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Harnessing technological innovation and renewable energy and their impact on environmental pollution in G-20 countries

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Climate change and environmental degradation are critical global challenges, and the G-20 nations play a pivotal role in addressing these issues due to their substantial contributions to global GDP and carbon emissions. Transitioning toward renewable energy sources is imperative for mitigating CO2 emissions and achieving sustainable development. This study investigates the impact of technological innovation, gross domestic product (GDP), renewable energy consumption, economic freedom, and financial advancement on renewable energy use and environmental pollution levels in G-20 countries from 1995 to 2022. Utilizing the PMG-ARDL dynamic panel method, the research analyzes both long-term and short-term relationships among the variables. The findings reveal that technological innovation significantly boosts renewable energy adoption, with a 1% increase in technological innovation leading to a 0.33% rise in renewable energy use in the long run and a 0.17% increase in the short run. Additionally, increased renewable energy consumption is strongly associated with reductions in CO2 emissions, highlighting its critical role in promoting environmental sustainability. The study emphasizes the importance of policies designed to enhance technological innovation to foster renewable energy usage and reduce environmental pollution. It recommends expanding and reforming the technological sector to align international and local resources with renewable energy initiatives, providing a workable framework for supporting the green growth of institutions and achieving a more sustainable future for G-20 nations. This research contributes to understanding the intricate dynamics of renewable energy transitions, offering actionable insights for policymakers and stakeholders in addressing global environmental challenges.

Keywords Renewable energy, Technological innovation, Economic freedom, GDP, Environmental pollution, G-20

Abbreviations

PMG-ARDL	Pooled mean group-Auto-regressive distributed lag
RE	Renewable energy
CO2	Carbon dioxide
GDP	Gross domestic product
EPOL	Environmental pollution
TI	Technological Innovation
EF	Economic Freedom
G-20	Group of 20 countries
EKC	Environmental Kuznets Curve
FDI	Foreign direct investment
BP	British Petroleum
IEA	International Energy Agency
FA	Financial advancement

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Climate change has emerged as one of the most critical global challenges of the contemporary era, primarily driven by the emission of greenhouse gases[1]. According to[2], global carbon dioxide (CO2) emissions from fossil fuels surged to 33,890.8 million tons in 2018, a dramatic increase from 11,190 million tons recorded in 1965. The annual growth rate of CO2 emissions reached 2.0% in 2018, marking the highest rate observed in the preceding seven years. This alarming trend underscores the urgency of addressing climate change, which poses significant threats to human health, ecosystems, and global security[3,4]. The consequences of inaction include escalating air pollution, extreme weather events, and long-term risks to human well-being and survival[5–7].

Renewable energy (RE) has been widely recognized as a cornerstone in the fight against climate change, offering a sustainable alternative to fossil fuels[8,9] and contributing to reducing CO2 emissions[10]. Sources such as solar, wind, biomass, and geothermal energy have demonstrated their potential to mitigate greenhouse gas emissions, with many studies identifying renewable energy as a critical enabler of environmental quality[11–14]. However, the environmental benefits of renewable energy remain a topic of debate, as some studies indicate that its adoption does not consistently yield significant reductions in CO_2 emissions[15–17]. Therefore, the relationship between renewable energy utilization and environmental improvement requires deeper exploration[15,18].

Technological innovation is pivotal in enhancing renewable energy capacity by enabling efficient resource utilization and accelerating the transition toward clean energy systems[19–21]. However, disparities exist among countries in their renewable energy adoption trends[22–24]. While most G-20 nations are steadily increasing their renewable energy consumption, countries like Indonesia exhibit declining trends[25,26] (see Fig. 1), signaling a need for targeted interventions and policy enhancements[27]. These dynamics raise critical questions about the interplay between technological innovation, economic growth (measured by GDP), financial advancement, economic freedom, and environmental pollution in shaping renewable energy adoption[28–32].

This study addresses these issues by examining the role of technological innovation in renewable energy utilization within G-20 countries. Specifically, it investigates the relationship between renewable energy consumption, CO2 emissions, and key economic indicators such as GDP and financial advancement. By employing robust econometric methodologies, including the PMG-ARDL, FMOLS, and DOLS models, the research ensures comprehensive and reliable insights into these interactions[28,34].

This study seeks to address several innovative research questions that explore the dynamic relationships between technological innovation, renewable energy adoption, and associated economic and environmental factors in G-20 countries. First, it investigates how technological innovation influences the adoption and efficiency of renewable energy utilization and examines the role of technological advancements in mitigating CO_2 emissions through enhanced renewable energy deployment. Second, the study explores the relationship between economic growth, measured by GDP, and renewable energy adoption in G-20 nations, alongside the impact of financial advancements, including investments in green technologies, on the integration of renewable energy sources. Third, it examines how economic freedom affects the adoption and expansion of renewable energy in these countries and identifies policy interventions that can strengthen the relationship between renewable energy consumption and environmental sustainability. Furthermore, the study assesses the extent to which renewable energy utilization contributes to reducing CO2 emissions and analyzes how variations in

