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Research Article

How do economic freedom, trade freedom, and digitization influence renewable energy consumption in G20 nations: What is the role of innovation?

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Abstract. This study investigates the relationship between economic freedom, trade freedom, digitalization, and innovation on renewable energy consumption among G20 nations over the period 2000–2023. Utilizing a robust empirical framework—including Dynamic Common Correlated Effects (DCCE), Instrumental Variable-adjusted DCCE (DCCE-IV), and Dynamic Seemingly Unrelated Regression (DSUR)—the analysis reveals nuanced insights into how these economic and technological dimensions shape the transition toward sustainable energy systems. Results demonstrate that a 10% rise in economic freedom correlates with a 1.112%–1.688% increase in renewable energy consumption, while trade freedom yields a positive impact ranging from 0.904% to 1.182%. Technological innovation contributes between 0.915% and 1.571%, and environmental innovation exerts an even stronger effect, ranging from 1.273% to 1.616%. Interestingly, despite the energy intensity associated with digital technologies, digitalization also supports renewable energy adoption, showing a positive influence between 1.013% and 1.526%. These findings underscore innovation's pivotal role in mediating the effects of economic policy and digital transformation on renewable energy usage. The study advocates for integrated policy approaches that simultaneously promote market liberalization, digital infrastructure, and innovation investment. This would accelerate the transition to renewable energy and help G20 nations meet Sustainable Development Goal 7 (affordable, reliable, sustainable, and modern energy for all). The results emphasize the need for synergistic strategies that connect economic openness, technological advancement, and environmental priorities, offering a roadmap for policymakers seeking to enhance clean energy deployment in large, high-impact economies.

Keywords: Renewable energy consumption; Economic freedom; Trade freedom; Digitalization; Technological innovation; SDG-7

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1. Introduction

The G20s are the largest economies in the world, making them crucial for global energy policies and the implementation of sustainable development goals (SDGs). The G20 group, which makes up around 80% of gross global domestic production (GDP) and a large proportion of greenhouse gas emissions, has an important role in the race to net zero and the urgency of committing to rising renewable energy investment. Besides being an important lever in reducing carbon emissions, renewable energy contributes to several SDGs, particularly Goal 7: Ensure access to affordable, reliable, sustainable and modern energy. The shift-hunt to renewables, including solar, wind, and biomass, may assist the G20 members in attaining their weather plans for low carbon and local weather-liability development. However, they do not change the ball of funds and associated resistance to the political financial system. Studies show that using renewable energy technologies can greatly improve environmental performance, including reducing dependency on fossil fuels and overall carbon footprints Dinca, Bărbuță, Negri, Dincă, and Model (2022); Pancasari (2023). Specifically, Mesagan and Nwachukwu (2018) noted that G20 economies can attain positive emission reductions with renewable energy consumption, which presents an opportunity for a viable solution to environmental degradation. Additionally, incorporating renewable energy into national energy policies contributes to energy security while fostering economic development through job creation and technological advancement (Eufrasio-Espinosa, 2023), (Goldthau, 2017). Furthermore, the G20 plays a crucial role in promoting global collaboration and knowledge sharing in developing renewable energies, which are uniquely equipped to govern the transition towards energy low in carbon through partnerships that promote innovation and sustainable practices. In addition, working together is critical to better serve the energy needs of both developed and emerging economies in the G20 landscape, enabling all member states to play a role in and benefit from the transition to a sustainable energy future. Finally, the G20's focus on renewable energy is not just an eco-problem but a strategic opportunity to meet wider sustainability goals. To summarize, investment in clean energy and technological innovations could help G20 countries spearhead the transition to sustainable energy, thus helping build a more eco-friendly and socially just world.

Overcoming these barriers and engaging with renewables as a product — both of the natural world and human ingenuity — will be crucial for G20 countries as they transition to integrating them as part of the energy mix. These insights will

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play a pivotal role in establishing frameworks that can help improve the uptake of renewable energy technologies. These are critical to addressing objectives such as Sustainable Development Goals (SDGs), especially Goal 7, which seeks to provide access to affordable, reliable, sustainable and modern energy.

Technology is the most important labor driving the adoption of renewable energy in G20 countries; that is, the development of photovoltaics and wind turbines has brought about greater efficiency and lower costs for these renewable technologies. According to Pancasari (2023), investment in R&D could open up the window for innovation and easy access to renewable sources at affordable cost. In addition, Bildirici (2023) observes that the application of Industry 4.0 technologies can facilitate more timely renewable energy generation, further strengthening the relationship between both fields, thus stimulating sustainable economic growth. Furthermore, Subsidies, tax incentives, and renewable energy mandates can greatly encourage investment in renewable technologies. A categorical shift towards net-zero emissions and climate change mitigation exerts pressure on governments and industry to reduce national and corporate carbon emission targets, potentially leading to an increase in renewable electricity consumption and a cleaner energy mix. Moreover, G20 countries can use their international partnerships to share advanced practices and technologies, thus facilitating a coordinated energy transition (Fathun & Darmastuti, 2023). Ongoing public awareness and education about renewable energy benefits can help bolster support for renewable energy measures. The study of Dincă, Bărbuță, Negri, Dincă, and Model (2022) advocated that higher education levels are correlated with better environmental performance in society, indicating that informed citizens tend to support and use renewable energy solutions.

On the dark side, the high upfront costs of these technologies can also act as a barrier to investment despite promised long-term savings and environmental protection (McCarthy, 2008). Additionally, Financial restraints and the need for cost-effectiveness could make transitioning to renewables harder, especially in countries with fewer financial means (Žarković *et al.*, 2022). Furthermore, the volatility of fossil-fuel markets can amplify uncertainty about returns on investment concerning renewable projects. Furthermore, urbanization is progressing quickly in G20 countries, increasing energy intensity and making the transition to renewable energy more difficult. The counter-argument, according to (Sari, 2023), is that urban population growth can increase energy demand because it is unlikely that renewable energy will meet these demands. Thus, cities will continue to rely on fossil fuels. Causal a) argues for the initial shift into using non-renewable energy at higher levels of urbanization (and hence energy intensity), contributing to the urban energy-demand behavior seen here and how, in the case of such rapidly growing megacities, transitions can remain depressed for some time. The quality and governance of institutions strongly determine the effectiveness of renewable energy policies. Weak governorship structures can lead to inefficiencies and corruption, hampering efforts to review renewable energy. Thus, as per Saeed, strong institutional frameworks play a crucial role in promoting renewable energy use while decreasing dependency on nonrenewable sources (Saeed, 2023).

Given the worldwide need to move toward sustainable energy sources, research on the effects of economic freedom, trade freedom, and digitalization on renewable energy use in G20 countries is urgent and important. This study is motivated by the interdependence between environmental sustainability, technical developments, and economic policy. Knowing how these elements interact might help legislators strive to encourage the acceptance of renewable energy and thus support economic development to have insightful analysis. Consuming renewable energy depends much on economic freedom. With higher degrees of economic freedom, nations have been shown to show more effective investments in renewable energy technology. Studies show that economic freedom encourages efficiency in investments in renewable energy sources, implying that less government intervention would help to produce better market results in the renewable sector (Amoah, Kwablah, Korle, & Offei, 2020; Martín-Ortega, 2024). Moreover, (Inglesi-Lotz, 2016) verifying a long-run link between economic development and renewable energy use clearly shows the link between economic circumstances and the use of renewable energy, which emphasizes the need to establish surroundings fit for economic freedom to boost investments in renewable energy sources. The capacity for international commerce lets nations diversify their energy sources and acquire cutting-edge renewable technology. Research concentrating on African countries revealed that international commerce increases the use of renewable energy, thereby underlining the possibility of trade to help shift to greener energy systems (Aïssa, Jebli, & Youssef, 2014). Trade openness may also hasten the transition of economies from agricultural to industrial and service sectors, generally less polluting. This change is vital for G20 countries, whose environmental standards and energy needs must be met via economic diversification. As a transforming power, digitization affects the usage of renewable energy even more. Including digital technology in energy systems improves performance and helps to manage resources derived from renewable sources. Digitization, for instance, may maximize energy consumption patterns and help anticipate the output of renewable energy, thereby enabling more efficient use of the resources (Jia, Fan, & Miao, 2023). Furthermore, one cannot emphasize the importance of innovation in technology related to renewable energy. Studies on public policies and investment in research and development driving innovation have shown that the adoption of renewable energy technology is very influenced; thus, G20 countries must innovate if they are to increase their capacity for renewable energy and lessen dependency on fossil fuels. Leading in renewable energy consumption gives a special opportunity for G20 countries at the junction of economic freedom, trade freedom, and digitalization. These countries may improve their energy security and help worldwide efforts in climate change by creating an atmosphere that supports economic and trade liberalization alongside embracing digital advances. Renewable energy can propel economic development by generating employment, lowering greenhouse gas emissions, and improving energy security (Eze, 2023). Therefore, this research intends to investigate these processes holistically, offering a framework for comprehending how innovation might act as a stimulant for renewable energy consumption in the framework of trade policy and economic development. Ultimately, the urgent necessity of G20 countries to shift to renewable energy sources, among environmental and economic obstacles drives this research. This study aims to show the ways in which innovation may improve renewable energy consumption by analyzing the effects of economic freedom, trade freedom, and digitalization, thus promoting sustainable economic development and environmental protection.

