026	1.913	1.085
France	TI	2.161	0.076	–0.454	1.998	1.676
	REN	7.991	1.995	0.436	1.935	1.738
Germany	TI	2.759	0.290	0.217	1.714	1.689
	REN	9.477	4.396	–0.103	1.826	1.303
Italy	TI	1.233	0.159	0.165	1.696	1.657
	REN	12.854	5.005	–0.075	1.468	2.172
Japan	TI	3.153	0.133	–0.706	2.640	1.944
	REN	4.268	1.228	0.795	2.294	2.773
Netherlands	TI	1.935	0.226	0.221	1.416	2.477
	REN	4.291	1.982	0.728	3.077	1.949
Sweden	TI	3.345	0.185	1.185	4.259	6.598
	REN	33.666	6.003	0.179	2.073	0.906
Switzerland	TI	2.885	0.350	–0.052	1.867	1.186
	REN	18.947	2.618	0.364	1.945	1.507
UK	TI	1.639	0.058	0.348	2.442	0.729
	REN	5.421	4.312	0.702	2.119	2.518
USA	TI	2.737	0.165	0.546	2.444	1.378
	REN	5.998	1.506	0.215	1.669	1.793

about the depletion of precious oil supplies and energy security have prompted a shift to renewable energy (Su et al. 2019). As a result, REN is the most realistic solution for ensuring energy supply for long-term growth. However, REN development may need a favourable climate and government policy backing. REN growth is fuelled by strong economic expansion, raising energy consumption and leading to transition. As a result, REN is driven by energy demand, environmental problems, energy security, and TI (Su et al. 2022). The percentage of a country's GDP spent on research and development (R&D) in current and capital forms is equal to TI (Khan et al. 2022b). The contribution of renewables to total primary energy is known as REN, which includes hydro, geothermal, solar, wind, and tide while measured in thousand toes (Khan and Su 2021). The data is retrieved from the Organization for Economic Cooperation and Development (OECD).

Table 1 demonstrates the variable basic summary information. It records the positive mean value for TI and REN in these countries. Belgium and Switzerland exhibit the highest standard deviation for TI, so spending on R&D has frequent ups and downs, which has considerable consequences for technology development. The positive skewness of TI is detected in countries except Canada, France, Japan, and Switzerland. Similarly, the kurtosis values of TI explore the leptokurtic distribution for all G10 countries. Moreover, the normality distribution is confirmed for TI of all countries.

The summary statistics of REN show that Sweden and Italy have the greater standard deviations, respectively. The negative skewness values of REN are detected for Canada, Germany, and Italy, while the remaining are positively skewed. Similarly, REN is the leptokurtic distributed in countries except for the Netherlands. Last, the Jarque–Bera test reveals the normal distribution for REN.

Empirical analysis

The cross-sectional dependence and heterogeneity tests are used to choose the best estimators for panel causality. Countries may be highly integrated and have economic links, necessitating the examination of cross-sectional dependency and heterogeneity (Liu et al. 2014). As a result, the study's initial part looks at the cross-sectional reliance and heterogeneity across these countries. Four tests are used to reach this goal (LM , CD_{lm} , and LM_{adj}), and Table 2 illustrates the outcomes (Khan et al. 2018). At the 1% significance level, the null hypothesis of cross-sectional dependency is rejected, showing that the SUR procedure is superior to country-by-country OLS valuation. It states that disturbance in any of these nations have a contagion effect on the rest of the G10 countries. The slope of the homogeneity findings suggests that causality varies among G10 nations and that causal relation may differ.