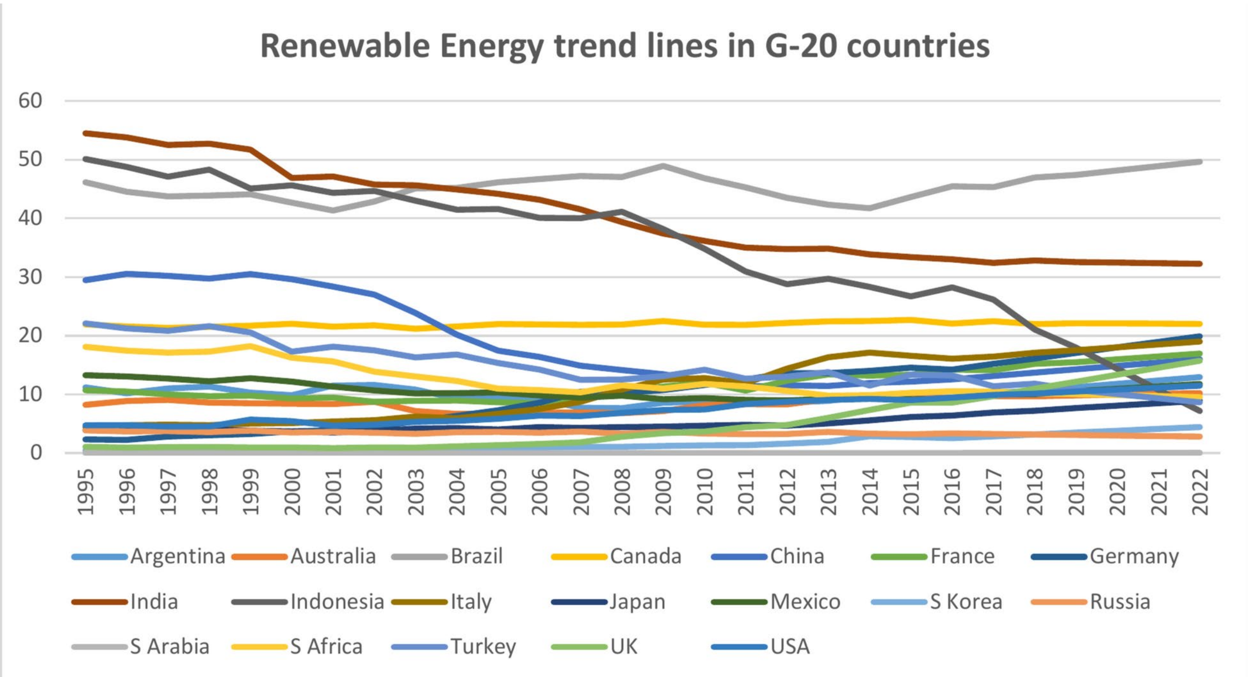

Fig. 1. Authors own compilation of data from WDI and HFI sources[33]. The trend of renewable energy in G20 nations.

renewable energy adoption among G-20 nations influence their environmental pollution levels. Additionally, it investigates why some G-20 nations, such as Indonesia, exhibit declining trends in renewable energy adoption despite global sustainability efforts, and considers lessons from countries with high renewable energy adoption rates to enhance the performance of lagging nations. Finally, the study evaluates how advanced econometric models, such as PMG-ARDL, FMOLS, and DOLS, contribute to understanding the relationship between technological innovation and renewable energy adoption. These questions aim to address critical gaps in the literature, providing actionable insights for policymakers and researchers while advancing the global discourse on sustainable energy transitions.

Objective of the study

The study aims to evaluate how technological innovation influences renewable energy adoption and contributes to reducing CO2 emissions. It further explores the interconnections between renewable energy, economic growth, financial advancement, economic freedom, and environmental pollution in the context of G-20 nations. By addressing these relationships, the research provides actionable insights for policymakers and stakeholders to accelerate the global transition toward sustainable energy systems.

This article is broken down into several sections. Initially, we critically review what has previously been published to generate some research hypotheses. The methods are discussed in the next section, followed by a detailed discussion of the empirical findings and results. In the final section, we conclude the paper make policy recommendations, and suggest future directions.

Literature review

This study conducts a comprehensive literature review on the topics of technological innovation (TI), renewable energy (RE), gross domestic product (GDP), financial advancement (FA), and economic freedom (EF), focusing on their potential to mitigate environmental degradation, particularly in reducing carbon dioxide (CO_2) emissions. Empirical evidence has been discovered in various regions worldwide, and relevant literature has been identified.

The existing literature on the TI nexus across different countries has been examined in several studies, including[19,35,36]. These studies collectively provide evidence supporting the beneficial impact of TI on environmental quality. Findings from the ARDL approach provide empirical evidence of a long-term association between non-renewable energy, renewable energy (RE), technological innovation (TI), and economic growth, specifically concerning CO2 emissions[37]. Empirical evidence suggests an inverse relationship between TI and RE with CO2 emissions in the economy. Conversely, non-renewable energy and GDP growth show a positive association with an increase in CO2 emissions in the long run[38]. Re-evaluating the existing literature on the correlation between RE and TI is necessary by implementing the autoregressive distributed lag (ARDL) technique.

Our study contributes to the findings of[39] revealing a clear correlation between TI and the attainment of RE. A scholarly publication by[37] employed the PMG-ARDL approach to investigate the perception of technological progress in addressing pollution in 26 OECD countries between 1995 and 2011. It is recommended that governments implement mechanisms tailored towards fostering environmental innovation, as opposed to other types of innovation, to facilitate the emergence of green technology and its associated knowledge outcomes. The purpose of this initiative is to promote sustainability using innovative technological approaches.

The literature on energy economics has deeply explored the link between low-carbon energy use and prosperity. However, the inadequate study of the G-20 has led to an unbalanced understanding of renewable energy among its members. This research addresses this gap by focusing on work from the past five years that employed the ARDL analytic technique. New findings by[40] examine how China may improve its banking system, grow its economy, and use renewable energy. Renewable energy practices are more likely to be adopted during economic booms, and the studied long-term relationships highlight China's complex interplay of economic and environmental factors.

According to the data gathered, stock market value has a positive and lasting impact on renewable energy development. Sun[40] proposes that a rising stock market preference increases renewable energy use. Furthermore,[41] suggests that China's environmental sustainability policies incentivize investments in eco-friendly initiatives to strengthen the renewable energy market. They employed the ARDL approach to analyze data from 1980 to 2018. Finally,[42] assessed the lasting impact of economic growth on RE use in low, middle, and high-income countries.

The extent to which energy is utilized is a crucial determinant of the quality of the surrounding ecological system. A significant body of academic research has demonstrated this correlation. The study by[43] utilized data from 1980 to 2014 to examine the relationship between variables in a comparative analysis, indicating a robust correlation between the variables. The outcomes suggest a unidirectional causal relationship between these variables, as established by[44] who highlighted that using renewable energy sources reduces CO_2 emissions based on their analysis of panel time-series data.

The Environmental Kuznets Curve (EKC) hypothesis was found to be supported in the case of African nations. The PMG-ARDL methodology was employed by[45] to investigate the validity of the inverted U-shaped EKC hypothesis in the context of 20 sub-Saharan African (SSA) states. Furthermore, employing renewable energy sources enhances the environment in member states of the G-20[46].

This research focuses on the impact of technological innovation (TI), gross domestic product (GDP), and economic freedom (EF) on the utilization of renewable energy (RE)[16]. The study found a lack of compelling evidence indicating that foreign direct investment (FDI) inflows significantly impact the adoption and utilization of RE sources across varying income levels. Similar results were reported concerning four economies in Southeast Asia[47]. Overall, seeking FDI has the potential to aid developing nations with limited shares of renewable power generation. Market expansion is closely linked to economic freedom, crucial for achieving economic success through export-oriented manufacturing, energy-efficient technology adoption, and strengthening bilateral trade relationships. Economic expansion involves improving production possibilities and reallocating resources, promoting entrepreneurial activities within the economy[48].

Several studies employed the ARDL technique to investigate the relationship between FDI and renewable energy usage, noting that investment in renewable energy sources attracts FDI from other countries. A study[49] examined how using renewable energy sources affected Tunisia's foreign trade. Additionally, between 1972 and 2015, FDI facilitated progress in renewable energy production in Bangladesh[50]. Panel time-series data analysis revealed the connections between renewable energy and U-shaped FDI trends over long periods using the autoregressive distributed lags with a structural break approach.