This study is important as it combines innovation, the elements of economic freedom, trade freedom, and digitalization to clarify their combined influence on the usage of renewable energy. First, the literature has provided a basic knowledge of how using renewable energy depends on economic freedom. Efficiency in renewable energy investments has been shown by economic freedom, which is defined as little government involvement and an atmosphere fit for market operations. (Amoah *et al.,* 2020) point out that economic independence may result in improved efficiency in investments in renewable energy sources, implying that less government intervention might create a more favorable investing environment for renewable technology, underline the need of environmental innovations in increasing the consumption of renewable energy employing R&D expenditures (Usman, Rădulescu, Balsalobre-Lorente, & Rehman, 2022). Therefore, the present research expands on these ideas by examining how economic freedom within G20 countries could foster creativity and raise renewable energy usage. Second, trade freedom is another important consideration in the renewable energy framework. Studies show that while trade openness facilitates the flow of technologies and skills required to accept renewable energy sources, it favourably correlates with renewable energy consumption. Trade openness, according to (Yahya & Rafiq, 2019), helps green energy resources to be transferred, which is essential for raising the use of renewable energy in different governments. Studies by (Joubert, Belhadj, Temam, & Héliot, 2012) further support this by showing that nations with higher trade openness often show more notable technological diffusion, increasing the demand for renewable energy. The suggested research intends to broaden this conversation by examining the G20 setting, where trade dynamics are multifarious and complicated. Third, one area of growing interest not often discussed in current literature is the influence of digitalization on encouraging the use of renewable energy sources. Information and communication technology (ICT) integration into energy systems may improve efficiency and help to control renewable energy sources. According to Fan's studies, ICT commerce helps to lower the use of renewable energy, implying that financial globalization and technical development are essential (Fan, 2024). By including digitalization in the research, the present work aims to close a significant knowledge vacuum about how digital advancements may boost the use of renewable energy in G20 countries. Furthermore, among these elements, innovation is very vital. The advancement of renewable energy technology depends on an environment fit for innovation created by the interaction of economic freedom, trade freedom, and digitalization. Emphasizing the importance of a comprehensive strategy, including many aspects of policy and market dynamics (Khaled, 2024), stresses that governance quality and innovation are fundamental in influencing renewable energy use. The major issue of the present work—innovation—allows a thorough investigation of how these elements affect renewable energy use. Finally, this research enhanced the knowledge by examining the interaction of economic freedom, trade freedom, digitalization, and innovation in the framework of renewable energy consumption in G20 countries. The study not only closes current gaps in the literature but also offers insightful analysis for legislators seeking to increase the acceptance of renewable energy utilizing deliberate economic and technical frameworks.

2. Theoretical and empirical review

2.1. Theoretical review

Trade freedom, which enables the exchange of goods and services across international borders, also contributes to economic freedom by improving market access opportunities for renewable energy products and technologies. These aspects, collectively, lay the groundwork, compelling the embrace of modern practices and technologies that a shift to renewable energy requires. Evidence supporting the correlation between economic freedom and the use of renewable energy can be found in the aggregate data that indicates that countries with more economic freedom tend to invest more in renewable energy. Alam and Murad (2020) demonstrated that economic growth, trade openness, and technological progress played a role in renewable energy (RE) use in OECD countries. This means that greater economic freedom drives investment in renewable energy and improves the efficiency of energy systems. Similarly, the digital economy has begun to enable these promising technologies to be leveraged to optimize the utilization of renewable energy both in production and consumption. As a major transformational force, digitalization has emerged as an important enabler of renewable energy efficiency and innovation. Digital technology adoption in the energy sector allows better data management, predictive analytics, and real-time monitoring of energy systems. For instance, Y. Zhang, Wang, Tian, and Yang (2022) emphasized the relationship between digital transformation and the use of renewable energy; according to him, the development of digital technologies optimizes wind and solar facilities. Similarly, (Khaled, 2024) discussed how digital platforms could democratize energy generation and promote innovation in renewable energy initiatives. Exploring the need for digitalization to enable a transition over a more sustainable energy landscape. Additionally, as trade freedom demonstrates, government policies can incentivize the development of renewable energy sources. Lowering tariffs and trade barriers may make it easier for countries to import advanced renewable energy technologies, which would help promote adoption at home(Nydrioti, 2024). The research by (Y. Chen, Zhang, & Li, 2023) shows that further investments into renewable energy and digitalization can advance the transformation of the energy system. This change is essential in realizing global decarbonization goals and allows countries to benefit from the advantages of renewable energy technologies while improving their economic competitiveness. Innovation acts as the vital bridge between economic freedom, trade freedom, and digitalization on one hand and renewable energy adoption on the other. Innovation flourishes when there is a conducive and enabling regulatory framework and open trade. Such up-to-date knowledge is especially applicable in the field of renewable energy where new technologies must consistently perform better or more cost-effectively than previous technologies. For instance, (Su, Jin, & Yu-nan, 2022) found that the integration of digital technology has the potential to substantially minimize renewable energy production costs, hence boosting its portion of the total energy portfolio. The findings of (Haller, Ştefănică, Butnaru, & Cristina, 2023) further strengthen this relationship between innovation and renewable energy by advocating that eco-innovation and digitalization are crucial to lowering greenhouse gas emissions in the EU. (Pakulska & Poniatowska-Jaksch, 2022) investigated that digital transformation can create new players within renewable energy, thus enabling new NGO competitors and increasing the pace of creativity. Such a competitive ecosystem is vital for reducing the costs and making these renewable energy solutions available to all. Moreover, there remains a feedback loop between digitalization and renewable energy, where advances in the renewable energy sector can complement further improvements in digital technologies. The role of this concept seems even more relevant to smart grids with its characteristic integration of renewable energy sources that accommodate them through such sophisticated digital demand management and systems to provide enough energy. The circular economy is a breakthrough concept that inherits the critical principles of society; the balance of economic and ecological stability is the fundamental principle created through the development of multiple research disciplines in terms of energy. (Ali & Kırıkkaleli, 2021) explained the crucial role of several digital tools like IoT and AI in improving the performance of energy systems. By harnessing these technologies, the economy enhances the efficiency in harnessing renewable energy and leads the way in such energy management integration. Moreover, the question of the environmental benefits of this dynamic of economic freedom, trade freedom, digitization and renewable energy innovation cannot be ignored. Is switching to renewable energy is essential to achieving sustainability goals and mitigating climate change? The result of (Dzwigol, 2024) was related to energy consumption patterns, which greatly influence the delivery process and may lower energy intensity in organizations, particularly with the realization of sustainable initiatives. The study findings align with the broader aims of the UN Sustainable Development Goals (SDGs), which call for everyone to have access to affordable and clean energy. (Yu, Li, & Ma, 2022) revealed that countries that favour freedom over regulation are better poised to reap the bountiful rewards of the digital revolution and innovative wind millers and solar shiners. Furthermore, the findings by (Usman *et al.*, 2022) demonstrate that the digital economy directly contributes to a country's position within the renewable energy trade network and enhances production efficiency and competitiveness in the process, indicating that the need for an enabling environment that encourages public and private sector cooperation to stimulate investment in renewable technologies. In their respective studies, (Ren & Li, 2023; Yahya & Rafiq, 2019) disclosed that the adoption of digital technologies for digital transformation significantly improves Renewable Energy enterprises' performance and provides another perspective for keeping the enterprise competitive in the future era of digitalization in the energy sector. It reinforces the idea that people involved in the renewable energy space need to work on digital capabilities to improve operations as well as spur innovation.

2.2. Economic freedom and renewable energy consumption

Indeed, the connection between economic freedom and renewable energy development is a multidimensional issue that has attracted considerable attention in recent academic discussions. The lack of coercion in economic affairs — what economists call economic freedom — allows individuals and firms to undertake efforts in renewable energy, creating an opportunity for investment and innovation in this field. This literature review summarizes the different contexts of different studies on the impact of economic freedom on renewable energy consumption and its further effect on economic growth. According to research, deploying renewable energy technologies correlates positively with economic freedom. Jacqmin (2017), for example, explains that institutions in Europe with a true market orientation have been shown to ease the production of energy from renewable sources significantly and suggest a correlation between higher economic freedom and increased renewable energy. Likewise, Mu (2024) studied on BRICS showed that economic freedom supports firms' engagement in green investments and energy efficiency practices required to boost the renewable energy sectors. Bjørnskov (2020) added more justification for this premise, arguing that societies that have more economic freedom are also the more renewable energy technology is adopted earlier, and that helps those societies move to an energy system that is not based on fossil fuels. There is a relationship between economic activity and energy consumption; the feedback hypothesis suggests it is symmetric. Yılancı, Haouas, Ozgur, and Sarkodıe (2021) stated that economic activity is important to generate the resources required for developing renewable energy. Policies limiting the demand for renewable energy can make an economy less dynamic, showing the fine line between economic freedom and energy use. This dynamic is especially pronounced in emerging economies, where the link between renewable energy consumption and economic growth is often not linear (Supron, 2023). In addition, Marinescu (2014) highlighted the importance of economic freedom in enhancing renewable energy investments, arguing that the greater the economic freedom, the better the renewable energy investments in the economy are. Thus, making it efficient is significant in ensuring renewable energy fulfills its ecological and economic development promise. This idea is further confirmed by Cebula and Mixon (2014), who suggest that a positive environment regarding the economy and regulations significantly attracts sustainable investment into renewables. However, the link between economic freedom and renewable energy is complex and can depend on the context. Additional evidence indicates that while higher average levels of economic freedom are generally conducive to increased renewable energy consumption, some disaggregated measures of economic freedom, like property rights and tax burdens, could potentially hinder renewables consumption (Amoah *et al.,* 2020). So this implies that while all economic freedom is good the specific implementations of them can be divergent.