Table 2 Cross-sectional dependency and homogeneity test

	Test	TI	REN
Breusch and Pagan (1980)	<i>LM</i>	87.495***	142.841***
Pesaran (2004)	<i>CD_m</i>	3.098***	8.375***
Pesaran (2004)	<i>CD</i>	3.259***	8.637***
Swamy (1970)	<i>s</i>	8.654***	10.137***
Pesaran and Yamagata (2008)	Δ	0.499***	0.184***
Pesaran and Yamagata (2008)	Δ_{adj}	0.536***	0.197***

*** indicates significance at the 1% level

Table 3 The Granger causality from TI to REN

Country	<i>C</i>	Wald Statistics	Bootstrap critical value		
			1%	5%	10%
Belgium	0.044	15.225	87.469	49.497	35.041
Canada	-0.039	5.448	47.21	22.785	14.795
France	0.006	1.639	51.577	26.106	17.485
Germany	0.037	32.208**	47.127	24.408	16.783
Italy	-0.001	0.217	69.390	37.829	25.934
Japan	-0.008	0.381	23.473	11.781	7.812
Netherlands	0.030	28.269*	78.294	38.987	25.293
Sweden	0.009	7.555*	22.322	11.281	7.474
Switzerland	0.031	2.491	64.251	32.222	21.897
UK	0.008	23.857**	39.006	21.414	13.461
USA	0.027	44.951*	96.089	55.296	40.306

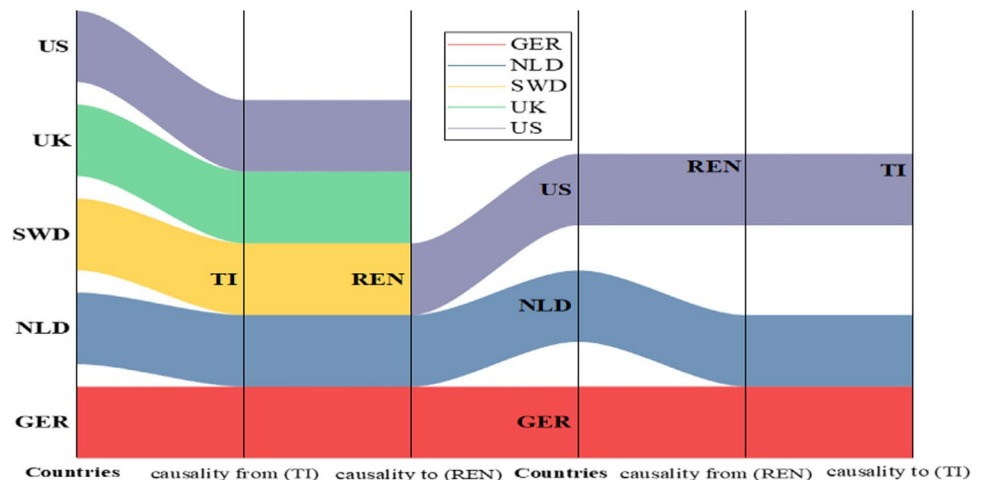
*** specify significance at the 10% and 5% levels

The panel bootstrap Granger causality test is employed to examine the nexus between TI and REN. The results of the preceding tests justify using the bootstrap panel causality test; Table 3 shows the results. As per the findings, the null hypothesis of causality is rejected at 5% and 10% significance levels, respectively, in Germany, Netherlands, Sweden, the UK, and the USA. The results show that TI

significantly impacts these countries' REN, while the rest countries have no connection. The results are in line with Su et al. (2022), who state that TI is one of the leading contributors to REN. Furthermore, TI may hasten the deployment of REN to meet energy demand. As a result, REN and TI have a close relationship and are essential contributors to energy transformation. Similarly, REN Granger causes TI in Germany, the Netherlands, and the USA, which suggests that REN development boosts TI. The economic growth in these countries provides an impetus to translate innovation into renewable development (Doytch and Narayan 2021). Figure 2 illustrates the evidence of the causality between TI and REN in G10 countries.