The research examines the impact of disaggregated renewable energy sources on the displacement of fossil fuels in 36 Organization for Economic Cooperation and Development (OECD) nations from 2000 to 2020. The results indicate a clear trend in the replacement of fossil fuels by diverse renewable energy sources. To successfully replace 1% of fossil fuels, an average growth of 1.15% in renewable power capacity is required[51]. Moreover, a study demonstrates that developing nations have improved their adoption of sustainable energy practices, increasing the proportion of renewable power production[52]. As consumer prices decrease and technological innovation improves, there is a growing understanding of the importance of energy transition[53]. Shifting towards renewable energy sources is crucial for reducing global dependence on carbon, mitigating climate change, and minimizing carbon dioxide (CO_2) and nitrogen oxide (NO) emissions, thus lessening their adverse effects on global warming[18,28,54].

Researchers in the academic world are increasingly interested in understanding how energy use affects GDP growth. A longitudinal study in 38 IEA member nations by[55] examined the connections between energy transition, renewable energy (RE), and GDP. The empirical findings suggest that while energy transition can hinder economic development (GDP increase), energy utilization tends to promote it. Another study by[56] analyzed, and found no correlation between renewable energy consumption and African countries' GDP growth, indicating that renewable energy practices may not necessarily foster long-term economic development. However, other studies have shown that renewable energy sources significantly contribute to GDP expansion over the long run, employing empirical research techniques such as structural equation modeling[57–59].

Some studies have focused on determining the factors influencing CO2 emissions and how they relate to GDP. For example,[60] investigates the negative correlation between economic growth and environmental quality, suggesting that the initial stages of GDP growth may not lead to increased emissions. Similarly,[61] used the ARDL methodology to examine the short-term and long-term relationships between CO_2 emissions, renewable energy consumption, GDP growth, and exports in Pakistan, using data from 1991 to 2022. The findings reveal that while GDP growth is associated with increased CO2 emissions, the impact weakens as the country's economic growth matures. Additionally,[62] used a dynamic ARDL (DYNARDL) approach to investigate China's GDP growth rate and its negative influence on CO2 emissions, highlighting the nuanced effects of GDP and per capita GDP growth on emissions across different studies. A study examines the influence of climate policy uncertainties and oil prices on contemporary renewable energy sources, including solar, wind, geothermal, and biofuels. The latest monthly data from 1989 to 2023 are analyzed using the Residual Augmented Least Squares (RALS) approach. The empirical evidence indicates that uncertainty over climate policy is prompting a transition in the US energy mix, emphasizing solar energy, wind energy, and biofuels[27].

The influence of the energy mix on the ecological footprint using the Fourier ADL and ARDL models for Cameroon from 1980 to 2018. The research evaluates the effects of the energy mix by including non-renewable energy, current renewable energy, combustible renewables, and waste. The empirical results indicate that GDP and power production from non-renewable energy sources are the primary contributors to environmental degradation in Cameroon[63]. The effect of India's substantial investments in solar and wind power facilities on alleviating environmental deterioration by decreasing dependence on coal-fired electricity. The empirical findings demonstrate that solar and wind energy are significantly and inversely correlated with ecological footprint, suggesting that they mitigate environmental deterioration[64].

The effects of green innovation, environmental policy strategies, and environmental taxation on the material footprint of 30 OECD nations from 2000 to 2019, using the cross-sectional ARDL (CS-ARDL) methodology within the context of the environmental Kuznets Curve (EKC). The results demonstrate that the Environmental Kuznets Curve theory applies to the material footprint. Furthermore, the long-term findings demonstrate that green innovation, stringent environmental policies, and environmental levies are crucial policy instruments for mitigating material footprint[65]. In the same way, research aims to investigate the external impact of digitalization on green innovation, renewable energy, and financial development concerning environmental sustainability. The research utilizes the System Generalized Method of Moments (SYS-GMM) for 36 OECD nations from 2000 to 2018. The empirical evidence demonstrates that digitization, green innovation, renewable energy, and financial development significantly enhance environmental sustainability[66].

The research aims to analyze the influence of energy security, green innovation, economic policy stringency, and wealth on the fossil fuel material footprint across 24 OECD nations from 1995 to 2018. This research employs the Augmented Mean Group (AMG) technique and an innovative Half Panel Jackknife (HPJ) methodology for causation and estimate. The AMG findings indicate that an increase in the energy security risk index lowers the material footprint, but green innovation and stringent economic policies have little influence on environmental deterioration[67].

Research gap

The current literature extensively examines factors significantly influencing CO2 emissions, including renewable energy (RE), financial development (FA), environmental pollution (EPOL), technological innovation (TI), economic freedom (EF), and gross domestic product (GDP). Studies have focused on various countries such as China, Malaysia, Bangladesh, Pakistan, the USA, and Japan, with China being particularly prominent in research. Additionally, some studies have explored groups of countries like BRI, BRICS, EU-5, and OECD.

However, upon reviewing the existing literature, it becomes evident that there are few studies examining the interaction effects between types of technological innovation and renewable energy or between specific technologies and energy resources. This gap is noted in studies by[19,68,69] highlighting a need for deeper exploration. Therefore, our study aims to address this gap by investigating the overlapping effects of TI and RE sources on EPOL within the G-20 group. We employ panel methodological paths such as PMG-ARDL to contribute significantly to filling this knowledge gap.

This study focuses on the role of renewable energy in G20 countries, discussing how CO2 emissions are reduced through technological innovation, economic freedom, financial advancement, foreign direct investment (FDI), and GDP. Figure 2 below illustrates the map of G20 countries. Recent literature supports the crucial role of technological innovation in promoting renewable energy and reducing carbon emissions. For instance, a study by[1] found that advancements in renewable energy technologies significantly enhance energy efficiency and reduce greenhouse gas emissions in major economies. Similarly,[70] highlights that economic freedom and financial advancement are critical in facilitating investments in renewable energy projects, thus contributing to sustainable development. Furthermore, research by[71] indicates that foreign direct investment in renewable energy sectors accelerates technological transfer and innovation, leading to substantial environmental benefits.

Additionally,[72] emphasizes that government policies promoting economic freedom can create favorable conditions for renewable energy investments, which in turn reduce CO2 emissions. Financial development plays a pivotal role in supporting renewable energy projects by providing necessary funding and reducing financial risks[70,73–75]. A study by[76] also confirms that foreign direct investment in renewable energy not only boosts technological advancements but also leads to significant reductions in carbon emissions. This study builds on the existing literature by examining the interplay of these selected variables in G20 nations, providing a comprehensive analysis of how policy and economic dynamics influence renewable energy adoption and CO_2 emission reduction.