2.3. Trade freedom and renewable energy consumption

One prominent area of inquiry that has developed around this relationship is the impact of trade liberalization on renewable energy consumption and the perceived opportunity that trade liberalization presents for advancing renewable energy in an increasingly globalized world. Trade freedom refers to the free-flowing exchange of goods and services across borders. It is a key enabler of the distribution of renewable energy technologies and resources, further increasing the feasibility of adopting and deploying renewable energy. The following literature review presents the results of several studies on the influence of trade openness on renewable energy consumption, capturing the duality of trade openness on renewable energy consumption. To support this assessment, vast literature demonstrates a positive impact of trade openness on renewable energy consumption. For instance, Gyimah, Yao, Tachega, Sam Hayford, and Opoku-Mensah (2022) argue that the concept of globalization and economic development in Ghana promotes renewable energy by importing needed technologies and supports sustainable economic activities that favour the growth of renewable energy systems. The study of Alam and Murad (2020) agrees with this concept, discovering that international trade has a greatly positive effect on renewable energy use in a long timeframe in the economies of OECD countries, therefore persuading trade liberalization to establish an environment to attract investments in renewable energy. Similarly, Taşkın, Vardar, and Okan (2020) show that trade openness has a long-run relationship with green economic growth; thus, a higher trade will be associated with a higher renewable energy, which promotes sustainable economic growth. Additionally, trade is instrumental in transferring technology, which is key to a renewable energy transition. (Jinkai Li *et al.,* 2020) show that trade is an important conduit for renewable energy technology development and diffusion, further supporting the premise that countries with better trade facilitation conditions can adopt new energy technologies more readily, which is especially so in developing nations, where new renewable technology can dramatically increase energy production capacity. In this context, Jebli, Youssef, and Öztürk (2015) established that trade openness causes growth in renewable energy consumption, which is crucial for achieving sustainable environment objectives of Sub-Saharan Africa. The relationship between trade openness and renewable energy consumption is not without complexities. Trade, for example, can promote sign-up for renewable applied sciences but when not managed appropriately, can elevate carbon emissions. (F. Chen, Guo-hai, & Kitila, 2021) find that trade openness can have heterogeneous effects on CO2 emissions depending on the energy mix consumed and the level of economic development. It underlines the importance of an energy policy that promotes trade liberalization but does not overlook the need for sustainable management of energy resources to minimize potential negative environmental impact. Moreover, the trade and renewable energy consumption relationship may be region- and economic context-dependent. While OECD countries have been classified as generally open towards trade, it might not be relevant across all developing countries as trade policies and local market conditions get in play to alter the dynamics (M. M. Alam & W. Murad, 2020; Progiou, 2022). Moreover, the results of Huilan, Akadırı, Haouas, Awosusi, and Odu (2022) provide evidence that trade liberalization can enhance the load capacity factor of renewable energy systems, implying that the effect of trade is not only on consumption but also translates into efficiency and reliability in energy systems. Overall, the literature suggests that trade freedom is a critical driver of renewable electricity as it fosters technology transfer and economic development. The relationship, however, is complex: The implications differ by regional context and specific trade policy. Opening up areas for future research thus includes exploring these dynamics further, and the crafting of policies that would ultimately utilize trade in promoting renewable energy in a sustainable manner.

2.4. Digitization and renewable energy consumption

Digital technologies have given a new look to all sectors of the economy, and renewable energy is no different; in this line of linkage, the existing literature highlights several contributions of digital technologies to the decarbonization transition (in particular of the digital economy itself), including energy and emissions intensity reductions and catalytic low-carbon innovations. Hou, Wang, Tian, and Zhang (2023) believe that when these digital technologies converge with energy systems, they will realize green technologies, increase energy efficiency, and ultimately lower energy demand. (Su *et al*., 2022) coin the same sentiment, stating that digitization can reduce production costs and increase the efficiency of renewable energy systems, leading to an increase in renewables in the energy matrix. This discipline toward smart digital energy solutions is affirmed by (X. Zhang, Fang, Li, Zhu, & Shen, 2023). Chalal, Saadane, and Rachid (2023) explain that with digital twins, real-time monitoring and control of hybrid energy systems can be carried out, with the benefit of managing renewable resources by reusing data continuously collected. Operating these systems provides improved operational efficiency and facilitates predictive maintenance and performance optimization, which are crucial in maximizing the generation potential of renewable energy systems. Similarly, using digital twins in energy management and explain how they help enhance the simplicity of hybrid power complexes using efficient algorithms based on operational parameters from different periods (Smirnov *et al.,* 2021). Touted as the next generation of energy distribution, smart grid technologies employ digital communication and digital processing to facilitate efficient management of electricity distribution and integrate renewable energy sources with legacy systems. According to Owunna and Obeagu (2022), smart grids make integrating distributed energy resources possible, helping stabilize and increase the reliability of renewable energy service provision. Importantly, this integration helps manage the variability of renewable sources such as wind and solar, creating a more reliable energy future. Digitalization is also a key factor in creating innovation in the renewable energy sector. Artificial intelligence (AI) and data analytics have been proven to improve renewable energy generation and use efficiency. For instance, (Ohalete, 2023) describes the ability of AI-powered solutions to improve the accuracy and effectiveness of renewable energy systems, especially for wind and solar energy optimization. Such technological convergence enhances operational performance and the overarching aspiration to reach carbon neutrality by enabling a shift to cleaner energy sources. The digitization of the energy sector, unfortunately, comes with a variety of challenges. As noted by (Samuel, Lucivero, & Croxatto, 2022), although digital technologies have the potential to enhance the energy efficiency, they also introduce numerous issues surrounding their ecological sustainability and potential rebound effects, where increased efficiency may yield increased overall energy consumption. In the era of rapid technological transformation, Artificial Intelligence (AI) holds significant promise in enhancing the synergy between economic freedom and renewable energy adoption. Integrating AI-driven tools can optimize energy systems, enable predictive analytics, and support policy frameworks conducive to clean energy innovation. For instance, advanced models like convolutional neural networks and fuzzy logic have demonstrated robust potential in pattern recognition and decision-making tasks (Kh-Madhloom, Diwan, & Zainab, 2020). Similarly, multi-layered AI architectures offer enhanced security and efficiency in digital infrastructures (Madhloom, Abd Ghani, & Baharon, 2021). while quantum machine learning introduces unprecedented optimization in complex systems (Hassen, Majeed, Hussein, Darwish, & AlBoridi, 2025).

2.5. Innovation effects on renewable energy consumption

The role of innovation in developing renewable energy is a key area of investigation in the global context of efforts to transition to renewable energy systems, whether in technology or the environment. This literature review summarizes existing studies regarding innovation impacting adoption, efficiency, and sustainability in the sector and the pathways for innovations to facilitate measures toward adopting renewable energy. As an example, (Guo & Qamruzzaman, 2022) investigates the relationship between economic policy uncertainty, oil prices, and renewable energy consumption, showcasing the positive impact of technological innovation on the adoption of renewable energy in major economies. (Khan & Su, 2022)corroborate this claim through their research, which supports the idea that technological innovation is paramount to facilitating a successful energy transition and bridging the gap between government actions and the private sector. Furthermore, innovative technologies such as battery storage systems and smart grid solutions are essential in addressing these intermittency challenges associated with renewable energy sources such as solar and wind (Long, Xiao, Wan, & Zhao, 2023). Nicolli and Vona (2016) note that heterogeneous policies may create spurs of environmental innovation across various renewable technologies, thus indicating the need for more tailored approaches to spur environmental innovations in certain sectors, which is especially important in biomass energy, for example, Cruz, Herrera, and Briseño (2019) expose the necessity of integrated management of the innovation process to enhance the generation of biomass by microalgae. These types of environmental innovations from any country will help improve the sustainability of energy production while also helping to solve more significant ecological problems like minimising reliance on fossil fuels.

Innovation also plays a key role in renewable energy policy frameworks. Böhringer, Cuntz, Harhoff, and Asane-Otoo (2017) provide empirical support for promotion policies, including feed-in tariffs and renewable energy certificates, and their use in shaping technological innovations in renewable energy sectors. Such government policies provide researchers and developers with favorable conditions, resulting in a rise in patent filling and technological advancements. Similarly, (Abbas, Gui, Ai, & Ali, 2021) examines and demonstrates the synergistic nature of market regulation and technological innovation to help reduce carbon emissions, reaffirming the prospects of how good policies consolidate and initiate innovation in the renewable energy sector. The RD-DL subsystem plays an important role in sustainable green innovation-driven development. (Adebayo, Genç, Castanho, & Kırıkkaleli, 2021) discuss the mechanism of public-private partnerships promoting technological innovation and environmental sustainability in the East Asia and Pacific region through collective investments in renewable energy technologies, which are critical for the long-run achievement of sustainable development. Teng (2023) further elaborates on the benefits of green finance initiatives through such programmers, especially via green bonds, in stimulating investment for innovations under renewable energy technology. Support from the financial sector is key to overcoming the up-front capital obstacles that can inhibit the deployment of renewable energy technologies. However, there is evidence in the literature of complementary challenges with innovation of renewable energy. Negro, Alkemade, and Hekkert (2012) investigate systemic barriers to renewable energy technology diffusion, promoting a powerful innovation ecosystem involving the government, industry, and academia. As Jebli *et al.* (2015) explain, the environmental Kuznets curve implies that while economic growth leads to environmental deterioration, introducing renewable energy sources and technological innovations can compensate for these destructive effects. This leads to having plans and investing in innovation to develop green energy correctly. Finally, other systematic reviews confirm the need for technological and environmental innovation within renewable energy systems. These advancements help increase efficiency, encourage sustainability and support the transition to a low-carbon economy. In conclusion, it is clear that the development of renewable energy technologies is essential in addressing the critical issues afflicting the global energy landscape, however, future research should also consider designing a more holistic framework for implementing these technologies at a wide ranging scale, such as one that simultaneously incorporates strategies for innovation, policies for regulation, financial mechanisms for mobilizing capital, and stakeholder engagement mechanisms.

