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Innovation Led Renewable Energy Consumption in OECD Nations: Evidence from Fourier Functions

Md Qamruzzaman*, Sharmin Rahman Swarna

School of Business and Economics, United International University, Bangladesh. *Email: qamruzzaman@bus.uiu.ac.bd

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ABSTRACT

This study investigates how technological, environmental, and financial innovations influence renewable energy consumption in OECD countries, with implications for sustainable energy transitions. Using CS-ARDL and Fourier-based econometric techniques, this study analyzes panel data from 2004 to 2022 across OECD countries to capture both symmetric and asymmetric relationships and long-run dynamics. Technological innovation significantly promotes renewable energy consumption, with a 1% increase leading to a 0.1385% rise in the long run. Environmental innovation also fosters renewable adoption (0.1273%), driven by green policies and eco-technologies. Financial innovation exerts the strongest effect (0.1891%), highlighting the role of green finance, bonds, and inclusive financial mechanisms. However, global uncertainty negatively impacts renewable energy investment and usage (−0.1215%). Control variables like financial development show a positive effect, while natural resource rents inhibit renewable uptake. Strong long-run equilibrium adjustment ensures model stability. These results underscore the synergistic value of innovation and governance for advancing energy sustainability in OECD nations. This study is novel in integrating technological, environmental, and financial innovation dimensions using a Fourier-based CS-ARDL approach, accounting for cross-sectional dependence and nonlinearity. It uniquely captures asymmetric effects across OECD nations and links macro-level innovation drivers to renewable energy consumption in the context of uncertainty and institutional quality. Governments should enhance green finance mechanisms, incentivize R&D in clean technologies, and ensure institutional stability to stimulate innovation-led renewable energy transitions aligned with climate and sustainability commitments.

Keywords: Innovation, Renewable Energy, OECD, Financial Innovation, Sustainability
JEL Classifications: Q42, O31, G23, C33

1. INTRODUCTION

Consumption of renewable energies has become a paradigm changer worldwide, transforming the energy scene and constituting an important factor in bringing solutions to pressing global issues like climate change, energy security, and sustainable development Iqbal et al. (2021). Methane generation is increasingly receiving attention as an important renewable energy source and a means of managing greenhouse gases. Adebayo (2022). The growing depletion of fossil energy reserves, massive fossil energy consumption emissions and pollution, coupled with increased global interest in climate change Obobisa et al. (2022), have all spurred interest in the identification and use of alternative energy sources. These events have catalyzed the rapid progressive adoption of renewable energy sources (solar, [4] wind, [5] hydroelectric, [6] biomass, [7] and geothermal [8]) for the drastic recovery of traditional systems. This transition is driven by increasing worries about greenhouse gas emissions, dwindling fossil fuel deposits, and the adverse environmental effects of traditional energy generation. One of the most prominent impacts of RE consumption is its significant contribution to climate change mitigation. As a result, it is a healthier and more sustainable alternative to traditional fossil fuel-based energy production Su et al. (2021). Renewable energy helps to reduce the global carbon footprint by replacing coal, oil, and natural gas in the energy flow, which leads to reduced carbon dioxide and some other harmful output pollutant emissions Bashir et al. (2023). This crucial contribution is rooted in goals set in the Paris Agreement, where countries pledged to limit global warming to well below two degrees Celsius above pre-industrial levels. Moreover, no less underestimated are the broader economic implications of the dramatic growth of renewable energy, such as investment, job creation, and industrial development. The renewable energy industry has emerged as a new dynamic for the economy, followed by the influx of major capital investments in R&D and the implementation of clean energy technology Zhen et al. (2022). As a result, it facilitates innovation and technology while creating jobs across multiple industries, supporting local economies, and encouraging sustainable development. In addition, renewable energy enhances energy security and diversifies the energy mix, thereby decreasing dependency on imported fossil fuels and increasing energy resilience Su et al. (2021). By leveraging natural capabilities, countries can tap into plentiful and home-grown renewable resources, thus mitigating dependence on price and geopolitical volatility stemming from importing fossil fuels Obobisa et al. (2022). It allows countries to create energy systems that are self-sufficient and sustainable which will protect them from interruptions in energy supply and volatility. Beyond the aforementioned advantages, meteorological and climate energy deployment creates social and environmental co-benefits Archer and Idun (2023). The access to renewable energy sources increases the availability and affordability of energy for marginalized communities, especially in remote areas. Such energy democratization brings power back to households and neighbourhoods, promoting socio-economic development and helping to combat poverty Habiba et al. (2022). At the same time, renewable energy initiatives often encompass environmental protections and sustainable practices, which help to protect biodiversity, conserve natural resources, and prevent ecological destruction Kahia et al. (2022). Nevertheless, several barriers exist to the full realization of renewable energy. A wide range of initial barriers preventing the increased deployment of renewables include infrastructure limitations, the initial costs of grid integration, intermittency concerns, and many institutional rigidities Zheng et al. (2022). Overcoming these challenges will require collaboration among policymakers, businesses, and stakeholders to facilitate a smooth energy transition Olanrewaju et al. (2022). Renewable energy consumption has an impact on the economic, social, and security parts of the global world as well as environmental impact Guo et al. (2021). As the world embarks on a collective effort to create a sustainable future, renewable energy is at the forefront of this transformative journey towards a low-carbon, resilient and inclusive energy future Usman et al. (2022). The relentless effort in the domain of renewable energy adaptation will, without a doubt, determine development worldwide and will safeguard the earth for ages to come Kahia et al. (2022).