Methodology

The sources[33] and[78] provide information on technological innovation (TI), financial advancement (FA), gross domestic product (GDP), and CO_2 emissions (as a measure of environmental pollution), as well as economic freedom (EF) indices. These sources are instrumental in understanding how these factors interrelate, particularly

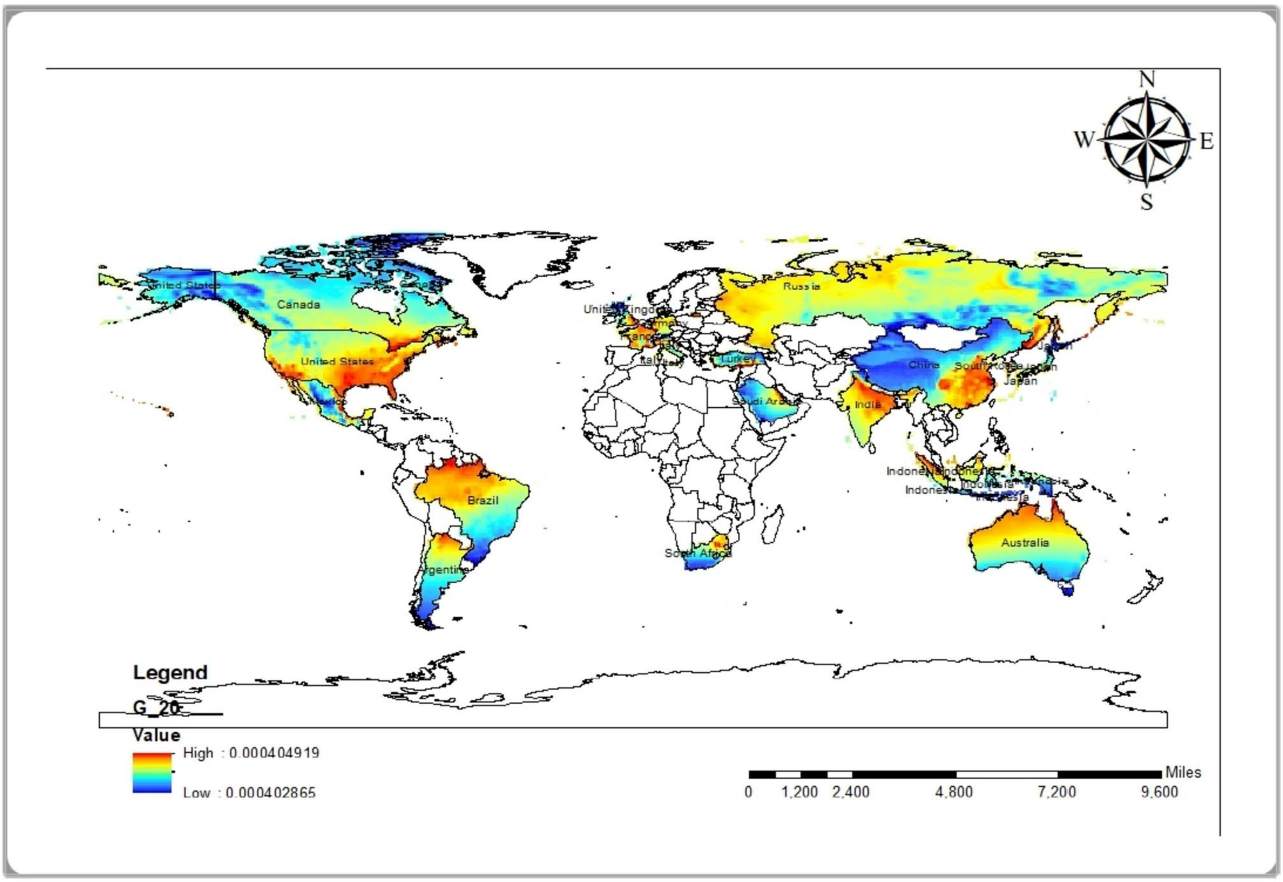

Fig. 2. G-20 countries map, and EPOL variable in Red color shows the environmental pollution from fossil fuel sources. Renewable energy is needed at higher usage levels in red color areas[77].

in the context of promoting sustainable economic growth through renewable energy adoption. The study period from 1995 to 2022 is selected to capture critical developments in renewable energy adoption, technological innovation, and environmental policies within G-20 countries. This timeframe includes significant milestones such as the[79] and[80], alongside advancements in renewable technologies and global shifts in energy consumption patterns. Starting in 1995 allows for analysis of post-globalization trends, while extending to 2022 ensures inclusion of the latest data, reflecting recent policy shifts and technological progress. This period provides a comprehensive view of long-term and short-term dynamics, offering valuable insights for sustainable energy policies. Research and development in renewable energy are crucial for achieving technological advancements and reducing reliance on fossil fuels, which in turn helps mitigate environmental pollution[81]. Increased access to capital is also pivotal in advancing the renewable energy market[82].

Methodologically, our study employs a structured approach to investigate these connections. We utilize methods such as panel data analysis, likely including PMG-ARDL or similar econometric techniques, to analyze longitudinal data across the G-20 countries or other relevant groups. This approach allows us to explore the complex relationships between TI, FA, GDP, CO2 emissions, and EF comprehensively.

$$\mathrm{RE} = \mathrm{f}\,(\mathrm{TI}, \mathrm{FA}, \mathrm{GDP}, \mathrm{EPOL}, \mathrm{EF}) \quad (1)$$

The equation above defines RE as the dependent variable, representing the composite utilization of renewable energy. Here, TI stands for technological innovation, FA denotes financial advancement, EPOL represents environmental pollution, and EF signifies economic freedom.

To address potential issues with heteroscedasticity, the data concerning these variables have been transformed into natural logarithmic form. The empirical equation can be expressed as follows:

$$\mathrm{LRE} = \beta 0 + \beta 1\mathrm{TI} + \beta 2\mathrm{LFA} + \beta 2\mathrm{LGDP} + \beta 3\mathrm{LEPOL} + \beta 4\mathrm{LEF} + \mu \quad (2)$$

LRE, LFA, LGDP, LEPOL, and LEF represent the natural logarithms of renewable energy (RE), technological innovation (TI), financial advancement (FA), gross domestic product (GDP), environmental pollution (EPOL), and economic freedom (EF) indexes, respectively. These logarithmic transformations are employed to mitigate potential issues such as heteroscedasticity in the empirical analysis. The descriptive analysis of the study is presented here in Table 1. The table provides descriptive statistics for six variables Economic Freedom (EF), Environmental Policy (EP), Financial Advancement (FA), Gross Domestic Product (GDP), Renewable Energy (RE), and Technological Innovation (TI) across G-20 countries.

The mean values indicate that the average economic freedom score is 64.44, while the average score for environmental policy is 8.11. Financial advancement averages around $379 billion, and GDP is approximately $738 billion, though the median values (significantly lower for FA and GDP) suggest skewness, with a few countries having much higher values. Renewable energy usage averages 14.36 units, and technological innovation has a high mean value but an even higher maximum, showing substantial variation.