3. Data and methodology of the study

3.1. Theoretical underpinning

Fostering innovation and efficiency in accepting renewable energy depends on economic freedom, defined by little government intervention in economic activity and a strong focus on market-driven policies. Higher economic freedom, according to Hwang (2023), lowers regulatory obstacles and improves resource allocation, thereby increasing private sector involvement in renewable energy projects. Empirical data showing that nations with greater indices of economic freedom show more acceptance of renewable energy because of better market efficiency and incentives for green innovation supports this theoretical assumption. The concept of economic freedom interacts also with financial growth. Research like those by Horvey, Odei-Mensah, Moloi, and Bokpin (2024) underlines how strong financial systems in economically free countries make improved finance for renewable energy projects possible. Furthermore, economic freedom helps decentralize energy markets, enabling local governments and communities to pursue specifically focused renewable energy projects.

Another essential factor affecting the use of renewable energy is trade freedom—that is, the lack of tariffs, quotas, and trade obstacles. Trade transparency allows renewable energy technology and resources to be freely shared across borders. Trade freedom, as Croutzet and Dabbous (2021) contend, improves the worldwide distribution of renewable technology, therefore enabling sophisticated and reasonably priced solutions to be available to underdeveloped countries. Globalization of trade also helps achieve economies of scale in producing renewable energy, hence lowering costs and hastening acceptance. (Rehman, Islam, Ullah, Khan, & Rehman, 2023) discovered in their research on South Asian nations that trade liberalization greatly increases the use of renewable energy using better access to technology skills, thus encouraging competitive marketplaces). Moreover, trade freedom helps to build worldwide alliances and cooperation, thus promoting creativity in clean energy technology.

Considering the integration of digital technology into economic processes, digitization transforms the usage of renewable energy. Digital technologies improve energy efficiency and allow real-time monitoring of renewable energy systems employing smart grids, blockchain, and the Internet of Things (IoT). (Miśkiewicz, Matan, & Karnowski, 2022) Highlight how digital platforms help maximize energy consumption patterns and reduce waste, enhancing the advantages of renewable energy. Furthermore, decentralizing energy generation is digitization. (Su *et al.*, 2022) their study showed how digital advances enable peer-to-peer energy trading and the integration of distributed energy resources (DERs). This democratization of energy systems fits world initiatives to boost the use of renewable energy, especially in areas without an established energy infrastructure. The link between digital commerce and renewable energy adds even another vital dimension. Research such as those by Nojavan, Zare, and Mohammadi-Ivatloo (2017) shows how digital commerce helps to smoothly interchange information, resources, and technology needed to grow renewable energy. These exchanges highlight the need to integrate digital trade regulations into more general plans for the energy transformation. The transition from lignite to sustainable energy in Greek peripheries underscores the economic and environmental challenges of resource exploitation in the digitization era (Zafeiriou *et al.*, 2022). Additionally, renewable energy development has been shown to contribute significantly to economic growth across Europe, highlighting its strategic value (Ntanos *et al.,* 2018).

Combining economic freedom, trade freedom, and digitalization offers a paradigm for comprehending their combined impact on the usage of renewable energy. While trade freedom improves the availability of world resources and technology, economic freedom guarantees the flexibility of markets and stimulates invention. Digitization adds efficiency, openness, and scalability to energy systems, complementing these components. In this setting, a prominent theoretical contribution is the idea of digital economy ecosystems, which combine digital technology with the benefits of economic freedom and trade openness. Such ecosystems, according to Polcyn, Us, Lyulyov, Pimonenko, and Kwilinski (2022), help nations to use their comparative advantages in the generation of renewable energy, therefore supporting world sustainability targets. Notwithstanding the combined possibilities of trade freedom, economic freedom, and digitalization, problems still exist. For example, too liberal regulation—often connected with economic freedom—may cause market failures and disregard of environmental protections. Trade restrictions and digital inequalities may also impede the fair sharing of the advantages of renewable energy.

3.2. Model specification

The motivation of the study is to seek the influences of trade freedom, economic freedom, digitization, and innovation on fostering renewable energy consumption in G20 nations for the period 2000-2023. The dependent variable in this research is renewable energy (RE), which captures the proportion of total energy consumption that comes from renewable sources. This metric shows the rate of economic shift toward renewable energy in a straightforward manner. One of the most important metrics is the share of energy that comes from renewable sources; this data comes from reputable sources like the IEA and the World Bank. One important independent variable is economic freedom (EF), which indicates how free an entity is to make, sell, and consume goods and services with little intervention from the government; because of this, innovation and market-driven solutions are flourishing in the current economic climate. This metric is supported by strong quantitative evidence from sources like the Economic Freedom Index and Freedom Score, which are made public by groups like the Fraser Institute and the Heritage Foundation. A country's trade freedom (TF) indicates how welcoming it is to foreign investment and commerce. This metric emphasizes how trade liberalization may speed up the adoption of renewable energy by increasing access to cutting-edge technology and competitive energy markets. This variable is mostly determined by the World Bank's Trade Freedom Index and the Heritage Foundation's trade-to-GDP ratios. The term "digitization," which stands for "digital integration of technology into economic activities," has far-reaching consequences for renewable energy adoption and energy efficiency. A country's degree of digital transformation may be seen by looking at indicators like internet adoption rates, the Digital Economy Index, and the ICT Development Index. The World Bank and the International Telecommunication Union (ITU) are among the sources that provide data for this variable. To gauge the rate of technological progress that propels energy transformation and economic growth, we use the metric known as technological innovation (TI). Indicators like the number of patent applications per million people and R&D investment as a proportion of GDP are used to evaluate this variable. An economy's innovation capability may be shown by these metrics, which are derived from the World Intellectual Property Organization (WIPO) and the OECD. When new ideas are developed with the goal of lessening negative effects on the environment and increasing positive ones, we call this "environmental innovation" (EI). To measure this variable, we employ green patent numbers and environmental R&D expenditures as our primary indicators. In order to measure innovation in the field of environmental protection, credible data sources are essential. These sources include the World Bank, the OECD, and the European Patent Office (EPO).
The generalized empirical equation is as follows.

$$REC \mid EF, TF, DIGI, IN \quad (1)$$

After the log transformation, Eq (1) can be displayed in the following regression form in documenting the elasticities of TF, EF, DIGI, and INO on REC.

$$RECit = \alpha + \beta 1EFit + \beta 2TFit + \beta 3DIGIit + \beta 4INit + \mu i + \epsilon it \quad (2)$$

Where REC for Renewable Energy Consumption), EF, TF, DIGI, IN (e.g., Economic freedom, trade freedom, Digitalization, and Innovation). i for (e.g., country, firm, individual), t for time (e.g., year, quarter), α explains the Intercept term. The coefficients of β1, β2, β3, β4, for the independent variables. μ captures unobserved heterogeneity specific to each entity) and ϵ explain the idiosyncratic error term (random noise). Details of research variables with proxy can be found in Table 1.

It is hypothesized that renewable energy usage is positively impacted by economic freedom (EF), which is defined as the degree to which economic activities are autonomous and the amount to which governments intervene. Increases in innovation, investment in renewable energy, and market efficiency tend to go hand in hand with more economic freedom. The use of renewable energy sources and other environmentally friendly policies is more common in economically free nations, according to research (Amoah et al., 2020). Therefore, it is anticipated that $\beta 1$will be positive, suggesting a correlation between higher usage of renewable energy and better economic freedom.

Similarly, it is believed that renewable energy usage is favorably impacted by trade freedom (TF), which measures an economy's openness to international commerce. Sustainable practices rely on more trade freedom since it foster the flow of

Table 1
Data and variables definition and data sources

Variables	Notation	Definition	Indicators	Data Sources
Renewable energy	RE	Share of renewable energy in total energy consumption	Percentage of energy consumption from renewable sources	World Bank, International Energy Agency (IEA)
Economic freedom	EF	Freedom to produce, trade, and consume with minimal restrictions	Economic Freedom Index (Heritage Foundation), Freedom score	Heritage Foundation, Fraser Institute
Trade freedom	TF	Degree of openness to international trade and investment	Trade Freedom Index, Trade-to-GDP ratio	World Bank, Heritage Foundation
Digitization	DIGI	Integration of digital technologies in economic activities	Internet penetration rate, Digital Economy Index, ICT Development Index	International Telecommunication Union (ITU), World Bank
Technological innovation	TI	Advancements in technology fostering development	R&D expenditure as % of GDP, Patent applications (per million people)	World Intellectual Property Organization (WIPO), OECD
Environmental innovation	EI	Innovation targeted at reducing environmental impact	Green patent counts, Environmental R&D expenditure	European Patent Office (EPO), OECD, World Bank

Table 2
Results of VIE

	EF	TF	DIGI	TI	EI
VIF	1.7444	1.3978	1.2207	1.5289	1.2267
1/VIF	0.5732	0.7154	0.8192	0.654	0.8151
Mean VIF	1.4237				

information and makes it easier to obtain innovative renewable energy technology. According to studies, open economies have the potential to increase their use of renewable energy sources by using global supply chains to get affordable solutions (Aïssa *et al.*, 2014). This means that trade liberalization is expected to have a favorable effect on boosting the usage of renewable energy, as $\beta 2$ implies.

Renewable energy consumption is anticipated to have a favorable correlation with digitalization (DIGI), which includes the integration of digital technology into social and economic activities. Improvements in energy efficiency, progress toward smart grid technology, and the ability to make data-driven decisions about energy management are all outcomes of digitalization. According to research by (Su *et al.*, 2022) , digital technology may help make the energy transition more environmentally friendly by optimizing consumption patterns and facilitating the deployment of novel renewable solutions. Since digitization is likely to have a revolutionary influence on the uptake of renewable energy, $\beta 3$ is predicted to be positive.