The results recommend that TI significantly influences REN in Germany, consistent with He et al. (2018) asserting that TI is the driving force behind REN advancement. The government has significant resources, such as spending on research and policy support, that lead to REN development. The government has established a roadmap for achieving the energy transition, referred to as the "National High-Tech Strategy 2006." This provides innovative policy to aid technological development and renewables, assuming long-term collaboration between business and government (Naudé and Nagler 2017). The "Energiewende" energy transformation strategy continues, with modest revisions in its goals (Rechsteiner, 2021). The new tasks have been established and widened the notion of innovation to include technological and social advancements. Meanwhile, Germany has increased R&D funding, with energy and technology receiving the most public money. For most technologies, the "Energiewende" in 2014 stipulates a shift to an auction mechanism that can encourage REN generation. According to the policy, the feed-in tariff should speed up the adoption of RETs. Similarly, the results of the Netherlands explore that TI has a causal on REN. It is technologically advanced, with a well-developed infrastructure, high-tech systems, and creative industries. One of the top performers is meeting

Fig. 2 Causality evidence between TI and REN of G10 countries



high expectations for the energy transition. The air quality has significantly improved, and key air pollutants have been decoupled from economic development due to RETs development. The Netherlands is at the forefront of the deployment of technologies for energy generation due to a solid technological base and remains a catalyst for developing REN. In the Netherlands, the offshore wind innovation system has progressed, new expectations have been formed, and offshore oil and gas have continued to fall. Similarly, larger-scale projects and the industry are performing well in translating the innovation into REN. Meanwhile, the country has spent more on assisting the development of the offshore wind innovation system. Government resources have been committed to developing business networking, lobbying groups, and R&D funding (Van der Loos et al. 2021).

In the case of Sweden, the findings recommend that TI has Granger cause on REN. Sweden has jumped ahead of the rest of the EU, with REN accounting for over 60% of its total energy consumption. It has outpaced the national renewable target, and innovation is one of the leading drivers of REN. Moreover, the country produces lithium batteries with green energy for electric vehicles, which may boost renewable development. The production of fossil-free steel by switching the traditional coal and coke to hydrogen gas made from REN. Similarly, buildings stand third for energy used with new technology with behavioral change; a significant decrease in energy use is possible. The result explores the significant impact of TI on REN in the UK. TI has improved REN, lowering the cost of production and allowing for the generation of REN. Furthermore, battery technology has advanced significantly and improved the transition process. Meanwhile, some technologies onshore wind and biomass boilers are relatively mature because of innovation, which can substantially contribute to renewables. The country has allocated huge funds to support offshore and marine technologies innovation, which may boost REN. The battery cost falls, resulting in the rapid advancement in battery technology, which is critical for the next generation of electric cars. The findings reveal that TI Granger causes REN in the USA. It is one of the leading innovative countries committed to achieving environmental targets. TI has possible digitalization, which allows REN integration, and production is enhanced by analytic and artificial intelligence. These aspects have become groundbreaking in the REN market (Su et al. 2022). RETs significantly contribute to and are focused on enhancing plant efficiency and ensuring sound production. Moreover, the country's policies prioritize carbon technological advancement, which leads to a causal link between TI and REN.

The remaining countries' results indicate no causal impact of TI on REN. This might be possible that TI is not affordable, reliable, and effective to be adopted. On a similar note, TI has no impact on REN in Belgium. The

country is a hub of innovation that touches every sector, from fashion technology to the process of big data. According to Bloomberg, the country is among the most innovative in mobile broadband and digital technology integration. However, REN innovation is limited because the country remains reliant on fossil fuels and faces energy security issues. Meanwhile, nuclear energy meets half of the country's electricity needs and the government intends to phase out nuclear power by 2025. The country with the lowest proportion of REN with 7.9% and the 2020 target has been extended to 2030 due to slow technological progress, as well as the application and deployment of R&D. In the case of Canada, the result concludes no significant causality from TI to REN. Canada is the leader in technology, innovation, and competitive economies globally. Furthermore, the country produces 17.3% of total electricity from renewable which is mainly generated from hydropower. This may be why Canada's TI has less impact on renewable generation. Moreover, the shares of the REN in the total energy supply are low compared to nuclear and fossil fuels, which might be why TI does not translate into REN.