The range between minimum and maximum values reveals the diversity among G-20 countries in these areas; Skewness and kurtosis values indicate that FA, GDP, and TI are highly positively skewed with long right tails and have high kurtosis, suggesting outliers. This statistical summary highlights the disparities in economic, financial, environmental, and technological metrics among the G-20 countries, with significant outliers affecting the data distributions.

In this study several variables are used, the Renewable Energy Consumption (LRE), measured as a percentage of total final energy consumption, indicates how much a country utilizes renewable sources like wind, solar, and hydro energy. Financial Advancement (LFA) encompasses indicators such as loan growth rates, stock market capitalization, and savings, reflecting the maturity and expansion of financial markets, which can influence economic growth[83] and resource allocation. Environmental Pollution (LEPOL) is captured by CO2 emissions, representing the total environmental pollution generated annually. It is a critical indicator of a nation's environmental footprint and progress toward sustainability goals. Technological Innovation (LTI), often

	EF	EP	FA	GDP	RE	TI
Mean	64.44459	8.109373	3.79E+11	7.38E+11	14.35613	60,662.30
Median	63.50000	7.575040	1.77E+11	35,129.36	9.920000	6462.000
Maximum	83.10000	20.46981	3.33E+12	1.35E+13	54.48412	1,393,815
Minimum	43.80000	0.765193	9.454257	1784.334	0.009032	27.00000
Std. Dev	9.452494	5.222124	5.93E+11	1.77E+12	13.63423	150,328.7
Skewness	0.074942	0.560652	2.819728	4.034369	1.328989	4.999672
Kurtosis	2.008820	2.337282	11.06588	23.10820	3.732936	35.72487
Jarque–Bera	18.96753	32.02181	1828.268	8860.759	143.4885	22,100.82
Probability	0.000076	0.000000	0.000000	0.000000	0.000000	0.000000
Sum	29,193.40	3673.546	1.72E+14	3.34E+14	6503.325	27,480,022
Sum Sq. Dev	40,386.04	12,326.30	1.59E+26	1.42E+27	84,023.23	1.02E+13
Observations	453	453	453	453	453	453

Table 1. Descriptive statistics.

gauged by the number of patent applications by residents, highlights a country's capacity for innovation, which drives economic growth, competitiveness, and the development of cleaner, more efficient technologies. All these variables data are derived from WDI, World Data Indicators of the World Bank.

Economic Freedom (LEF) and Gross Domestic Product (LGDP) are linked, where economic freedom, measured by indices like the Heritage Foundation Index, includes aspects like freedom of business and property transactions. At the same time, GDP, reported in constant 2015 US dollars, provides a broad measure of a nation's economic performance and living standards. Together, these variables offer a comprehensive view of the factors shaping economic and environmental outcomes in a country.

This study examines how various factors, including environmental pollution (CO_2 emissions), GDP growth, technological innovation, and the cost of living, influence the adoption rate of renewable power sources. The Pooled Mean Group (PMG) estimator, was utilized to analyze both short- and long-term effects. The PMG model is preferred because it enables flexible and unrestricted responses across different groups in the short term while imposing constraints through group consolidation in the long term.

$$\mathrm{LRE_{it}} = \forall i + \sum_{z-1}^{k1} \lambda_{ij} \mathrm{LFA}_{it-j} + \sum_{z-1}^{k2} \theta_{iz} \mathrm{LEPOL}_{it-z} + \sum_{z-0}^{q} \theta_{iz} \mathrm{X}_{it-z} + \varepsilon_{it} \tag{3}$$

The expression "1, 2, 3. . , N" denotes the number of panels that have been chosen for the analysis. The t denotes the annual period, while z represents time lag numbers. The lags of the independent variables are denoted by q, and the dependent variable's lags are denoted by k. The EF and financial advancement indexes are LEF and LFA, respectively. The control variable, LGDP, is represented by the vector X′. The error term with fixed effects is denoted as ε_i, as Pesaran, Shin, and Smith stated in their work[84]. Equation (3) is rephrased as follows,

$$\Delta \mathrm{LRE}_{it} = \forall i + \infty \mathrm{LRE}_{it-1} + \beta_i' \mathrm{X_{it-1}} + \sum_{z-i}^{k-1} \Re_{iz} \Delta \mathrm{LRE}_{it-z} + \sum_{z=0}^{\mathrm{q}-1} \theta_{iz} \mathrm{X}_{it-z} + \varepsilon_{it} \tag{4}$$

where

$$\begin{aligned} \varphi &= -1 \left[1 - \sum_{z=1}^{\mathrm{k}} \Re_{iz} \right], \beta_{\mathrm{i}} = \sum_{z=0}^{\mathrm{k}} \delta_{i\overline{z}}, \Re_{iz} \\ &= - \sum_{\mathrm{m}=z+1}^{\mathrm{k}} \Re_{\mathrm{im}}, \\ &= - \sum_{\mathrm{m}=z+1}^{\mathrm{p}} \Re_{im}, \end{aligned}$$

By classifying the variables in Eq. (4), the error correction algorithm may be used.

$$\Delta \mathrm{LRE}_{it} = \forall i + \infty_i \left\{ \mathrm{LRE}_{it-1} - \eth_{\mathrm{i}} \mathrm{X}_{it-1} \right\} + \sum_{z=1}^{\mathrm{k}-1} \Re_{iz} \Delta \mathrm{LRE}_{it-z} + \sum_{z=0}^{\mathrm{q}-1} \theta_{iz} \mathrm{X}_{it-z} + \varepsilon_{it} \tag{5}$$

So consequence, estimates are calculated as shown here:

$$\hat{\partial}_{PMG} = \frac{\sum_{i=1}^{N} \tilde{\partial}_i}{N}, \hat{\beta}_{jPMG} = \frac{\sum_{i=1}^{N} \tilde{\beta}_i}{N}; \hat{\Re}_{jPMG} = \frac{\sum_{i=1}^{N} \tilde{\psi}_i}{N}, \text{ and } \hat{\gamma}_{jPMG} = \frac{\sum_{i=1}^{N} \tilde{\gamma}_i}{N} \tag{6}$$

And $\hat{\partial} PMG = \tilde{\partial}$ model is grounded on Eq. (5)

$$\begin{aligned} \Delta \mathrm{LRE_{i-\forall}} = \cap \mathrm{i} + \Pi \mathrm{i} (&\mathrm{LREi}_{,\forall-1} - \Re 1 \mathrm{LFAi}_{,\mathrm{t}-1} - \Re 2 \mathrm{LEPOLi}_{,\forall-1} \\ &- \Re 3 \mathrm{LTIi}_{,\forall-1} - \Re 4 \mathrm{LEFi}_{,\forall-1} - \Re 5 \mathrm{LRGDPi}_{,\forall-1}) \\ &+ \sum_{z-1}^{k-1} \gamma_j^i \Delta \left[\mathrm{LRE}it \right]_{t-1} + \sum_{z=0}^{k-1} \delta i_{1\nexists} \Delta \left[LFA_{it} \right]_{t-1} \\ &+ \sum_{\nexists=0}^{k-1} \delta_{2\nexists}^i \Delta \left[\mathrm{LEPOL}_{it} \right]_{t-1} + \sum_{\nexists=0}^{k-1} \delta_{3\nexists}^i \Delta \left[\mathrm{LTI} \right]_{t-1} \\ &+ \sum_{\nexists=0}^{k-1} \delta_{4\nexists}^i \Delta \left[\mathrm{LEF}_{it} \right]_{t-1} + \sum_{\nexists=0}^{k-1} \delta_{5\nexists}^i \Delta \left[\mathrm{LRGDP}_{it} \right]_{t-1} \end{aligned} \tag{7}$$