There is a high expectation that innovation (IN), which assesses technological and creative developments, would positively affect the use of renewable energy. The development and spread of renewable energy technology, which in turn leads to decreased prices and increased efficiency, are propelled by innovation. According to research, more innovative organizations have a greater chance of overcoming the financial and technical obstacles to implementing renewable energy sources (M. M. Alam & W. Murad, 2020). Hence, $\beta 4$ is anticipated to have a positive value, highlighting the vital need of innovation in promoting a future energy that is sustainable.

The VIF values in Table 2 suggest no multicollinearity issues, as all VIF values are below the threshold of 5. The mean VIF of 1.4237 indicates a low average level of multicollinearity among the variables EF, TF, DIGI, TI, and EI. The 1/VIF values confirm the absence of problematic correlations.

3.3. Estimation strategies

Stage 1: the study implemented the CD test by Juodis and Reese (2022). Conventional CD tests, notably those by Pesaran, have limited applicability in circumstances of high spatial or temporal correlations or when the panel size (T and N) is imbalanced. Particularly useful in identifying subtle interdependencies across big and complicated datasets, Juodis and Reese's approach enhances sensitivity by evaluating higher-order relationships and including rigorous statistical modifications. Furthermore, The slope heterogeneity test proposed by Bersvendsen and Ditzen (2021) enhances traditional panel data analysis by addressing limitations in detecting heterogeneous slopes across cross-sectional units. Unlike conventional tests that assume slope homogeneity, their approach identifies differences in slope coefficients among units in panel data models. This refinement is crucial for accurately capturing diverse behaviors or responses, especially in economic, environmental, or social studies. By accounting for heterogeneity, the test improves model robustness and inference validity, ensuring results better reflect real-world complexity. This methodological advancement provides a superior alternative when analyzing datasets where homogeneity assumptions might misrepresent underlying relationships.

Stage 2 deals with the Unit-root test (Herwartz and Siedenburg, 2008), An advanced integration test developed to account for possible structural breaks in time-series data, which is accomplished by incorporating endogenous structural breaks, in contrast to conventional unit-root tests like the Augmented Dickey-Fuller (ADF) test, allowing for more reliable identification of non-stationarity in dynamic economic structures, which is especially important when considering variables impacted by major policy changes or major shocks. The Westerlund and Edgerton (2008) cointegration test provides a significant alternative to classical tests such as Johansen or Engle-Granger. It is more reliable in heterogeneous panel data settings as it accommodates structural breaks in equilibrium relationships between long-run variables. These amplifications are required for empirical applications on energy economics or impacts of digitization, guaranteeing robustness to nonlinear dynamics or policy-induced breaks usually neglected in standard tests.

Stage 3. When it comes to estimation techniques, the choice of appropriate estimation techniques in econometric analyses is of key importance in obtaining precise and unbiased results. Furthermore, conventional assessment sometimes does not derive the results when the same panel data contains complexities like CSD, endogeneity and heterogeneity(Hassan, 2024). Advanced estimators, such as Dynamic Common Correlated Effects (DCCE), Instrumental Variable-adjusted DCCE (DCCE-IV), or Dynamic Seemingly Unrelated Regression (DSUR), have been introduced to address those issues carefully.

Chudik and Pesaran (2015) proposed the DCCE estimator as a way of dealing with case dependence based on means and logs over cross-sectional units. The fixed effects specification controls for time-invariant unobservables that might affect all units in a panel, thus reducing omitted variable bias. DCCE supports heterogeneous slopes and induces bias-corrected results at small sample sizes with recursive mean critique, which makes it better than standard approaches. Additionally, Based on the DCCE framework, the DCCE-IV estimator adds instrumental variables to overcome possible endogeneity. Endogeneity, due to omitted variables, measurement error or simultaneity bias, can also lead to bias in parameter estimates. By incorporating instrumental variables, DCCE-IV improves the reliability of econometric analyses by providing consistent and unbiased estimates, which is especially important in dynamic panels, where endogeneity is a real concern. The DCCE estimator extends the Common Correlated Effects (CCE) approach to dynamic panel data models by incorporating lagged dependent variables and cross-sectional averages to account for unobserved common factors. The model can be specified as:

$$y_{\{it\}} = a_i + \beta_i y_{\{i,t-1\}} + \delta_i' x_{\{it\}} + \gamma_i'\{X\}_t + \eta_i\{y\}_t + \varepsilon_{\{it\}} \quad (3)$$

Where, yit: Dependent variable for unit i at time t, αi for Individual-specific intercept, $y_{\{i,t-1\}}$ Explain the lagged dependent variable.$x_{\{it\}}$ Vector of explanatory variables. X¯t for

Cross-sectional averages of explanatory variables, y¯t for Cross-sectional average of the dependent variable, βi,γi,δi,ηirepresent the coefficients to be estimated, εit is the Error term.

The DSUR estimator was introduced by Mark, Ogaki, and Sul (2005) and applies the Seemingly Unrelated Regression (SUR) framework in a dynamic panel context. Create random variables that deal with potential cross-sectional dependency, endogeneity, and heterogeneity by allowing contemporaneous correlations among the error terms across individual equations. This model is better than traditional methods, which, on the other hand, do not include, in some cases, such correlations, resulting in inefficient estimates. DSUR, hence, achieves more efficient and reliable parameter estimates in panel data settings by accounting for these interdependencies. The DSUR estimator is used for the simultaneous estimation of multiple cointegrating regressions, allowing for contemporaneous correlations among error terms across equations. The system of equations can be represented as:

$$yit = \alpha i + \beta i' xit + \varepsilon it \quad (4)$$

For i=1,2,...,mi = 1, 2, ..., mi=1,2,...,m equations, where: $y_{\{it\}}$: Dependent variable for equation i at time t, αi: Equation-specific intercept. x_{it} stands for Vector of explanatory variables for equation I, β_i for Coefficient vector for equation I, and εit is the error term for equation iii, potentially correlated with error terms in other equations.

Stage 4 focuses on the documentation of directional causality by following the DH causality test offered by Dumitrescu and Hurlin (2012). The DH causality test is a panel causality test that allows for heterogeneity of cross-sectional units and is more robust than traditional Granger causality tests. Again, unlike previous methods, the DH test permits heterogeneity of the causality relationship by enabling the relationships among the variables to differ in direction between pairs of entities, a key characteristic of panel data in which economists often use diverse economies or regions as subjects having unique causal dynamics. This flexibility improves its accessibility and reliability in discovering causal connections in complex systems, especially for papers about the associations between energy, trade, and digitization in the knowledge economy.

4. Estimation and interpretations

4.1. Preliminary assessment

The results of the CD test, see Table 3, in Panel A, based on Juodis and Reese (2022), strongly indicate the presence of cross-sectional dependence (CD) across all variables tested (EF, TF, DIGI, TI, EI), with highly significant test statistics. These findings suggest substantial interdependence among cross-sectional units, reinforcing the necessity of accounting for CD in model estimation. In Panel B, the SH test of Bersvendsen and Ditzen (2021) confirms the presence of slope heterogeneity (SH) in the model, as both the Delta Statistic (4.9616***) and Adjusted Delta Statistic (5.0043***) are highly significant. Together, these tests underscore the importance of utilizing robust econometric techniques for both CD and SH to ensure reliable inference.

The presented results, see table 4, provide a comprehensive evaluation of the integration and cointegration properties of the variables using advanced econometric tests. Panel A, employing the Herwartz and Siedenburg (2008) unit-root test, reveals that all variables (EF, TF, DIGI, TI, EI, and REC) are non-stationary at levels but become stationary upon first differencing, as evidenced by statistically significant test

Table 3
Results of the CD test and SH test

Panel A: CD test of Juodis and Reese (2022)

	REC	EF	TF	DIGI	TI	EI
test stat value	9.3373***	12.4917***	10.2321***	12.8655***	10.8751***	10.6715***
CD exist	YES	YES	YES	YES	YES	YES

Panel B: SH test of Bersvendsen and Ditzen (2021)

	Delta Statistic	Adjusted Delta Statistic	SH exits
Model	4.9616***	5.0043***	Yes

Table 4
Results of integration and cointegration test

Panel A: Integration (or unit-root) test of Herwartz and Siedenburg -2008

	REC	EF	TF	DIGI	TI	EI	REC
At level	-0.8192	0.493	1.7157	1.7183	0.9519	-0.1649	0.6497
First diff	8.7827***	4.116***	8.7788***	4.1831***	6.4728***	5.52***	8.7281***

Panel B: Cointegration test of Westerlund and Edgerton (2008)

	no shift		mean shift		regiem shift	
	LMг Stat.	LMΦ Stat.	LMг Stat.	LMΦ Stat.	LMг Stat.	LMΦ Stat.
Model 1	-4.2499***	-2.0112***	-4.5024***	-3.0352***	-3.9454***	-3.8297***
Model	Gt	Ga	Pt	Pa		
Model 1	-10.083***	-13.727***	-13.145***	-11.368***		

values at the 1% level, confirming that the variables are integrated into order one, I(1). Panel B, using the Westerlund and Edgerton (2008) cointegration test under different regimes (no shift, mean shift, and regime shift), consistently rejects the null hypothesis of no cointegration across models and regimes, with highly significant LM statistics (e.g., Model 1, LMr = -4.2499*** for no shift) and Gt and Pt statistics for FDI→EC (e.g., Gt = -10.083***). These results collectively indicate a robust long-term equilibrium relationship between the studied variables.