France is trailing in implementation and has yet to meet its REN 2020 targets. The delivery gap is mainly caused by a lack of administrative staff and lengthy permitting processes. Implementing support mechanisms like new solar rates has been confusing and time-consuming. The retroactive reductions in incentives for solar plants constructed between 2006 and 2010 are eroding investor confidence and raising the risks and costs of future investment. Offshore wind is gaining traction slowly and lagging in strategy implementation and deployment speed. Furthermore, the electric power fleet is aging, and private investments in large-scale capacity expansions are not forthcoming, owing to a lack of long-term clarity of the electricity mix beyond 2035. The government places a high value on low-carbon electricity but does not give information on the sources and technical possibilities. The policy for the transformation of the energy system does not identify technology priorities.

Moreover, the finding suggests no causality between TI to REN in Italy. The patent position of low-carbon technologies faces a fundamental difficulty in terms of research investment and the structure of the industrial system, which is weaker than in other European nations. The capacity for innovation is linked to the system's features (Levantesi 2022). RETs do not contribute substantially because innovation primarily focuses on improving plant efficiency and assuring suitable production. REN development is not driven by innovation because of the slowing of the country's general impetus to innovate. Moreover, the country's typical adherence to EU policies prioritizing carbon reduction over technological advancement results in the lack of a relationship between TI and REN (Standish 2012). The results

Table 4 The Granger causality from REN to TI

Country	C	Wald Statistics	Bootstrap critical value		
			1%	5%	10%
Belgium	0.880	9.702	80.779	42.483	28.483
Canada	0.429	0.268	31.372	15.936	10.594
France	2.081	2.288	58.070	28.577	19.228
Germany	0.952	30.885*	70.356	38.333	26.643
Italy	0.613	0.155	75.094	39.676	28.134
Japan	0.223	1.058	50.835	24.436	15.604
Netherlands	0.111	20.552*	65.042	32.066	20.179
Sweden	-7.342	4.840	47.586	23.795	15.582
Switzerland	4.22	18.251	62.785	33.110	22.871
UK	-0.451	0.629	46.889	22.364	14.585
USA	0.696	17.835*	46.120	23.244	15.238

* show significance at the 0.10 level

explore no causal impact from TI to REN in Japan. Nevertheless, the performance of eco-innovation has increased, and there is considerable opportunity to focus on RETs. Following the Fukushima nuclear disaster, the government has to accelerate low-carbon technology to achieve progress in reducing carbon emissions. The solid TI foundation can play a critical role in creating technologies necessary to meet the ambitious climate objective. However, the lack of innovation policy in the RETs can not be diffused and adopted. The country has experienced problems in policy design with economic rationale and empirical evidence to bring new technologies to penetrate a market is not adopted. Political judgment and biasness may be the main reasons for the lackluster performance of technology development in REN in Japan. The findings reveal no causal relationship between TI and REN in Switzerland. The possible explanation is less concentration on technology diffusion because the largest renewable source is hydroelectric.

Table 4 illustrates the result of the causality running from REN to TI in G10 countries. The null hypothesis that REN does not Granger cause can be accepted in Germany, the Netherlands, and the USA, which suggests that REN development boosts TI. The remaining countries' finding reveals that REN and TI have no causality and the shares of REN in the total energy mix are insufficient, which can not create an impact on TI.

In the case of Germany, the results show a significant causal impact of REN on TI. Renewable development requires innovative systems for higher efficiency and securing sustainability with lower emissions. RETs may cover significant energy demand and play a vital role in sustainability. During the period, "Energiewende" is changed with new tasks to encourage electricity generation from renewable resources. Meanwhile, the country has allocated huge funds for R&D, which may boost innovations in RETs.