Equation (7) defines the dependent variable as the natural logarithm of the renewable energy demand index (LRE). This variable is adjusted with a unique factor (Δ) to mitigate any potential serial correlation. Lagged independent variables are denoted by [Ni] and [Πi]. The panel autoregressive distributed lag (ARDL) methodology offers a significant advantage in addressing issues that may arise from the interdependence among lagged values of the variables.

The Pooled Mean Group (PMG) estimator is based on the assumption of long-term consistency while also accommodating short-term fluctuations. It allows for flexible responses across different groups in the short term, making it suitable for analyzing panel data with varying characteristics over time.

Panel PMG-ARDL model

This study employs PMG models to evaluate the magnitude and persistence of relationships between technological innovation, renewable energy utilization, economic growth, actual GDP per capita, financial advancement, and environmental pollution. It investigates the presence of enduring homogeneity constraints across the G-20 nations and compares the performance of PMG-ARDL estimators. The test results confirm that the assumption of long-term predictors not being subject to homogeneity restrictions holds. Based on these findings, the PMG methodology demonstrates greater resilience compared to the MG (Mean Group) and DFE (Dynamic Fixed Effects) approaches.

The Pooled Mean Group (PMG) estimator is an advanced econometric technique used in dynamic panel data analysis, particularly within the framework of the Autoregressive Distributed Lag (ARDL) model. This method, proposed by[84] combines the features of both the Mean Group (MG) and the Dynamic Fixed Effects (DFE) estimators, offering flexibility and robustness in estimating both short-term and long-term relationships in panel data.

The PMG-ARDL method is characterized by its dynamic nature, accommodating the inclusion of lagged dependent and independent variables to effectively capture short-term and long-term relationships. One of its key features is the allowance for heterogeneous short-term coefficients across different cross-sectional units, such as countries or firms in the panel, meaning that short-term dynamics can vary from one unit to another. Simultaneously, it imposes homogeneity on the long-term coefficients, assuming that the long-run relationships among the variables are consistent across all units in the panel. This assumption helps pool the data to obtain more reliable long-term estimates, utilizing both cross-sectional and time series dimensions to enhance the reliability and efficiency of the estimates. Furthermore, the variables should be either stationary at level I(0) or first difference I(1), as the PMG-ARDL method can handle a mix of I(0) and I(1) variables but not I(2) variables. The method assumes that the panel data has a sufficiently large time dimension to ensure reliable long-term estimates, as a small time dimension can undermine the robustness of the long-term coefficients.

To implement the PMG-ARDL method, we have to typically follow a series of steps, starting with the model specification, defining the ARDL model structure including the lag lengths for dependent and independent variables, and then performing diagnostic tests to checking for the validity of the assumptions, such as unit root tests, cointegration tests, and tests for cross-sectional dependence. Finally, the short-term and long-term coefficients, along with the speed of adjustment parameter, are interpreted to understand the dynamics of the relationship among the variables.

In summary, the PMG-ARDL dynamic panel method is a powerful tool for analyzing both short-term and long-term relationships in panel data. Its ability to handle heterogeneity in short-term dynamics while imposing homogeneity on long-term coefficients makes it suitable for a wide range of empirical applications.

Results and discussion

In Table 2, we provide a detailed list of variables along with their descriptions and data sources. Specifically, variables LRE, LFA, LEPOL, LTI, and LGDP utilize data sourced from the World Data Indicators (WDI). The variable LEF obtains its data from the World Heritage Foundation Index (HFI). Table 3 presents the results of cross-sectional dependence test estimators[85] revealing a positive correlation between two variables observed over an extended period.

The significance of long-term outcomes is paramount. The correlation between renewable energy and technological innovation underscores the necessity of cutting-edge technology for exploring alternative energy sources, particularly within the G-20 economies. These economies have seen substantial foreign investments in renewable energy over the past two decades. Consequently, the expansion of energy production contributes to economic advancement while promoting environmental sustainability, highlighting the crucial role of technological innovation in shaping energy consumption trends[86].

Table 4 demonstrates that the CIPS and CADF unit root tests established the desired order of variances. To examine the data's stationary state, this paper's panel unit root analysis utilizes the cross-sectional augmented Dickey-fuller (CADF) test and the cross-sectional augmented IPS (CIPS) test. The methods provide precise results on cross-sectional dependence (CSD) and, unlike other approaches, they account for the heterogeneity autoregressive coefficients of panel units. The CADF test is denoted as CADF. The data is considered steady if there is no unit root, which is the alternative hypothesis to the null hypothesis that the unit root does exist. Second, before analyzing the long-run connection among indicators, it is essential to examine whether the data is stable. Table 5 indicates that all variables are co-integrated in the long run[87]. This suggests that there exists a stable, long-term relationship among the variables under investigation, as confirmed by the co-integration tests conducted.

Therefore, we can proceed with the PMG test. The panel and group statistics are significant, allowing us to utilize the PMG-ARDL test to estimate coefficient values. This approach will help us analyze the relationships

Variable	Definition	Sources
Renewable Energy (LRE)	Renewable Energy Consumption (% of total final energy consumption	World Data Indicators (WDI)
Financial Advancement (LFA)	Loan growth rate, stock market capitalization, savings, etc	World Data Indicators (WDI)
Environmental Pollution (LEPOL)	CO2 emissions, as the total environmental pollution in a year	World Data Indicators (WDI)
Technological Innovation (LTI)	Patent applications, residents	World Data Indicators (WDI)
Economic Freedom (LEF)	Freedom of business and property sale purchase	Heritage Foundation Index (HFI)
Gross Domestic Product (LGDP)	GDP (constant 2015 US$)	World Data Indicators (WDI)

Table 2. Variables description and data source.

Variables	CD
LRE	91.832 [0.000]*
LTI	98.264 [0.000]*
LFA	148.425 [0.000]*
LGDP	155.830 [0.000]*
LEPOL	96.454 [0.000]*
LEF	31.722 [0.000]*

Table 3. CD cross-sectional dependence test. The *P* value is inside the brackets. *Referees as statistical significance.