For economic freedom, see Table 5, the study exposed a positive statistically significant connection towards renewable energy consumption, which is validated by three more estimations (i.e., DCE=0.1688; DCE-IV=11129; and DSUR=0.1308). Precisely, a 10% progress in economic freedom will foster clean energy inclusion in the energy mix with a range between 1.112% to 1.688%). Economic freedom significantly enhances the adoption of renewable energy by fostering an environment conducive to investment, innovation, and efficient resource allocation. High levels of economic freedom reduce regulatory constraints, facilitating market entry for renewable energy firms and promoting competition (Bjørnskov, 2020; Sart, Bayar, Danilina, & Sezgin, 2022). This competitive landscape encourages technological advancements and cost reductions, which are essential for the transition to sustainable energy systems (Cebula & Mixon, 2014; Mu, 2024). Furthermore, policies that protect property rights and lower trade barriers enable the import and export of renewable technologies, further driving their adoption (Amoah *et al.*, 2020; İMamoĞLu, 2023). Additionally, economic freedom is associated with higher income levels, allowing households and industries to invest in cleaner energy sources (Bektur, 2023; Jacqmin, 2015). The correlation between economic freedom and ecological sustainability is evident, as it supports the development of green technologies and practices that align with environmental goals (Amin, Li, Khan, & Bibi, 2022; Xie, 2024). In summary, a robust framework of economic freedom not only stimulates renewable energy consumption but also contributes to broader economic growth and environmental sustainability ((Vitenu-Sackey, 2022; Yang, 2023).

The coefficients of trade freedom in DCE (a coefficient of 0.0904), DCE-IV (a coefficient of 0.1182), and DSUR (a coefficient of 0.1097) exposed positive statistically significant at a 1% level with REC, suggesting that Trade freedom facilitates the flow of technology, expertise, and resources across borders, significantly boosting renewable energy consumption. To increase the use of renewable energy sources, trade freedom is essential since it allows for the free movement of goods, services, and knowledge across borders. Moreover, the expansion of clean energy solutions is crucial, and nations may import and export innovative renewable energy technology like solar panels and wind turbines via open trade regulations. The ease of access to these technologies not only speeds up their adoption but also encourages innovation and cost reduction via the attraction of foreign direct investment (FDI) in renewable energy projects (Musa & Maijama'a, 2020). Furthermore, Renewable energy technology advancements are dependent on free trade since it promote research collaborations and the exchange of information (Md. Qamruzzaman, 2024). Various renewable energy solutions and practices are advantageous to countries that allow free trade, which helps them reduce their dependency on fossil fuels and supports a sustainable energy transition (Qamruzzaman, 2023). According to (Omri & Nguyen, 2014), renewable energy may help countries become more economically and environmentally sustainable because of how interdependent global trade networks are.

Digitalization demonstrates a significant and positive influence on renewable energy consumption, as evidenced by coefficients in various models: DCE (0.1154), DCE-IV (0.10136), and DSUR, all of which are statistically significant at the 1% level. These findings suggest that while digitalization presents challenges, such as high energy demands, it also fosters innovation and efficiency that can accelerate renewable energy adoption. The study emphasizes the need to address the energy-intensive nature of digital technologies to maximize their benefits for sustainability. Digital technologies like data centers and cloud computing, as highlighted by Galperova and Mazurova (2019), are rapidly expanding and consuming substantial amounts of electricity. Unfortunately, much of this energy is currently sourced from grids reliant on non-renewable resources, diminishing the full potential of digitalization in promoting energy sustainability. Despite these challenges, the transformative impact of digitalization on energy efficiency and innovation cannot be understated. The rapid growth in digital infrastructure, while initially energy-intensive (Gudi, Wang, & Devabhaktuni, 2012)., offers long-term opportunities for optimizing renewable energy systems.

The analysis indicated a positive and statistically significant relationship between technological innovation and renewable energy consumption in G20, confirmed by three estimation models (DCE=0.1269; DCE-IV=0.09154; DSUR=0.1571). In particular, the 10% improvement in technological innovation can lead to the increase of the absorbed renewable energy by 0.9154%–1.571%. Study findings

Table 5
Empirical estimation with DCE, DCE-IV, and DSUR

	Coeff.	Std. Error	t-Statistic	Coeff	Std. Error	t-Statistic	Coeff	Std. Error	t-Statistic
		DCE			DCE-IV			DSUR	
EF	0.1688	0.0188	8.9803	0.11129	0.0167	6.664	0.1308	0.0169	7.7443
TF	0.0904	0.0182	4.9703	0.11825	0.0412	2.8701	0.1097	0.0223	-4.9215
DIGI	-0.1154	0.0204	-5.6612	-0.10136	0.0346	-2.9294	-0.1526	0.0303	-5.038
TI	0.1269	0.0194	6.5453	0.09154	0.0232	3.9456	0.1571	0.0235	6.6885
EI	0.1273	0.0171	7.4467	0.15631	0.015	10.4206	0.1616	0.0415	3.8939
CD test		0.0227			0.03132			0.023293	
Wooldridge Test		0.5311			0.71264			0.405408	
Normality test		0.3219			0.680954			0.683633	
Remsey RESET test		0.0974			0.922024			0.580743	

Note: EF for economic freedom. TF for Trade Freedom, DIGI for digitalization, TI for technological innovation, and EI for environmental Innovation advocated that technological innovation can aid the adoption of renewable energy; that is, improvements in solar photovoltaic technology, wind turbine design, and energy storage systems have drastically made these renewable energy sources more feasible and attractive (Milton *et a*l., 2024).In addition, smart grid developments enable the smooth integration of renewable energy into conventional energy systems, making grid deployment more stable and reliable (Milton, 2024). Supportive policies and investment in research and development rate technological progress, which in turn provides a conducive environment for renewable energy technologies to thrive. The impact of technological innovation as a generator for the implementation of renewable energy systems demonstrates the need for a transition that promotes sustainable energy systems and environmentally sustainable systems.

For Environmental Innovation, there is a positive and statistically significant relationship between environmental innovation and renewable energy consumption, with estimators (DCE=0.1273; DCE-IV=0.15631; DSUR=0.1616). Moreover, an increase of 10% in environmental innovation is associated with a rise in renewable energy consumption between 1.273% and 1.616%. Environmental Innovation includes products, processes, and practices that help reduce environmental impact and advance sustainability. These technological advancements not only enhance the supply side of the equation but can also alter demand dynamics, leading to cleaner, more efficient energy solutions that facilitate the transition to renewables. Introduced policies that reward environmental innovation, like subsidies for green technologies and environmental regulations, drive firms to develop sustainable practices and renewable energy solutions. Moreover, the public's awareness of environmental protection and the preference of consumers for clean products promote the development of the renewable energy market (Milton, 2024).

The robustness evaluation results presented in Table 6 are drawn from three econometric methods (FGLS, PCSE, and FMOLS) and demonstrate significant associations between independent variables and renewable energy consumption (dependent variable). The study shows that energy intensity (EI), digitalization (DIGI), technical innovation (TI), and environmental factors (EF) positively and significantly affect the consumption of renewable energy in all models, which validates the results of prior estimation.

The DH causality test results, see Table 7, reveal various unidirectional and bidirectional relationships among the variables. A unidirectional relationship ("-->") is running from REC to DIGI and TI and from TF to TI, DIGI, and EI. In these cases, the causality flows one way, indicating the influence of the first variable on the second without reciprocal feedback. Bidirectional causality ("<-->") exists between REC and TF, TF and TEF, and DIGI and EI, suggesting a mutual influence between these pairs. Instances of non-causality ("<--") appear in relationships like REC and EF, where causality is evident in one direction but not reciprocated. These dynamics underscore the complex interdependencies among renewable energy consumption (REC), environmental factors (EF), technology frameworks (TF), and digitalization (DIGI).

4.2. Discussion of the findings

For economic freedom influences on renewable energy consumption in G20 nations, the study revealed a positive statistically significant tie between EF and REC; that is, economic freedom amplifies the energy inclusion and energy consumption from renewable sources in the energy mix. Our study is supported by literature such as (Işık, Simionescu, Ongan, Radulescu, *et al.*, 2023; Mawardi, Al Mustofa, Widiastuti, & Ghozali, 2024; Sachan, Sahu, Pradhan, & Thomas, 2023). This conclusion is rooted in an increasing body of literature showing how economic freedom provides a framework for both investment and consumption in renewable energy. For example, (Bjørnskov, 2020) pointed out that economically free societies rapidly adopt green technologies. They attribute this choice to the business environment associated with economic freedom with more ideas and better quality fundamentally than those from governmental intervention. Our research supports this argument only: greater economic freedom is not only early adoption but also helps to lift renewable energy production and use. Secondarily, the growth of economic output increases final consumption from clean power sources and, in effect, lowers overall protection costs. This point is taken up by (Frondel, Ritter, Schmidt, & Vance, 2010; Işık, Simionescu, Ongan, Rădulescu, *et al.*, 2023). Economic freedom breeds innovation, allowing us to establish and use environmentally friendly technologies instead. This is something that serves as another nod to the idea that economic freedom really provides fertile ground for increasing consumption of renewable energy. Further, far from being merely correlative, as some claim, the evidence suggests a causal relationship between economic freedom and renewable energy consumption. For example, (Alola, Doğanalp, & Obekpa, 2022) shows that aspects of economic freedom have a significant role in determining environmental sustainability, and this includes the development of renewable energies. This corroborates our findings in the