The "Renewable Energy Sources Act," updated in 2014, is aimed at helping new technologies enter the market by providing set rates and purchasing guarantees. The cheap technologies of wind power and photovoltaics slash the costs and improve REN's outlook. Similarly, the outcome shows that REN has a causal impact on TI in the Netherlands. The transformation process allows the country to become less reliant on scarce raw material imports while improving the environment. The national government has set aside significant funding to execute REN projects and climate-related activities. This comprises making the best use of raw materials, substituting sustainable and renewable for fossil-based components, and creating long-lasting products. Per the project, all government building built should be zero-emission recycled materials used in construction. Environmental and economic benefits are derivative of technological innovation. The outcomes suggest that REN has a significant positive impact on TI in the US Wind which is the leading source of renewable electricity generation. In contrast, solar generation is the rapidly increasing electricity source in the US RETs like wind and solar photovoltaics (PV) which need very little or no water to create electricity. Still, fossil fuel-based power plants use a lot of water to run. Wind, solar, geothermal, and biofuels are examples of RETs that will compete with fossil fuels. The cost may be driven down by dynamic growth, which spurs rapid technological advances. Wind and solar power are becoming increasingly essential compared to the older and more recognized hydroelectric power sources.

In the case of Belgium, REN has no significant effect on TI. It might be possible that Belgium heavily depends on external energy, resulting in a slow development of renewable (Hewitt et al. 2019). Furthermore, while significant progress has been made in several areas, technological advancements cause to speed up in terms of the rate of invention and deployment of R&D. Similarly, REN lags in meeting its goal because of the political and differences between different regional and federal authorities. REN has no causal impact on TI in Canada, as the country is a leader in the production and use of renewable resources but water is the most important source of REN generation. Meanwhile, energy prices and regulatory development are the primary drivers of REN other than technological innovation. The finding reveals no causality relationship running from REN to TI in France. The government's current rate of deployment of low-carbon energy technology does not satisfy energy and climate goals. Similarly, the country is lagging in renewables, which partly explains that nearly 70% of its electricity production is based on nuclear power. As a result, the energy sector has experienced weakness and struggling with TI. Moreover, the production from REN remains below expectation and the state-owned group is heavily indebted. Similarly, Italy's results explore no association between REN and TI. The

country is weak as it invests less in renewables than in other technologies. Moreover, the rising trend of importing RETs is observed, and the country is lagging compared with other European countries. Similarly, subsidies for REN encourage the more widespread application of existing technologies rather than innovation (Standish 2012).

The results for Japan also confirm the insignificant impact of REN on TI. The country is one of the world's most technologically advanced and innovative countries. Despite this, it is behind the curve in energy policy, with one of the highest carbon emissions per capita. Similarly, the higher cost of REN is one of the leading challenges as currently the price is double that of Germany. Furthermore, the onshore wind development projects are challenging due to the lengthy approval processes and land-use restrictions. In the case of Sweden, REN is mainly produced from hydroelectric, which may be a reason to require less technology innovation and does not translate into technology innovation. Moreover, Sweden's underperformance might be due to a decrease in gross domestic investment in R&D. Meanwhile, the total value of green early-stage investments declines because many companies are deceptive in environmental technology. In Switzerland, most of the energy is produced from hydroelectric and nuclear. The country is one of the most innovative in the world in terms of Fintech and has a commanding lead on the number of patents of inventions. However, on the other side, the results find no relationship between REN and TI, which might be possible that the largest mix of energy is produced from the water, which is less dependent on technology. The results reveal that REN significantly impacts TI in the UK. The expected explanation is the range of cost uncertainty which is large for technologies. RET costs are presently high and uncertain, still in the early phases of commercial adoption in the UK. In contrast, biomass and heat technologies for supply chains have not yet been tested on the scale.