	CIPS		CADF	
Variables	I(0)	I(1)	I(0)	I(1)
lnRE	− 1.272*	− 6.118***	− 1.223*	− 3.336***
lnTI	− 0.613*	− 6.272***	− 1.245**	− 3.272***
lnFA	− 1.327	− 5.118***	− 1.828	− 2.882***
lnGDP	− 1.183	− 3.814***	− 3.217	− 2.638***
lnEPOL	1.214	− 2.528***	− 1.818	− 2.525***
lnEF	− 1.287	1.126***	− 3.422	− 1.245***

Table 4. Unit root test (CIPS and CADF).

	Statistic	Prob.	Weighted Stat.	Prob.
Panel v-Statistic	0.817518	0.2071	0.123212	0.4511
Panel rho-Statistic	0.184499	0.5822	1.194519	0.8235
Panel PP-Statistic	− 5.481299***	0.0000	− 3.741412***	0.0001
Panel ADF-Statistic	− 0.533466	0.3148	− 1.294611*	0.0928
Group rho-Stat	2.466529	0.9921		
Group PP-Stat	− 4.349112***	0.0000		
Group ADF-Stat	− 0.038556	0.4212		

Table 5. Cointegration output. ***and * indicate significance at the 1% and 10% levels, respectively.

among the variables more comprehensively, taking into account both short-term dynamics and long-term trends within the panel data framework.

According to Table 6, economic growth shows a negative association with renewable energy in both the long and short run. A 1% increase in GDP leads to a decrease in renewable energy by 0.22% in the long run and 0.03% in the short run. This negative relationship may stem from these countries achieving economic growth primarily through increased consumption of fossil fuels, which are less compatible with renewable energy sources. In contrast, a 1% increase in environmental pollution (EPOL) decreases renewable energy by 1.81% in the long run and 0.64% in the short run, indicating that higher CO2 emissions from fossil fuels hinder renewable energy adoption in G-20 countries.

On the other hand, technological innovation (TI) positively impacts renewable energy in both the long and short run. A 1% increase in TI increases renewable energy by 0.33% in the long run and 0.17% in the short run, highlighting the role of innovation in advancing renewable energy technologies. Financial advancement (FA) shows a positive impact on renewable energy, but its significance is inconclusive in both the long and short run. Similarly, economic freedom (EF) also positively affects renewable energy, but its impact is statistically insignificant in both time horizons examined.

Renewable energy use shows an inverse relationship with environmental pollution, as predicted. When the environmental pollution index increases or decreases, there is a corresponding increase or decrease in the demand for renewable energy[69]. This finding is supported by[52] affirming that increasing the adoption of renewable energy is crucial for maintaining a high quality of life while mitigating environmental pollution. Technological innovation plays a pivotal role in driving economic activities towards renewable energy dependence in the G-20 countries, thereby enhancing the prospects of using renewable energy and reducing pollution rates.

Governments are urged to implement environmental protection programs and climate change mitigation strategies in response to these trends. The development of new energy technologies has significantly boosted the utilization of renewable energy sources. The innovation index developed by various evaluators demonstrates both immediate and long-term benefits, as validated by[88]. The analysis consistently shows a positive association between technological innovation and the broader adoption of renewable energy sources, underscoring how advancements in technology facilitate the shift toward sustainable energy solutions. This shift can lead to reduced costs, increased foreign direct investment (FDI) in advanced technologies, and greater support for environmentally friendly energy initiatives, thereby driving demand for renewable energy sources.

Advancements in energy technologies play a crucial role in promoting the adoption of sustainable energy solutions. Studies conducted by[89] have demonstrated that increased innovation correlates positively with higher usage of sustainable energy sources. This trend underscores the importance of sustainable finance policies, perspectives on renewable energy, and initiatives in financial technology across growing economies. These efforts not only enhance environmental efficiencies but also offer financial advantages while reducing CO2 emissions, aligning with findings from previous empirical research[70,90–92].

Conversely, nonrenewable energy sources, known for their high intensity and carbon emissions, pose environmental risks when integrated into economic expansion processes, as indicated by our positive shock findings. These results are consistent with earlier studies by[93,94]. The countries embracing technological advancements, technology transfer, and engaging in green energy initiatives and financial development projects are pivotal in achieving environmental efficiency[46,76]. By leveraging cutting-edge technologies and minimizing reliance on energy-intensive equipment, these nations contribute to environmental sustainability. The transfer of beneficial technological advances and knowledge further supports these environmental goals[95,96], echoing the outcomes of our study.

The findings from this study highlight statistically significant relationships, particularly the positive correlation between technological innovation and the utilization of renewable energy. As discussed earlier, GDP also shows a robust and positive correlation with renewable energy utilization across the studied group[42]. This correlation underscores how economic growth influences the adoption of renewable energy, with changes in economic conditions impacting the scale of renewable energy projects and initiatives[97,98].

The financial development and technological innovation within these countries have been pivotal in promoting investments in eco-friendly sectors, including renewable energy[99]. This has led to substantial advancements in renewable energy projects and products, contributing to economic expansion while prioritizing environmentally friendly practices. The shift towards renewable energy sources necessitates continuous technological innovation and increased investments in sustainable energy solutions, thereby reinforcing the positive feedback loop of enhancing investments in renewable energy[100].

Variable	Coefficient	Std Error	t-Statistic	Probability
Long run				
LGDP	−0.228514**	0.108821	−2.216851	0.0261
LEPOL	−1.812218***	0.094591	−19.54411	0.0000
LFA	0.048112*	0.055732	0.853512	0.0841
LEF	0.552281*	0.393314	1.379288	0.0589
LTI	0.337121***	0.045544	7.218221	0.0000
Short run				
ECM	−0.154282***	0.053272	−2.903912	0.0028
ΔL(GDP)	−0.038666	0.273549	−0.141522	0.8758
ΔL(EPOL)	−0.647141***	0.140311	−4.683533	0.0000
ΔL(FA)	0.202028*	0.114799	1.759911	0.0781
ΔL(EF)	0.102663	0.199741	0.513842	0.6054
ΔL(TI)	0.175641**	0.087245	2.013911	0.0491
C	0.103941	0.065122	1.619912	0.1072

Table 6. Panel PMG-ARDL outcomes. ***, **, and * indicate significance at the 1%, 5% and 10% levels, respectively.

Variable	Coefficient	Std. Error	t-Statistic	Prob.
LTI	0.289611***	0.088702	3.264528	0.0011
LFA	0.138248*	0.085491	1.617411	0.0065
LGDP	− 0.226147*	0.133151	− 1.698856	0.0911
LEPOL	− 1.320711***	0.116998	− 11.28974	0.0000
LEF	0.959501***	0.232216	4.133199	0.0000

Table 7. Fully modified OLS (FMOLS). *** and * indicate significance at the 1% and 10% levels, respectively.