Systems of renewable energy consumption are complex, multi-dimensional constructs made up of various elements that collectively shape the unique patterns of renewable energy use and integration in countries around the world. As countries realize the need for a sustainable energy future, it is essential to understand these determinants and formulate policies and strategies that encourage the use of renewable energy. This holistic review provides an overview of the root causes of renewable energy usage based on previous studies and empirical views. In addition, policy and regulatory frameworks are the cornerstones of the use of renewable energy. One of the main catalysts of renewable energy uptake is the presence of supportive and robust policy frameworks Kahia et al. (2022). Incentives (such as grants, subsidies, feed-in tariffs, tax credits, renewable portfolio standards, etc.) from the government can motivate investment and deployment in the renewable energy sector Wang et al. (2020). Having definitions and stable regulations encourage certainty for investors, leading to the potential for long-term investments in renewable energy projects Jamshidi et al. (2023). Advancements in technology are vital to improving the efficiency and cost-effectiveness of renewable energy technologies Fang (2023). These ongoing research and development activities lead to improved solar panels, wind turbines, energy storage systems, and bioenergy processes, making renewable energy more competitive than conventional fossil fuels Sibt-e-Ali et al. (2023). The cost-effectiveness of renewable energy projects is a key reason behind their adoption Kahia et al. (2022). With cheaper renewable technologies, decreasing levelized electricity costs (LCOE), and improving competitiveness with fossil fuels Zhen et al. (2022). The adoption of renewable energy sources is driven by increasing demand for energy and growing concerns about energy security Sharma et al. (2021). Thus, countries aim to shift their energy balance by reducing their dependency on imported fossil fuels and increasing energy self-sufficiency via domestic renewable resources You et al. (2022). A growing awareness of the high environmental cost of fossil fuel-based energy production (e.g. greenhouse gas emissions and air pollution) drives the transition towards cleaner and lower-carbon renewable energy sources Ali et al. (2021). Renewable energy is considered an effective way to reduce climate change and preserve environmental quality Ahmad et al. (2021). Global action on climate change will enable renewable energy investment. For example, international agreements and commitments like the Paris Agreement are putting pressure on countries to decrease carbon emissions and shift to renewable energy Li et al. (2020). The energy sector needs to speed up its transition to renewable energy, aligning with global climate targets. The sales and availability of renewable resources (sunlight, wind, water, and biomass) are contributing factors to the enabling of renewable assets development in different regions. Geography is a key discriminator of suitable renewable technologies Guo et al. (2021). Human-human interaction is invaluable given the capital of big data and human-machine synergy. Venture capital, private sector investment, and affordable financing help pace the uptake of renewable Khan et al. (2021). Also, integrate it with infrastructure and the grid. Both the presence of reliable and strong energy infrastructure, like smart grids and energy storage systems, enhance the integration of fluctuating renewables into the existing energy grid Bashir et al. (2023). One of the most important factors in creating demand and acceptance for renewable energy is the perception and knowledge of renewing energy within the public. This can be achieved via education and awareness campaigns to dispel misconceptions and to stimulate public support for renewable energy initiatives Su and Gao (2022). Renewable energy needs a stable political environment, which ensures competent governance to fulfil its potential. Long-term planning and implementation need to maintain consistent policies and strong political commitment Su et al. (2021). Involving local communities and considering possible social concerns such as land use and environmental impacts are key to achieving social acceptance and ensuring the sustainable development of renewable energy systems Archer and Idun (2023). The transition of renewable energy towards the widespread use of renewable energy for the planet is driven by significant environmental advantages including Olanrewaju et al. (2022). It needs to be dealt with urgently by the men in power, entrepreneurs and individuals in order to save the Earth from disastrous conditions e.g. climate change, and renewable energy has turned out to be the most favourable Abbas et al. (2022). Government plans for strict environmental regulations, emission reduction objectives and commitments to international climate agreements drive the demand for renewable energy. Countries and regions with high climate targets are more likely to invest in renewable energy infrastructure to achieve carbon neutrality and sustainable development Iqbal et al. (2021). Renewable energy demands, in particular, relevant paradigms of financial innovation such as green finance and sustainable investment instruments Ben Belgacem et al. (2023). Green bonds, climate funds, and impact investments work to absorb capital into renewable energy projects, thus facilitating their financial viability and lowering perceived investment risk Khan et al. (2020b). The availability of capital and the mechanism for funding affect the growing scope and pace of renewable energy adoption. Innovative financing models (crowdfunding, peer-to-peer lending, etc.) that foster community involvement and democratize access to renewable energy projects Ben Belgacem et al. (2023). Risk mitigation and insurance products. Financial innovations cover risk mitigation and insurance products tailored to renewable energy projects. Insurance from weather-related risks, political instability, and technological malfunction supports investor confidence and leads Najam (2023) to invest in renewable energy. In addition, Financial Innovation also facilitates research and development (R&D) for renewable energy sources. Ali et al. (2021). To tap capital into renewable energy initiatives, governments and financial institutions provide green investment incentives (e.g. preferential loans and tax benefits) Ramzan et al. (2023). But they are left adding up His-interest on-future Risk: Don't encourage sustainable investments. Environmental, Social, and Governance (ESG) Factors Environmental, social and governance (ESG) considerations become an essential component of investment decision-making. Such a preference is accorded to firms and initiatives that exhibit a robust ESG footprint, such as a promise to transition to green energy and environmental sustainability Kahia et al. (2022). Green banking refers to the integrated approach of financing that financial institutions adopt so as to maintain their path most aligned with the environment, through providing sustainable finance solutions. It sponsors projects for renewable energy and helps mitigate financial-related risks due to the climate Anton and Nucu (2020). Innovations in Financial Technology (FinTech) like blockchain technology and digital currencies provide new ways to finance and transact with renewable energy. These technologies accelerate financial processes and market transparency in renewable energy sector Sibt-e-Ali et al. (2023).