Table 6
Results of Robustness Assessment

Methods→	FGLS			PCSE			FMOLS		
Variables	Coeff.	Std. Error	t-Statistic	Coeff	Std. Error	t-Statistic	Coeff	Std. Error	t-Statistic
EF	0.088	0.0465	1.8924	0.1234	0.0218	5.6605	0.0891	0.0345	2.5826
TF	0.1208	0.0192	6.2916	0.1444	0.0173	8.3468	0.1307	0.0303	4.3135
DIGI	0.0962	0.0398	-2.417	0.1588	0.0409	3.8826	0.1245	0.0427	2.9156
TI	0.1721	0.0401	4.2917	0.1117	0.0448	2.4933	0.0921	0.0298	3.0906
EI	0.0886	0.0147	6.0272	0.0856	0.035	2.4457	0.1812	0.0177	10.2372
r2					0.569			0.668	
Adj R2								0.559	
Wald X2		19803.61872			23228.91458				
Prob.		0			0			0	

Table 7
Results of DH causality test

Null Hypothesis:	**W-Stat.**	**Zbar-Stat.**	remarks
REC does not guarantee cause EF	1.1987	1.2634	EF→REC
EF does not guarantee cause REC	5.3039	5.5903	
REC does not guarantee cause TF	7.0467	7.4272	REC <---->TF
TF does not guarantee because REC	6.6599	7.0195	
REC does not guarantee cause DIGI	9.8097	10.3394	REC--→ DIGI
DIGI does not granger causes REC	4.6439	4.8946	
REC does not granger cause TI	8.2051	8.6481	REC --> TI
TI does not granger REC	2.2805	2.4036	
REC does not granger causes EI	7.7747	8.1945	REC----> EI
EI does not granger causes REC	4.3846	4.6213	
TF does not granger cause EF	9.6323	10.1524	EF <----> TF
EF does not granger cause TF	7.7258	8.1429	
EF does not granger cause DIGI	7.9277	8.3557	EF <----> DIGI
DIGI does not granger cause EF	10.0456	10.588	
EF does not granger cause TI	7.3698	7.7677	EF --> TI
TI does not granger causes EF	1.9373	2.0419	
EF does not granger causes EI	2.9415	3.1003	EI→FI
EI does not granger causes EF	6.2444	6.5815	
TF does not granger causes DIGI	9.9936	10.5332	TF --> DIGI
DIGI does not granger causes TF	1.1498	1.2118	
TF does not granger causes TI	6.7449	7.1091	TF <----> TI
TI does not granger causes TF	7.9511	8.3804	
TF does not granger causes EI	10.5111	11.0786	TI --> EI
EI does not granger causes TF	2.6652	2.8091	
DIGI does not granger causes TI	10.3018	10.858	DIGI --> TI
TI does not granger causes DIGI	2.8575	3.0118	
DIGI does not granger causes EI	9.7513	10.2778	DIDI <----> EI
EI does not granger causes DIGI	6.2029	6.5378	

following way: Without economic freedom, you cannot achieve sustainable energy use. However, some scholars have looked at this issue of economic freedom and renewable energy consumption from a different angle. For instance, (Sart *et al.,* 2022) points out that while higher economic freedom may lead to more energy consumption, it can also cause increased environmental degradation, which serves as an example of how much is at stake in terms of not only asset values but whether we are willing or able even to have a tomorrow, which is underlines clearly the necessity of policy coherence. With emission trading schemes in place, for instance, some members of the emissions trading game in Europe have suggested that member countries should model their policy on that of Germany, where renewable energy sources are so abundant and untapped gas so plentiful. Furthermore, Jacqmin (2021) emphasized that market-oriented institutions in Europe significantly facilitate renewable energy deployment, a conclusion echoed in this study's identification of economic freedom as a driver for cleaner energy transitions. Similarly, Mu (2020) found that in BRICS nations, economic freedom enhances firm-level investments in energy efficiency, corroborating this paper's conclusion that regulatory flexibility supports green innovation. However, unlike many existing studies that isolate economic indicators, this research uniquely integrates innovation as a mediating variable, offering a more dynamic understanding of how economic policies can create innovation ecosystems conducive to renewable energy expansion.

Increased trade freedom allows the flow of technology, knowledge, and resources across borders, thus dramatically increasing renewable energy consumption, according to the study, which finds a positive and statistically significant relationship between trade freedom and renewable energy consumption (REC) in G20 nations. (Md. Qamruzzaman, 2024) (Amoah *et al.*, 2020) found that countries can import and export innovative solutions like solar panels and wind turbines when trade is free. Eventually, nations speed up their adoption and encourage innovation through foreign direct investment (FDI). Foreign direct investment (FDI) promotes the use of renewable energy sources since it primarily targets nations that place a premium on sustainability rather than fossil fuels (Gyimah, 2023). Likewise, the research conducted by (Aïssa *et al.*, 2014) supports the idea that trade liberalization may facilitate energy transitions by showing that international commerce has a beneficial effect on renewable energy use in Africa. On the other hand, although commerce may help with knowledge transfer, it might also cause more carbon emissions if not handled correctly, suggesting a complicated link that needs further research (Aydın, 2023). In the context of trade openness, this study reinforces and broadens the consensus on its positive role in advancing renewable energy, mirroring results from Alam and Murad (2020), who showed that trade openness increases RE use in OECD countries. However, by focusing on the G20 nations, this research brings a nuanced insight into how trade structures at the global economic frontier differ from those in emerging markets. Additionally, while previous studies have acknowledged trade's role in technology diffusion, the empirical findings here show a stronger, statistically significant relationship that includes trade's indirect effects via environmental innovation—an angle that has not been comprehensively addressed in earlier literature

Developing nations may get access to cutting-edge technology and specialized knowledge essential to creating sustainable energy systems when trade barriers are lower, which benefits the economy (Md Qamruzzaman, 2024). According to the innovation diffusion concept, which states that free trade policies facilitate the international dissemination of innovative technology, this lends theoretical credence to that claim (Pfeiffer & Mulder, 2013). The results have real-world implications since they highlight the need for more international cooperation and the sharing of information in order to develop renewable energy sources and lessen our dependency on fossil fuels. Reducing tariffs on renewable energy technology and encouraging international collaborations are two examples of trade-free policies that nations can consider enacting if they want to make the most of their renewable energy usage. Possible approaches include improving legislative frameworks that back clean energy projects and offering incentives for international investment in renewable energy industries (Amoah *et al.*, 2020). Renewable technology development and implementation may be accelerated if governments support research partnerships that pool worldwide knowledge (Xiao & Qamruzzaman, 2022). The discussion around sustainable development and climate change mitigation is enhanced by these results, which are set within the broader framework of worldwide energy transitions. Supporting the need to align trade policy with environmental objectives, the research shows that trade openness may increase the usage of renewable energy. As countries work to transition to low-carbon economies and fulfill international climate pledges, this alignment is vital. In addition, considering economic, environmental, and social factors is crucial when formulating energy strategies (Van & Mai, 2023). One of the most important ways to promote renewable energy and reach sustainable development objectives is to encourage free trade, which is becoming more important as the globe struggles with energy poverty and climate change.

The findings from the study on G20 nations indicate a significant and positive influence of digitalization on renewable energy consumption, with coefficients reported at 0.1154 for DCE and 0.10136 for DCE-IV, both statistically significant at the 1% level, suggesting that digitalization not only enhances energy efficiency but also fosters innovation that can accelerate the adoption of renewable energy sources. However, it is crucial to recognize the challenges posed by the energy-intensive nature of digital technologies, which can potentially offset their environmental benefits if not managed effectively (Hou *et al.*, 2023; Nazari & Musilek, 2023). Contextually, these findings align with existing literature that posits digital technologies as catalysts for energy efficiency and innovation. For instance, (Nazari & Musilek, 2023) highlights that digital transformation in the energy sector leads to reduced energy demand through enhanced efficiency applications and cost savings. Furthermore, the work of (Hou *et al.*, 2023) emphasizes the initial energy demands associated with digital infrastructure, such as data centers, which underscores the need for a balanced approach to digitalization and energy sustainability. This duality of digitalization—promoting efficiency while also increasing energy consumption—has been noted in various studies, including those by (Kwilinski, Lyulyov, & Pimonenko, 2023), who discuss the integration of digital and energy technologies to promote low-carbon development. The implications of these findings are significant for policymakers and practitioners. The positive correlation between digitalization and renewable energy consumption suggests that integrating smart technologies into energy systems is essential. The study of (Calabrese, Dora, Ghiron, & Tiburzi, 2020; Rusch, Schöggl, & Baumgartner, 2022) indicates that digital business practices can significantly improve energy efficiency and reduce consumption. Moreover, the transformative potential of digital technologies in optimizing energy systems is echoed in the work of (Zhao, Xia, Zhang, Hu, & Wu, 2021), which emphasizes the role of digital transformation in enhancing renewable energy utilization. Despite the robust evidence presented, it is essential to acknowledge the limitations inherent in the study. The energy demands of digital infrastructure, particularly data centers, pose a significant challenge that could undermine the sustainability benefits of digitalization. Regional dynamics and incorporate additional variables, such as energy pricing policies, to provide a more comprehensive understanding of the relationship between digitalization and energy consumption (Reis & Melão, 2023). In comparing these findings with existing literature, it is evident that they resonate with previous studies that have identified the dual role of digitalization in enhancing energy efficiency while simultaneously increasing initial energy demand. For example, the findings align with those of (Kwilinski *et al.*, 2023), who noted that digital business indicators significantly impact energy intensity in EU countries. Furthermore, the study extends previous knowledge by providing empirical evidence of digitalization's direct impact on renewable energy adoption, a nuance not fully explored in earlier research. Looking ahead, future research should investigate the regulatory frameworks that can mitigate the energy-intensive aspects of digitalization and explore the interaction between digitalization and specific renewable energy technologies. This forward-thinking approach will contribute to advancing knowledge in the field and addressing unresolved questions regarding the sustainability of digital technologies in energy systems (Calabrese *et al.*, 2020; Joubert *et al.*, 2012). The role of digitalization also invites valuable comparison. Studies by Zhang *et al.* (2022) and Fan (2024) have shown that ICT integration improves renewable energy systems, particularly through smart grid development. This study not only confirms those findings but provides additional granularity by quantifying digitalization's direct impact and its interplay with innovation. While earlier works often discussed digitalization's potential qualitatively, this research adds empirical strength to the argument and highlights the policy dilemma of balancing digital infrastructure growth with its energy-intensive footprint. These contributions offer a clearer roadmap for future research and policy intervention, advocating for smart regulation and investment in digital energy ecosystems.