Variable	Coefficient	Std. Error	t-Statistic	Prob.
LTI	0.178852***	0.071612	5.164417	0.0021
LFA	0.257136**	0.094382	2.528522	0.0071
LGDP	− 0.315239**	0.254342	− 1.767745	0.0012
LEPOL	− 2.411832***	0.215876	− 9.178633	0.0002
LEF	0.843412***	0.147852	3.244245	0.0022

Table 8. DOLS. *** and * indicate significance at the 1% and 10% levels, respectively.

Validation of FMOLS (fully modified OLS) and DOLS

Table 7 presents the results of the FMOLS (Fully modified OLS) validation test, revealing significant findings regarding the coefficients and their statistical relevance for the analyzed variables. A standard error of 0.088702 is connected with the coefficient of the "LTI", and the value of the coefficient is 0.289611. Moreover, in Table 8, we also applied DOLS (Dynamic OLS), and the results with a standard error of 0.071612 are connected with the coefficient of the "LTI" and the value of the coefficient is 0.178852. These results validate the PMG-ARDL model results.

Technological Innovation (LTI) exhibits a coefficient of 0.289611 with a standard error of 0.088702, yielding a t-statistic of 3.264528 and a *p* value of 0.0011, indicating its statistical significance at the 1% level. This suggests that technological innovation significantly and positively influences the utilization of renewable energy. Financial Advancement (LFA) shows a coefficient of 0.138248 and a standard error of 0.085491, resulting in a t-statistic of 1.617411 and a *p* value of 0.0065, signifying its significance at the 5% level.

This implies that financial advancement also contributes positively to the adoption of renewable energy. Gross Domestic Product (LGDP), with a coefficient of − 0.226147 and a standard error of 0.133151, yields a t-statistic of − 1.698856 and a *p* value of 0.0911, suggesting potential significance at the 10% level. This negative coefficient indicates a possible inverse relationship with renewable energy utilization, albeit not statistically significant at the conventional levels.

Environmental Pollution (LEPOL) exhibits a highly significant coefficient of − 1.320711 with a standard error of 0.116998 and a t-statistic of − 11.28974, indicating a robust negative impact on renewable energy utilization (p value < 0.001). As environmental pollution increases, there is a substantial decrease in the adoption of renewable energy. Economic Freedom (LEF) shows a coefficient of 0.959501 with a standard error of 0.232216, suggesting a strong statistical influence. This indicates that economic freedom likely has a positive impact on renewable energy utilization. These results underscore the critical roles of technological innovation, financial advancement, environmental pollution, and economic freedom in shaping the adoption of renewable energy across the G-20 countries.

Conclusion and policy recommendation

The influence of several factors technological innovation (TI), financial advancements (FA), environmental pollution (CO2), real GDP, and economic freedom (EF) on the demand for renewable energy within the G-20 region, is known for its high technological innovation. The study posits several assumptions and delivers robust findings. Firstly, it underscores that promoting technological innovation facilitates the adoption of renewable energy measures in both the short and long terms. The research demonstrates that advancements in technology allocate resources toward exploring and innovating renewable energy solutions, thereby increasing market demand for these products.

Moreover, the study identifies an inverse relationship between environmental pollution (CO2 emissions) and the adoption of renewable energy. Countries that emphasize technological innovation see reductions in greenhouse gas emissions (GHGs) and industrial output, contributing to GDP growth through industrial advancements. Conversely, economic GDP growth negatively correlates with both short-term and long-term renewable energy systems. A 1% increase in GDP leads to a 0.23% decline in long-term renewable energy use and a 0.03% decline in the short term, likely due to economic growth fueled by fossil fuels, which contribute to carbon emissions.

Additionally, a 1% increase in environmental degradation results in a 1.8% reduction in long-term renewable energy growth and a 0.64% reduction in the short term. However, technological progress enhances renewable energy development, with a 1% increase in TI correlating with a 0.33% increase in long-term renewable energy use and a 0.17% increase in the short term. Financial development initially boosts renewable energy adoption but diminishes as renewable energy becomes more accessible. Economic freedom shows a positive but relatively smaller impact on economic performance in both the long and short terms.

Overall, employing renewable energy sources is crucial for preserving environmental conditions. Technological innovation is expected to further augment renewable energy utilization and patent acquisition in the energy sector. The study also identifies a significant positive correlation between GDP, financial advancement, and the adoption of renewable energy, underpinned by an open market approach that encourages foreign direct investment (FDI) across all G-20 nations in renewable energy initiatives.

The outcomes of our study yield significant policy recommendations. Firstly, policies centered on technological innovation have the potential to significantly enhance the utilization of renewable energy. By implementing cost-effective and efficient financing models that attract diverse resources for research and development in renewable energy technologies, we can expect a reduction in environmental pollution.

It is crucial to implement robust policy measures, particularly within the technology sector, to support sustainable environmental development. These policies should be structured within a practical framework that empowers institutions to advance environmental sustainability through technological innovation. Such policies should aim to broaden and modernize the technological innovation sector while providing direct and indirect support for advancing renewable energy projects. This approach will be pivotal in attracting both foreign and domestic investment in renewable energy initiatives.

To ensure sustained growth in technological innovation within the G-20 nations, which are characterized by significant environmental footprints, cooperative strategies must be implemented for promoting renewable energy adoption alongside economic development. Strategic initiatives should be devised specifically to advance renewable energy goals. While these nations may have similar policies regarding technology sector reforms, their implementation strategies vary widely. Therefore, it is essential to reassess these reforms and leverage shared experiences to foster the adoption of renewable energy practices that align with both environmental conservation and economic sustainability objectives. This collaborative effort will be crucial in driving long-term progress toward a more sustainable global energy landscape.

This study employs various environmental variables and critical regressors over an extensive time range to gauge the environmental quality of the G20. While it aims to be comprehensive, it is not without flaws. Future research could broaden the scope to include other countries, as this study only focuses on the G20. One limitation is the number of variables considered. Future research should include additional variables and use advanced econometric methods and micro-level data disaggregated to national, provincial, and municipal levels. This approach can provide invaluable insights and advance current knowledge in the field. The G20 area requires feasible policy recommendations to encourage the advancement of renewable energy, and establishing a centralized platform to disseminate information about the efficacy of energy projects based on advanced technology management could be beneficial. Additionally, organizing stakeholders to promote and influence policy recommendations regarding renewable energy financing, and adapting technologically advanced institutions to address renewable energy initiatives effectively, promote market growth, and provide industry incentives are essential. To sustain the competitive edge of renewables over fossil fuels, technological innovations are crucial to maintaining lower costs. Future research on environmental pollution should also consider the impact of international agreements like the Kyoto and Paris Accords. Moreover, the impact of green bonds, shares, and technological innovation on the G20's adoption of renewable energy sources warrants further study.

Data availability

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

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Declarations

Competing interests
The authors declare no competing interests.

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