With countries striving to achieve their climate goals and curtail carbon emissions, there is a pressing need for new solutions that can transition energy generation from fossil fuels to renewables Abbas et al. (2022). Advancements in technology have led to improvements in the efficiency and cost of renewable energy technologies, including solar photovoltaics, wind turbines, hydropower systems, and bioenergy. Through environmental innovation, the performance of these technologies has improved significantly, resulting in greater competitiveness with traditional energy sources. Environmental Innovation also covers energy conservation and demand-side management in addition to energy production Olanrewaju et al. (2022). Innovations such as advanced grid technologies, energy storage systems, and demand response mechanisms not only optimize energy consumption but also assist in integrating intermittent renewable energy sources into the infrastructure Khan et al. (2020b). The renewable energy revolution is being driven by technological innovation. Over the past decade, technological breakthroughs have enabled renewable energy to be more frequently deployed Fang (2023). Technological advancement enables renewable energy technologies to become more sustainable, deployable, and affordable. The factor of technological innovation refers to improved energy conversion efficiencies, lifespan, and smaller negative impacts for new renewable energy technologies, which helps in the early adoption of renewable energy Zang et al. (2023). These advancements help to broaden the array of renewable energy solutions that are technically and financially viable and increase their competitiveness in the market. As an example, the third generation of solar cells and photovoltaic materials, which show the potential to provide higher energy yields at lower production costs, have been developed through continued research and development into solar energy Sun et al. (2022). Similarly, innovations in wind turbine design and materials have generated larger, more efficient turbines that harness wind energy more effectively. In addition, technological innovation in energy storage technologies can also solve the intermittent characteristics of renewable energy sources Liu et al. (2022). Through energy storage systems like batteries and pumped hydro storage, excess renewable energy can be stored and discharged when demand is high or generation is low Liu et al. (2022). Financial innovation, as it helps mobilise capital and invest in renewable energy projects, is a key facilitator of renewable energy consumption. Financial innovation provides its financing mechanisms with the novelty that makes renewable energy projects economically attractive to investors, minimizing the amount of capital needed upfront Su and Gao (2022). Financial innovations for renewable energy projects include green finance, sustainable investment instruments, and impact investing Ben Belgacem et al. (2023). Financial innovations for renewable energy projects include green finance, sustainable investment instruments, and impact investing Cao (2023). For instance, green bonds are intended to fund environmentally sustainable ventures like renewable energy projects. In addition to this, financial innovation can reduce the perceived risks of investing in renewable energy sources, making them attractive to investors Haldar and Sethi (2022). Specialized insurance products for renewable energy projects, weather derivatives, and risk-sharing arrangements enhance investor confidence and reduce financial risks Ben Belgacem et al. (2023). Moreover, financial innovation fosters financial inclusion in the renewable energy sector, enabling access to affordable financing for underrepresented communities and small-scale renewable energy projects. Microfinance and crowdfunding platforms allow local communities to invest in renewable energy projects and contribute to sustainable development Bakhsh et al. (2023).

Synergies between the environment, technology, and finance drive the upsurge of renewable energy usage (Qamruzzaman and Kler, 2023). Environmental innovation encourages the exploration of both sustainable/effective renewable energy technologies, while technological innovation enhances both their performance and their ability for grid integration Sahoo et al. (2022). On the flip side, financial innovation aggregates the necessary capital and minimizes financial risks to ensure renewable projects are lucrative and attractive to investors Kahia et al. (2022). Harnessing the synergy effect of these innovations can facilitate the transition of nations to a sustainable energy future and attain the target of renewable energy consumers Khan et al. (2020a).

Using Fourier function analysis, this study seeks to achieve five primary goals regarding innovation-led renewable energy consumption in OECD countries. Firstly, it seeks to evaluate the effectiveness of technological innovation in the growth and efficiency of renewable energy utilization, exploring the role of clean energy technologies, smart grids and storage solutions in facilitating sustainable energy transitions. Second, it examines how environmental innovation facilitates renewable energy adoption, postulating to what extent environmental policies, renewable energy incentives, and eco-friendly infrastructure are related to the lessening dependence on fossil fuels. Third, it assesses the role of financial innovation for renewable energy investments by exploring how green finance, impact investing, and innovative financing mechanisms contribute to a faster rollout of clean energy. Fourth, the study analyzes how the quality of institutions and policy frameworks affect the renewables landscape, seeking to establish whether regulatory stability, efficiencies of governance, and policy consistency act as either a facilitator or barrier to people adopting renewables. Finally, it investigates the role of economic complexity on long-term renewable energy sustainability, e.g. are highly developed, knowledge-intensive economies better equipped to sustain renewable energy transitions in the long term?

Based on the above objectives, the research questions guiding the study are as follows: RQ1: How has technological innovation been acting in the Netherlands on the transition and implementation of renewable energy generation build-up speed in OECD countries? RQ2: How does environmental innovation promote the transition towards a renewable energy-based economy? RQ3: How does financial innovation help increase investment and financial accessibility for renewable energy projects? RQ4: Which role institutions and policy frameworks play in the stability and efficiency of renewable energy transitions? RQ5: Is economic complexity a facilitator or a barrier to the long-term sustainability of renewable energy consumption?

2. LITERATURE REVIEW

2.1. Environmental Innovation led REC

Some studies confirm the positive association between environmental innovation and REC. Usman et al. (2022) determined how environmental technologies, investments, and expenses affected pollution in 15 European nations from 2005 to 2018. Panel econometric estimation finds a long-term stable relationship between variables. Environmental innovations, expenditure, research and development, and foreign direct investment reduce non-renewable energy use and promote renewable energy. Environmental investment diminishes renewable energy and boosts non-renewable energy. Causality tests show that energy usage drives environmental investment, expenditure, and FDI and that environmental innovations and R&D drive energy usage. The study suggests employing innovative methods to switch from non-renewables to renewables for efficient and sustainable energy use. Similarly, Ramzan et al. (2023) analyse how green innovation and financial globalization affect environmental sustainability and energy transition (ln) in the UK. The study finds unidirectional causality between lnGRN and lnFIG and lnEFT and lnENT using quarterly data from 1995 to 2020 and a time-varying rolling window approach. lncRNA, lnFIG, and lnGDP reduce lnEFT and increase energy transition. However, lnGDP, lnETX, and lnFIG harm the environment and the energy transition. The paper recommends policies to promote financial globalization, green innovation, renewable energy, and environmental taxes. Also, Adebayo (2022) discusses load capacity factor (LCF), fossil fuel (FF), renewable energy (REC), economic complexity (ECI), and foreign direct investment (FDI) in Spain from 1970Q1 to 2017Q4. LCF and exogenous factors are analyzed using wavelet coherence at various frequencies and timeframes. The wavelet-based Granger causality study shows bidirectional predictive correlations between all variables at various frequencies. Zhao et al. (2022) used the Environmental Kuznets Curve theory to investigate the relationship between solar energy, eco-innovations, and carbon emissions in G7 countries from 1995 to 2018. Using panel estimation techniques, it is determined that solar energy and eco-innovation substantially negatively impact carbon dioxide emissions over the long term. The study suggests investing in environmentally friendly technologies and promoting the adoption of eco-innovations and solar energy to resolve environmental challenges and guide the development of policies for environmental degradation. This study by Kahia et al. (2022) evaluates the economy of Saudi Arabia for the period from 1990 to 2018 through several econometric techniques. Using data from October 2023, the Environmental Kuznets curve hypothesis is rejected, ultimately indicating that increasing economic growth leads to further degradation of the environment. study by Abbas et al. (2022), energy investment and innovation in the long-term mitigation of CO_2 emissions. This is why policymakers across the BRICS nations should lean into these factors for environmental sustainability in their countries. In this current research, Olanrewaju et al. (2022) evaluate environmental challenges in G7 countries using data from 1990 to 2019. It finds that renewables and environmental innovation reduce CO_2, while nonrenewable energy and trade openness increase it. It is about time for policymakers to focus on eco-friendly innovations to tackle environmental degradation while looking for sustainable sources of energy to help the planet in the long run. Iqbal et al. (2021) evaluate the role of export diversification, environmental technologies innovation, and fiscal decentralization in achieving carbon neutrality targets across 37 OECD economies from 1970 to 2019. Sophisticated cointegration methods, along with AMG, are used to analyze the long-run dynamic equilibrium of the variables. Export diversification, fiscal decentralization, GDP growth and renewable energy use all have positive effects on carbon emissions, but environment-related technical innovation helps the environment. In the short term, fiscal decentralization, export diversification, and environment-related technological innovation lead to carbon emissions. The report states that prudent fiscal and export policies, increased renewable energy consumption, and technological innovation are the key components of achieving climate change mitigation and sustainable development goals in OECD countries. Su et al. (2021) examines fiscal decentralization, environmental innovation and other factors in seven OECD countries from 1990 to 2018. According to empirical research, fiscal decentralization and environmental innovation increase renewable energy consumption and diminish non-renewable energy use. Improved political risk index and renewable energy R&D boost renewable and decrease non-renewable energy consumption. Fiscal decentralization empowers local governments to improve energy efficiency and move countries away from fossil fuels. These policy consequences support the Paris Climate Agreement and environmental sustainability. This research by Guo et al. (2021) investigates China's carbon neutrality aim using provincial and regional statistics from 1995 to 2017. The panel cointegration test shows that CO_2 emissions and its determinants—income, green innovation, renewable energy consumption, and energy industry investment—are constant across time. Major structural fractures at local, regional, and global levels affect CO_2 emissions. Income, environmental innovation, energy industry investment, and renewable energy usage explain how they control CO_2 emissions over time, confirming the environmental Kuznets curve concept. The study emphasizes the need to convert the Chinese economy to more sustainable energy sources and supports green innovation and investments to address environmental degradation.