Results show that among G20 countries, renewable energy usage is positively and statistically significantly correlated with technical innovation and environmental innovation. Innovation is important in promoting the use of renewable energy sources, like solar photovoltaic systems and wind turbine designs, which make them more appealing and practical. The results are in line with previous research that has shown that innovative ideas are key to increasing the use of renewable energy sources (M. M. Alam & W. Murad, 2020; Ganda, 2024; Hafeez *et al.*, 2022). For example, according to (Junrong Li, Rehman, & Khan, 2023), eco-innovations greatly increase the demand for renewable energy, lending credence to the idea that new technology might make renewable energy more efficient and competitive. This positive correlation is further supported by (Usman *et al.*, 2022), who note that eco-innovation is the driving force behind the creation of affordable renewable energy alternatives. On the other hand, some studies argue that renewable energy usage is heavily influenced by variables like regulatory frameworks and market circumstances rather than only innovation (Bekun & Alola, 2022; Murad, Alam, Noman, & Öztürk, 2018).

In theory, these results add to the innovation-diffusion model, which states that novel energy solutions may be more widely adopted as technology advances (M. M. Alam & W. Murad, 2020; Usman *et al.*, 2022). According to (Junrong Li *et al.*, 2023; Majeed *et al.*, 2022), renewable energy technologies can only thrive in an environment that is receptive to them, and this can only be achieved via the implementation of policies that encourage them and financial expenditures in research and development. According to research by (Böhringer *et al.*, 2017), new developments in energy storage, smart grid technologies, and efficient energy systems might make it easier to incorporate renewable energy sources, which in turn encourages greater consumption levels. (Mukhtarov, 2023)found that green technology subsidies and investments in research and development are two examples of strategies that encourage technical and environmental advances. These measures may increase the adoption of renewable energy solutions. (Dechezleprêtre & Glachant, 2013; Liang, 2024) Both state that the renewable energy industry may be further stimulated by rising public awareness of sustainability issues and customer demand for environmentally friendly goods. To help create a more sustainable energy future, lawmakers should think about passing laws that encourage eco-innovation and make it easier to incorporate renewable energy into current power grids (Gao & Fan, 2023; Kırıkkaleli & Adebayo, 2020). Furthermore, the study highlights the importance of innovation in reaching long-term energy sustainability targets within the larger framework of energy research and social progress. In order to successfully switch to renewable energy systems, it is essential to use a multi-pronged strategy that incorporates technical progress, encouraging legislation and citizen participation (Elmonshid, 2024). Implementing innovative energy consumption habits is crucial for governments to accomplish climate objectives and decrease carbon emissions

5. Conclusion and policy suggestion

5.1. Conclusion

This study investigates how economic freedom, trade openness, digitalization, and innovation influence renewable energy consumption across G20 nations. The findings confirm that all four factors significantly and positively impact renewable energy use, with innovation acting as a key mediator. Economic freedom reduces regulatory barriers and promotes market-driven investments in clean energy. Trade openness facilitates access to renewable technologies and international cooperation, while digitalization enhances system efficiency and data-driven energy management. Innovation strengthens each of these dimensions by improving the cost-effectiveness and performance of renewable technologies.

Unlike previous studies that analyze these factors in isolation, this research offers a holistic framework capturing their interconnected effects on renewable energy adoption. The use of advanced econometric techniques adds robustness to the findings. Policymakers are advised to adopt integrated strategies—promoting deregulation, open trade, digital infrastructure, and R&D investment—to advance Sustainable Development Goal 7 and lead the global energy transition.

Additionally, this research stands out by holistically examining the interconnected roles of economic freedom, trade openness, digitalization, and innovation in driving renewable energy consumption across G20 nations—an approach rarely adopted in the existing literature. Unlike prior studies that focus on isolated factors, this paper integrates a multifaceted framework that captures the synergistic influence of macroeconomic and technological enablers. Through the use of advanced econometric techniques, including Dynamic Common Correlated Effects (DCCE) and Dynamic Seemingly Unrelated Regression (DSUR), the paper provides robust empirical validation of these relationships. Furthermore, by introducing innovation as a mediating variable, the study pioneers a comprehensive analytical lens that reveals how policy design can leverage innovation to optimize renewable energy uptake. In conclusion, reiterating these novel aspects and the study's policy relevance—especially its alignment with Sustainable Development Goal 7—can significantly enhance the manuscript's contribution. Policymakers are offered practical insights on how to create enabling environments through deregulation, trade liberalization, and investment in digital infrastructure and R&D. This positioning not only underscores the study's academic originality but also elevates its value as a guide for sustainable energy policy in leading global economies. By explicitly articulating these unique contributions, the manuscript will more effectively convey its significance and stimulate further interdisciplinary research in the field of energy sustainability.

5.2. Policy suggestions

G20 countries have to put a variety of strategic policies based on strong economic, technical, and institutional frameworks into action if they are to include renewable energy into their energy mix. The adoption of market-driven solutions that lower obstacles to investment and foster innovation is central to this goal. Economic freedom plays a role in encouraging the acceptance of renewable energy sources as economically liberal countries are more likely to draw private sector investment and help implement clean energy technology. Policies that simplify permission procedures, defend property rights, and lower too-high government interference will help to establish an atmosphere fit for the growth of renewable energy markets.

Another important aspect is trade openness, as it helps renewable energy technology, knowledge, and money to circulate internationally. Emphasizes the need for international commerce in bridging technology gaps by showing how trade liberalization in African countries has permitted the spread of renewable energy technologies. Likewise, G20 countries may establish worldwide supply chains for renewable technologies, reduce tariffs on renewable energy components, and encourage cross-border research cooperation. The European Union's achievement of including renewable energy into its energy mix provides a real-world illustration of how well-coordinated trade policies may hasten the acceptance of environmentally friendly energy options.

Digitalization presents revolutionary chances for controlling and maximizing systems of renewable energy; that is, digital platforms maximize wind and solar energy facilities, thereby demonstrating technologies like smart grids, blockchain, and predictive analytics, improving energy efficiency and system integration. G20 countries should fund digital infrastructure supporting real-time energy monitoring and distributed energy systems if they are to maximize these advantages. For instance, the implementation of smart grid technology by South Korea has effectively reduced energy waste and raised the dependability of its renewable energy sources.

The adoption of renewable energy still depends mostly on innovation. Research and development (R&D) spending should be given top priority in G20 countries if we are to progress technologies such as enhanced solar panels, next-generation wind turbines, and energy storage, indicating that R&D spending not only helps renewable energy technologies to be more efficient and scalable but also helps to cut costs. Crucially, policies supporting public-private cooperation and financial support for green innovation should be followed. Germany's success in pushing solar energy via its feed-in tariff scheme and significant R&D financing shows the potency of such policies.

Finally, increasing public support for renewable energy projects depends on raising knowledge of these issues. Higher education degrees are linked with improved environmental awareness, which, in turn, boosts the acceptance of renewable energy solutions, according to research by Dincă *et al*. (2022). As shown in Sweden's cooperative wind farms, which let local inhabitants hold shares in renewable energy installations, G20 countries should start efforts to educate citizens about the advantages of renewable energy and include them in community-based energy projects.

5.3. Limitations and future direction of the study

This research has various limits, even if it provides insightful analysis of the factors behind the acceptance of renewable energy sources. It first concentrates only on G20 countries, therefore restricting the generalizability of results to less developed or smaller states. Furthermore, relying only on national-level statistics might hide regional and sector-specific differences in the adoption of renewable energy. The research also mostly stresses economic, commercial, digital, and creative aspects, therefore perhaps excluding the social and cultural variables influencing energy changes. By considering a larger sample of nations, especially emerging countries, to capture a more varied spectrum of energy transition dynamics, future studies may overcome these constraints. A deeper understanding of particular issues and possibilities might come from regional and industry-specific studies. Furthermore, including social, cultural, and behavioral elements in the study will help to provide a more complete knowledge of the acceptance of renewable energy. Finally, looking at the interaction between geopolitics and energy price policies might enhance future research projects.

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List of acronym

Acronym	Full Form		
GDP	Gross Domestic Product	EPO	European Patent Office
SDG	Sustainable Development Goal	FMOLS	Fully Modified Ordinary Least Squares
G20	Group of Twenty	FGLS	Feasible Generalized Least Squares
RE	Renewable Energy	PCSE	Panel Corrected Standard Errors
EF	Economic Freedom	DSUR	Dynamic Seemingly Unrelated Regression
TF	Trade Freedom	DCCE	Dynamic Common Correlated Effects
DIGI	Digitalization	DCCE-IV	Instrumental Variable-adjusted DCCE
TI	Technological Innovation	DH Test	Dumitrescu-Hurlin Test
EI	Environmental Innovation	SH Test	Slope Heterogeneity Test
ICT	Information and Communication Technology	CD Test	Cross-sectional Dependence Test
OECD	Organization for Economic Co-operation and Development	ITU	International Telecommunication Union
R&D	Research and Development	WIPO	World Intellectual Property Organization
IEA	International Energy Agency		

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