Robustness test

The System Generalized Method of Moment Regression (SGMM) is applied to examine the robustness of the results. It estimates the TI impact on REN in the following regression:

$$REN_{it} = \alpha_0 + \alpha_1 REN_{i,t-1} + \alpha_2 TI_{it} + \alpha_3 GDP_{it} + \alpha_4 CE_{it} + \alpha_5 X_{it} + \gamma_t + \epsilon_{it} \quad (3)$$

where X_{it} shows other variables such as the oil prices, regulatory quality, and nuclear energy; γ_t denotes exogenous variables; and α_1 to α_5 are coefficients. The findings of Granger causality explored that numerous factors such as economic growth (GDP), carbon emission (CE), oil prices (OP), nuclear energy (NEG), and regulatory quality (RQL) are the leading determinants that explain REN.

Table 5 TI and REN

Variables	SGMM	Significance values
REN(-1)	0.864***	0.041
TI	0.128***	0.003
GDP	0.148**	0.056
CE	0.124***	0.046
OP	0.081**	0.055
NEG	0.186	0.046
RQL	3.064	1.641
C	0.164***	0.037
Observation	220	
Countries	10	
AR(2)	0.8581	
<i>p</i> values Hansen test	0.33	

GDP economic growth, *CE* carbon emission, *OP* oil prices, *NEG* nuclear energy, *RQL* regulatory quality

The findings are illustrated in Table 5. It showed that TI, GDP, (CE), and (OP) positively impact REN, suggesting that economic development resulted in the huge R&D in these countries, contributing to REN. Moreover, environmental issues are one of the leading objectives for these countries and pursuing a robust roadmap to tackle carbon emissions. Similarly, the OP positively influenced the transition of REN because rising energy prices led the countries to the energy transition to maintain sustainable economic growth. However, the NEG and RQL do not affect REN. Therefore, the Hansen autocorrelation AR (2) test approves the model's validity and absence of second-order serial correlation.

Conclusion

This study unveils the causal association between TI and REN in G10 countries through the panel bootstrap Granger causality approach. Before the causality test, we confirm that TI and REN vary across different countries. Moreover, the causality reveals that TI does Granger cause REN in Germany, the Netherlands, Sweden, the UK, and the USA. It explains that TI is one of the critical factors in REN in these countries due to the strong innovative base and huge spending on R&D. However, the remaining countries' results indicate no causality from TI to REN which means there are other factors other than TI which leads to REN development. On the other hand, the findings show significant causality from REN to TI in Germany, the Netherlands, and the USA.

The study offers several policy suggestions in the following ways. First, the findings suggest that TI is one of the main factors in REN development in some of these countries. In contrast, the remaining countries show that TI is not the main

contributor to REN. As a result, these countries may be able to create more efficient renewable energy technologies that are low-cost, mature, and affordable. Furthermore, rather than investing in existing infrastructure, these governments must invest in implementation. Most nations have advanced technological capabilities that must be transferred to green energy and developed into REN-valued technologies. However, the slow progress on REN innovations results in lagging renewable sources to exploit. As a result, the development of RETs must be emphasized to restructure the energy system and establish technical priorities. Second, the increased dependence on fossil fuels and nuclear energy may leave renewables undeveloped, with less emphasis on renewable-technology diffusion. This lackluster performance may be reviewed through political commitment to phase out nuclear and fossil fuels. Moreover, these countries emphasize low-carbon electricity but do not provide details on the available sources and technology options. The lack of innovation policy in the RETs can not be diffused and adopted. The strong TI foundation has the potential to play an important part in the development of technologies needed to meet the ambitious climate target. Last, the future cornerstones of energy supply comprise offshore and onshore winds and solar, which are fluctuating sources. As a result, incorporating REN into the energy infrastructure is a major task. Therefore, weather-related changes in generation must be balanced. The current power infrastructure must be utilized, and a smart grid with increased REN storage capacity must be constructed. The fluctuating supply of electricity from REN requires power grid upgradation and new communication technology to recognize any blockages swiftly.

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Declarations

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