Ali et al. (2021) evaluate how trade and CO_2 emissions in the top 10 carbon emitter countries are affected by environmental innovation, trade, and renewable energy usage from 1990 to 2017. CO_2 emissions and income are in long-term equilibrium. Environmental innovation, trade, renewable energy use, and income explain long-term consumption-based and territory-based carbon emissions. The report emphasizes the need for ecologically friendly policies and renewable energy to counteract the environmental impacts of economic expansion and reduce greenhouse gas emissions. Khan et al. (2020a) employ advanced panel co-integration methods to determine G7 countries' 1990-2017 CO_2 emissions. CO_2 emissions, trade, income, environmental innovation, and renewable energy usage have been steady. Exports, environmental innovation, and renewable energy cut consumption-based carbon emissions, whereas imports and income increase them. Statistical tools support eco-friendly policies like supporting renewable energy technology for sustainable development. Policymakers should target exports, imports, revenue, and environmental innovation to address environmental concerns and reduce carbon emissions. Li et al. (2020) also look at the determinants of renewable energy consumption in OECD economies from 1990 to 2017. The Durbin-Hausman group mean cointegration test confirms long-term equilibrium among variables. Long-term renewable energy usage is favourably and strongly influenced by income, human capital, energy productivity, energy prices, and environmental innovation. The AMG approach verifies model robustness. Policies should enhance renewable energy in the energy mix to alleviate environmental issues and satisfy Paris Climate Agreement goals. Wang et al. (2020) evaluate G-7 countries' 1990-2017 carbon emissions, ecological innovation, and export diversification. Export diversification raises carbon emissions, but environmental innovation and renewable energy usage lower them. Positive environmental technologies mitigate the carbon emissions of export diversification. The study says G-7 countries should support renewable energy and green technology. It also indicates that government efforts at export diversification, ecological innovation and renewable energy use might take more than a year to lead to carbon emissions reductions. The study conducted by Khan et al. (2020b) examines the impact of eco-innovation and human capital on various energy sources. The panel cointegration method and the AMG method perform an analysis of data from 1995 to 2017, G-7 countries. A negative correlation is observed for R&D, total and non-renewable energy, energy price, eco-innovation, and human capital. Role of Financial Development in the Total/Non-Renewable Energy Use We found that human capital, eco-innovation, energy prices, and R&D spending have a facilitating effect on renewable energy use. But financial development reduces it. An investment in human capital and the formulation of regulations and policies in the financial sector, incentivizing eco-innovation, are both suggested in the report. Ahmad et al. (2021) fill the knowledge gap in environmental economics by introducing the innovation shocks in the EKC equation considering the twenty-six OECD economies from 1990 to 2014. The control variables are FDI, exports, renewable energy consumption, and GDP per capita. Positive innovation shocks enhance environmental quality, whereas adverse innovation shocks have the opposite effect. In the sampled economies, the analysis confirms the existence of EKC and the Pollution Halo Hypothesis (PHH). In addition, it emphasizes the incorporation of innovation shocks as a policy instrument for improved environmental policies and a sustainable future.

2.2. Technological Innovation and REC

Numerous studies must show evidence of a positive relationship between technological innovation and REC. The 32 Chinese provinces' carbon dioxide factors determining emissions from 2005 to 2019 are presented in the work of Fang (2023). These are the economic complexity index, energy sector investments, green technological innovation, and industrial structure growth. The data analysis applies advanced econometric methods, including cross-sectional dependency, unit root, co-integration, and models using GMM. The findings indicate that the economic complexity index is a contributor to the increase in carbon dioxide emissions. At the same time, they square, renewable energy, green technologies, and industrial structure show a negative effect on emissions. Sibt-e-Ali et al. (2023) also examined the role of technological innovation (TI), natural resources, globalization, and renewable energy consumption (REC) on environmental degradation across East and South Asia from 1990 to 2021. Globalization, TI, and REC lower regional emissions, whereas lots of natural resources are degrading the environment. This would mean that economic growth lowers environmental quality. Regional governments, the report claims, should "encourage more efficient use of natural resources via technology breakthroughs" and align energy consumption, globalization and economic growth policies with sustainable environmental objectives.

Javed et al. (2023) analyze the implications of green technology innovation (GTI), environmental taxes (ET), renewable energy consumption (REN), trade openness (TO), and GDP on Italy's ecological footprint (EFP) during the years 1994-2019. Using a dynamic simulated ARDL (DYARDL) model and a frequency domain causality (FDC) test, this study finds long-term cointegration among the variables. EFP, GTI, ET, and REN are correlated positively, while TO and GDP are negatively impacting the environment. Policymakers should promote green innovation and renewable energy investments to achieve ecological sustainability. Moreover, Zang et al. (2023) In line with this perspective, Hossain et al. The CS-ARDL method provides evidence of a long-term relationship between these variables and ecological footprint. Economic performance positively influences the environmental impact, while green energy and technical efficiency provide the foundation for sustainable development. The research indicated the use of renewable energy and green technology for sustainable European Union development. This study by Sun et al. (2022) explores the roles of both economic complexity and renewable energy in carbon emissions mitigation in BRICS countries. The results show, based on data from 1995 to 2018, that economic complexity and renewable energy reduce emissions, especially at higher emission levels, using the Method of momentum quantile regression. This relationship is reinforced through the interplay of the two variables, which further proves that economic complexity leads to a relatively higher reduction of carbon emissions through the renewable-energy transition. The results highlight the importance of investing in renewable energy and technology, innovation, human resources, and research and development to increase the complexity of economies and the sustainability of their environmental consequences. Similarly, Su and Fan (2022) use a spatial Durbin model (SDM) to analyze green development in 30 provinces and municipalities across China between 2013 and 2019, focusing on the relationships between renewable energy technology innovation and industrial structure upgrading. The findings show that renewable energy technology innovation and industrial structure rationalization have a positive impact on green development. On the contrary, upgrading industrial structures hinders their progress. Moreover, the innovation of renewable energy technology and the upgrading of industrial structure have mutually exclusive characteristics in their interaction, which inhibits their respective positive impact on green development. Nevertheless, the synergy of renewable energy technology innovation and industrial structure optimization can effectively promote the positive effect of renewable energy technology innovation on green development while curbing the negative effect of industrial structure optimization.

Ge et al. (2022) conducted a study on how renewable energy technological innovation (RETI) and green finance affected the industrial structure of China. PVAR model results confirm that RETI has played an important role in optimizing structure in these two dimensions. The results of threshold regression show that the relationship between RETI and industrial structure is nonlinear; the greater the green finance, the more balanced the effect. RETI has effectively facilitated the upgrading of industrial construction in eastern China. Thus, policymakers should focus on cultivating green finance and rolling out relevant green credit policies to stimulate renewable energy technology innovations. Jiang and Khan (2023) examine the impacts of technology improvements on renewable energy consumption and CO_2 emissions in Belt and Road Initiative countries from 1995 to 2019. Technological advances increase renewable energy use and CO_2 emissions all of these mentioned are eco-friendly; even by making trademarks, we are making sustainable marketing forms, which all lead to better environmental quality by reducing carbon dioxide emissions. The analysis confirms the Environmental Kuznets curve hypothesis in the sample countries. These results indicate that there is a need for technical innovation and renewable energy regulation for environmental sustainability in these nations. Obobisa et al. (2022) investigated CO_2 emissions in 25 African countries from 2000 to 2018 in relation to green technological innovation, institutional quality, renewable energy, fossil fuel energy, and economic growth. CO_2 emissions are reduced by, e.g., institutional quality, economic growth, and use of fossil fuel, but counterintuitively not by green technical innovation and renewable energy consumption. The report claims that African countries must consider investing in green technology and renewable energy, to allow for sustainable growth over traditional coal economies. This study by Habiba et al. (2022) also investigates the impact of socio-economic development, green technological innovations, and the consumption of renewable energy on carbon emissions (CE) for the 12 biggest polluters between 1991 and 2018. CE is increased by enhanced financial development and reduced by green technology and renewable energy consumption. Bidirectional causal relationships exist in generative causalities between financial development, green technology developments, renewable energy consumption, and CE.

In contrast, unidirectional causalities are seen for evoked causalities in both nonrenewable energy consumption, per capita income, and trade openness. It is anticipated that green technologies and growth transitions will progressively reduce CE through improved energy efficiency and fossil fuel consumption. These results can assist policies in sustaining CE with sustainability objectives. In this study, Khan et al. (2022a) examined the relationship between information and communication technology (ICT), renewable energy consumption, and innovation on carbon dioxide emissions in BRICS nations from 1990 to 2019. According to the findings, factors that harm carbon emissions are ICT measures, economic growth, and financial development. Without the ICT indicators, other factors cut emissions or raise emissions dramatically, such as innovation and renewable energy consumption, while trade openness and fixed telephone subscribers pushed emissions up. The study results suggest that such improvement in environmental quality in the countries can be achieved through coupling ICT expansion with innovation and financial development. The implications of these findings are considerable for the policymaking process of BRICS countries. Another research by Adebayo et al. (2022) uses the Morlet wavelet technique to demonstrate the structural dynamic relationship between CO_2 emissions, economic growth, renewable energy consumption, trade openness, and technical advancement in Portugal from 1980 until 2019. Overall, the frequency domain shows wavelet coherence and lead and lag linkages, while the time domain depicts opposing interactions. Trade openness, technical innovation, and economic expansion drive CO_2 emissions, while, on the contrary, the use of renewable energy decreases them in the long run. Policymakers can work to encourage increasing investment in renewables, the use of restrictive legislation, and innovation through the energy system, with environmental implications in mind in Portugal. This study by Zang et al. (2023) proposes an SDG framework to help Spain meet SDGs. It examines the impact of GDP growth, technological innovation, and non-renewable and renewable energy sources on CO_2 emissions in the EU from 1980 to 2018. By the nonlinear autoregressive distributed lag (NARDL) approach, positive shocks in renewable energy and technical innovation enhance environmental quality, while positive shocks in energy consumption worsen CO_2 emissions generation.

There you go, as such studies exist with both positive and negative associations. Ibrahim and Ajide (2021) examine the impact of renewable energy, nonrenewable energy, trade openness, and technology on G-7 CO_2 emissions between 1990 and 2019. Renewable energy decreases carbon dioxide emissions, while nonrenewable energy and trade openness increase emissions. CO_2 emissions are reduced considerably with research development and eco-innovation. Environmental Kuznets Curve validated. The research suggests wide disparities in environmental impact across G-7 countries. This study by Vural (2021) analyses renewable energy production for certain Latin American countries from 1991 to 2014. It finds that GDP, technological innovation and trade promote renewable energy, while carbon emissions have negative effects. Read the full press release: Interdisciplinary research report on Sustainable Energy Policies: A Recommendations Report. Khan et al. (2022b) Germany — empowering information: (2022b) LOGGER advancing technologies and energy sources L118 Development technologies rapidly impact renewable energy after 2000 until 2021. From the rolling window method, we see that technological progress can have a positive and destructive effect on the vulnerability of renewable energies over time. Renewable energy also has an impact, suggesting that technology innovation technology innovation investment encourages breakthroughs. The research highlights the importance of balancing weather-dependent energy sources in future energy supplies.

2.3. Financial Innovation and REC

Moreover, the literature review discusses financial innovation, renewable energy consumption, and environmental sustainability across regions and contexts. Nevertheless, the key studies show that financial innovation and renewable energy can reduce environmental degradation and provide sustainability. For example, Kirikkaleli (2023) and Najam (2023) present evidence on how financial innovation and usage of renewable energy curb environmental degradation and carbon emissions in the case of India and Asian countries, respectively. These studies inscribe sound evidence on the zero-carbon Environmental Kuznets Curve hypothesis, which asserts that with the proper green finance mechanisms and sustainable practices, we can achieve an effective zero-carbon transition throughout society. Augmenting the model, Cao (2023) studied the impact of energy diversification on economic growth in China, and the results indicate that energy diversification can promote long-term economic growth. However, its effect on economic growth in the short term may be negative in some circumstances. Studies by Ben Belgacem and co-workers65 Supporting this, recent works by Ben Belgacem et al. (2023) and Qamruzzaman and Kler (2023) have addressed the role of renewable energy and financial innovation for sustainability in Emiratis, Saudi Arabia, and Bangladesh. They also highlight the need for policies that will improve the performance of SMEs and protect the environment. There are some previous studies on this aspect, such as Jamshidi and Meybodi (2024), Zhan et al. (2023), and Su and Gao (2022), target the EU and China and investigate how to curb CO_2 emissions via financial innovation and green finance. They summarize that green financial measures and regulatory systems are very important to protect the environment and ensure economic sustainability. Likewise, Haldar and Sethi (2022) identify the use of ICT and renewable energy, as well as the reduction of emissions in emerging economies. In contrast, Archer and Idun (2023) and Assi et al. (2021) report negative relationships between financial innovation and sustainable development in Africa and the ASEAN+3 region, respectively. They conclude that although financial outreach appears to decrease carbon emissions, it also risks compromising social sustainability and renewable energy demand in some contexts. In general, the literature highlights the intricacies of the connection between financial innovation and renewable energy and sustainability. Notice that Most of these include promoting either green finance or renewable energy to achieve environmental and economic goals, whereas a number of others pointed out that the effect of these two articles varies significantly that depends on regional and economic conditions. This dynamics are relevant for any dynamics and should to further investigate not only for the aspects of geography and economic settings. Ultimately, such approaches should be use to design specialized and explore more tailored policy recommendations against the development sustainable. . Table 1 displayed the summary literature of the study.

3. DATA AND METHODOLOGY OF THE STUDY

3.1. Theoretical Foundation of the Study

Thus, the mechanisms of generating innovation are designed to work especially intensively in OECD countries, dominating the transition to renewable energy consumption at the expense of technological, environmental and financial innovation. These innovations are influencing the adoption of renewable energy solutions, sustainable practices and effectiveness. Based on these theoretical perspectives and the OECD countries as context, the study explores the effect of environmental innovation, technological innovation, and financial innovation on renewable energy consumption.

Regarding Environmental Innovation and REC, The Environmental Innovation Theory suggests that the development of environmentally sound technologies and processes is essential for sustainable energy solutions. As clean technologies, like low-carbohydrates technologies, energy-saving devices, and green production, become prevalent, the uptake of renewable energy sources becomes swift. Porter's Hypothesis suggests that environmental regulation can catalyze firms to produce new, cleaner technologies that comply with environmental regulations. In OECD countries, strong environmental policies and incentives, prompting firms to engage in green innovation, often catalyze this process Porter and Van der Linde (1995). Similarly, Eco-Innovation Theory elaborates how environmental innovations can contribute to both economic and environmental benefits by reducing the ecological footprint but also by providing opportunities for the development of new markets (del Río González, 2009).

In terms of Technological Innovation and REC: The central role of technological innovation in the wider adoption of renewable energy technologies The Schumpeterian Growth Theory reminds us that sustainable long-term economic growth relies on innovation. In the field of renewable energy, for example, technological developments, including improvements and innovations in solar, wind, and battery storage, are crucial for slashing prices and enhancing the productivity of renewable energy systems. The innovation theory emphasizes the transformation of an economy, focusing on energy consumption that is not left behind. Innovation in energy consumption is the core of developing new technologies that would significantly enhance energy use efficiency and substitution with renewable sources of energy Jin et al. (2018). Theory suggests that innovative processes will be able to significantly decrease the energy intensity of economic activities to result in a more sustainable pattern of energy consumption. Furthermore, Schumpeter's theory highlights the key role of technological progress in economic growth and structural change Zhou et al. (2021). This perspective puts great emphasis on innovation in the new products, services, and processes that could increase productivity and efficiency. In terms of energy use, that would mean, for example, that energy-technology innovation possibly leads to effective energy use, less waste, and maybe even a change from dirty to cleaner, renewable alternatives. This phenomenon is supported by the Technology Diffusion Theory, in the sense that technological innovation crosses the borders with trade and investment, meaning that the adoption of state-of-the-art renewable technologies in OECD countries occurs at a much faster rate. This idea is kept in line with Endogenous Growth Theory, which states that innovation in the energy sector stimulates economic growth but also fosters the shift to less carbon-intensive energy systems (Romer, 1990). On the other hand, Technological Lock Theory warns that existing energy infrastructures, if they do not innovate enough, can hinder the rapid uptake of new green technologies (Foxon, 2014).

Concerning financial innovation and REC, financial innovation theory suggests that new financial instruments and mechanisms (e.g., green bonds, green funds, renewable energy finance) can significantly enhance investments in renewable energy projects. In capital-intensive projects such as wind and solar farms, financial innovation is critical to lowering the cost of capital for renewable energy firms. As elaborated within Inclusive Green Finance Theory, innovative use of financial instruments improves financial inclusion in a way that makes renewable energy investments available to larger groups of actors, which may go beyond firms to small businesses or household installations (Samour et al., 2022). The Green Finance Theory complements this by promoting environmental criteria within the financial decision-making process, which will help catalyze private investments in the provision of sustainable energy solutions (Weber, 2014). Financial innovation plays a critical role here as it helps minimise risks related to the context of renewable energy investments, notably by creating financial products that alleviate long-term uncertainty and upfront capital costs.

Also, the theory of institutional complementarity states that the efficacy of one type of innovation is frequently improved when it accompanies complementary institutional frameworks. Such as environmental and technological innovations are always grounded in the presence of strong financial institutions and solid policies, which ultimately lead to a stable investment environment (Sart et al., 2025). For the mix of these theories, this analysis investigates the repercussions of environmental, technological, and financial innovations on the consumption of renewable energy in OECD countries through time series Fourier functions, allowing for non-linearity and potentially complex, non-linear relationships between multivariate data series and their trends over time.

3.2. Model Specification

The motivation of the study is to gauge the impact of innovation, such as financial innovation, environmental innovation, and technological innovation, on the progress in clean energy consumption in EU nations for the period 2004-2022. The generalized equation is as follows.

$$REC \int FI, TI, EI \quad (1)$$

Following the literature, the above equation (1) has been extended through the inclusion of a list of control variables, which are financial openness (FO), globalization (GLO), and institutional quality (IQ). The revised equation is as follows.

$$REC \int FI, TI, EI, FO, GLO, IQ \quad (2)$$

The log transformation of equation (2) can be displayed in the following regression form in Eq (3) to document the elasticities of independent and control variables on REC. For details please refer to Table 2.

3.3. Variable Definition and Expected Sign

Hypothesis H_2: Technological Innovation (TI) has a positive relationship with REC. Technological innovation can significantly transform the efficiency of renewable energy technologies as well as their efficacy, making them more affordable and accessible (Hafeez et al., 2022). Cost-effective innovations in solar and wind technologies have decreased the cost and improved energy efficiency, which can enable an even faster transition to renewable energy (Alam and Murad, 2020). Additionally, technological innovation is linked to improved energy efficiency, which can lead to an increase in the use of renewable energy as technology improvements make it easier to switch to clean forms of energy (Bibi et al., 2022; Ghosh, 2024).

Environmental Innovation (EI) refers to the development and implementation of new processes, products, or practices that improve environmental sustainability. Environmental innovation generally aims to reduce the environmental cost of energy consumption (Sahoo et al., 2022; Zhang et al., 2020). The expected relationship of environmental innovation (EI) with renewable energy consumption (REC) is also expected to be positive. Energy generation using renewable resources can be incorporated into the current energy structure through the application of energy storage methods and intelligent grid (Kırıkkaleli and Adebayo, 2021; Usman et al., 2021).

Financial innovation (FI) refers to the new financial instruments or strategies that can help increase investment in projects related to renewable energy. According to one assumption, financial institutions positively influence renewable energy consumption by offering the necessary capital for projects (Hafeez et al., 2022; Jafri and Liu, 2023). Green bonds and renewable energy investment funds, which are new financial inventions, can ease the entry barriers for renewable energy projects, thus accelerating their development and consumption (Liu et al., 2020; Rasoulinezhad and Saboori, 2018).

World Uncertainty (UR) embodies the global economic and political environment and its impact on renewable energy consumption. This can be used to study the interaction between uncertainty and renewable energy consumption. On the one hand, uncertainty might restrict investments in renewable energy because of the associated perceived risks. On the other hand, it could spur innovation as firms strive to mitigate these risks by implementing sustainable practices (Guo and Qamruzzaman, 2022; Li et al., 2022). This expected relationship is negative, indicating that more uncertainty leads to lower investments in renewable energy projects, thereby hindering Renewable Energy Certificates (REC) (Udeagha and Muchapondwa, 2022; Yahya and Rafiq, 2019). Table 3 reports the variables along with data sources.

3.4. Estimation Strategies

Cross-sectional dependence (CSD) in panel data arises via an interrelationship of cross-sectional units through common shocks, spillovers or systems. Failure to accounting CSD can produce biased estimates and cause wrong inferences (Chelva, 2018). Slope homogeneity tests determine whether the relations between independent and dependent variables are equal between all cross sections or vary a lot (Bersvendsen and Ditzen, 2021). Pesaran (2004) specifically, a widely used test of CSD in a panel of data is an important first step in the context of avoiding spurious results amid interdependent units (Pesaran, 2004). In this paper, Blomquist and Westerlund (2013) Blomquist and Westerlund (2013) propose a powerful framework that can be used to assess for slope homogeneity, suggesting heterogeneity of relationships in the presence of and controlling for CSD.

The Equation for Pesaran (2004) is as follows:

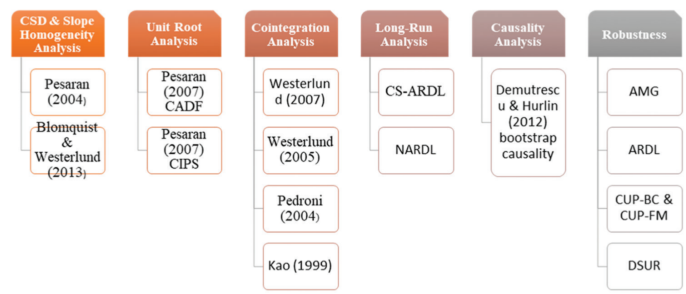
$$CD = \sqrt{\frac{2T}{N(N-1)}}\left(\sum_{i1}^{N-1}\sum_{j=i+1}^{N}\hat{\rho}_{ij}\right) \tag{1}$$

Where, $\hat{\rho}_{ij}$ = correlation coefficient between the residuals of the units i and j, N= number of cross-sectional units, T= number of time periods.

The Equation for Blomquist and Westerlund (2013) is as follows:

$$\Delta_{HAC} = \sqrt{N}\left(\frac{N^{-1}S_{HAC} - k}{\sqrt{2k}}\right) \sim X_k^2 \tag{2}$$

Where, Δ_{HAC} = test statistic for assessing slope homogeneity. N = number of cross-sectional units, S_{HAC} = HAC estimator for the variance-covariance matrix of the slope coefficients, k = degrees of freedom for the test, $\sim X_k^2$ = indicates the test statistic follows a Chi-squared distribution with k degrees of freedom.



Unit root tests are an inherent part of any time series analysis that ensures the stationarity of the series to give valid output. The CADF tests and CIPS tests Pesaran (2007) are extensions of ADF tests for panel data that take cross-sectional dependence among units into account.

$$\Delta REC_{it} = \mu_i + \theta_i REC_{i,t-1} + \gamma_i REC_{t-1} + \vartheta_i REC_t + \tau_{it} \tag{3}$$

Where, ΔREC_{it} = the change in the dependent variable (REC) for unit i at time t. μ_i =individual-specific intercept for unit i, θ_i= coefficient for the lagged value of the dependent variable for unit i, $REC_{i,t-1}$ = lagged value of the dependent variable (REC) for unit i at time t-1, γ_i = coefficient for the cross-sectional lagged dependent variable, REC_{t-1}= lagged value of the dependent variable (REC) for the cross-section at time t−1, ϑ_i= coefficient for the current value of the dependent variable, REC_t = current value of the dependent variable (REC) for unit i at time t, τ_{it}= error term for unit i at time t.

CIPS test equation:

$$CIPS = \frac{1}{N}\sum_{i=1}^{N} CADF_i \tag{4}$$

Where CIPS = test statistic for determining unit roots in panel data with cross-sectional dependence, N=number of cross-sectional units in the panel, $CADF_i$= cross-sectionally augmented dickey-fuller statistic for the i^{th} unit.

Cointegration analysis focuses on the long-run relationship between several time series. If two or more non-stationary series combine linearly, the combination is stationary, while the individual series are not. Those two or more series are said to be cointegrated. Panel data exhibiting cross-sectional dependence are unsatisfactory for unit root tests like the Augmented Dickey-Fuller (ADF) test. New tests, such as CADF and CIPS-type panel cointegration tests by taking the cross-sectional averages, have been proposed in recent years to account for cross-sectional dependence appropriately.

The equation for Westerlund (2007) is as follows:

$$\Delta REC_{it} = \alpha_i + \beta_i \left(REC_{i,t-1} - \theta_i \left(TI_{i,t-1} + EI_{i,t-1} + FI_{i,t-1} \right) \right) + \sum_{j=1}^{pi} \varnothing_{ij} \Delta REC_{i,t-j} + \sum_{j=1}^{qi} \psi_{ij} \Delta X_{i,t-j} + \epsilon_{it} \quad (5)$$

Where, REC_{it} = Renewable Energy Consumption (REC), dependent variable, $TI_{i,t-1} + EI_{i,t-1} + FI_{i,t-1}$ =Independent variables, θ_i = cointegration vector, β_i = speed of adjustment parameter, $\square_{it}$ = error term.

The equation for Westerlund (2005) is as follows:

$$\Delta REC_{it} = \beta_i \left(REC_{i,t-1} - \theta_i \left(TI_{i,t-1} + EI_{i,t-1} + FI_{i,t-1}\right)\right) + \varphi_{ij} \Delta X_{it} + \epsilon_{it} \quad (6)$$

Where, X_{it} = (Technological Innovation, Environmental Innovation, Financial Innovation)

The equation for Pedroni (2004) is as follows:

$$REC_{it} = \alpha_i + \delta_{it} + \beta_1 TI_{it} + \beta_2 EI_{it} + \beta_3 FI_{it} + \epsilon_{it} \quad (7)$$

Where, α_i =individual-specific intercept, $\delta_i t$ =time trend coefficient, β_1, β_2, β_3=cointegration coefficients for TI, EI, FI, ϵ_{it} = residual term.

The equation for Kao (1999) is as follows:

$$\epsilon_{it} = y_{it} - \alpha_i - \beta_i x_{it} \quad (8)$$

Where, ϵ_{it} =residual term which captures the unexplained variation in y_{it} after accounting for the estimated relationship between y_{it} and x_{it}, y_{it} = dependent variable, REC, x_{it} =independent variables (TI, EI, FI), α_i =individual-specific intercept for cross-sectional unit, β_i =slope coefficient representing the relationship between y_{it} and x_{it}.

Long-run analysis focuses on identifying persistent relationships between variables that extend beyond short-term fluctuations. Cointegration tests are crucial for examining these relationships within panel data. The CS-ARDL approach, developed by Chudik and Pesaran (2015), is particularly useful for analyzing interconnected data across different groups, allowing for the simultaneous investigation of both short-run and long-run relationships. Furthermore, NARDL models are valuable for capturing asymmetric effects, where positive and negative shocks to independent variables have different impacts on the dependent variable.

CS-ARDL equation:

$$\Delta REC_{it} = \alpha_i + \sum_{j=1}^{p} \beta_{ij} \Delta REC_{i,t-j} + \sum_{k=0}^{q} \gamma_{ik} \Delta TI_{i,t-k} + \sum_{m=0}^{q} \gamma_{im} \Delta EI_{i,t-m} + \sum_{n=0}^{q} \gamma_{in} \Delta FI_{i,t-n} + \varnothing_{i\overline{REC_t}} + \int_{it} \quad (9)$$

Where, ΔFS_{it} =change in Renewable Energy Consumption (REC) for entity i at time t, α_i =intercept term that represents the base level of REC for each entity, $\sum_{j=1}^{p} \beta_{ij} \Delta REC_{i,t-j}$ = This is the short-run lagged effects of REC on itself over p lags, $\sum_{k=0}^{q} \gamma_{ik} \Delta X_{i,t-k}$ = captures the short-term impact of changes in independent variables on REC, $\varnothing_{i\overline{REC_t}}$ = accounts for cross-sectional dependence by incorporating the average REC $(\overline{REC_t})$ across all entities, ϵ_{it} =error term.

NARDL equation:

$$\Delta REC_{it} = \beta_{0i} + \beta_{1t} REC_{t-1} + \beta_{2i} TI_{t-1} + \beta_{3i} EI_{t-1} + \beta_{4i} FI_{t-1} + \beta_{5i} EPU_{t-1} + \sum_{J=1}^{M-1} \gamma_{ij} \Delta REC_{it-j} + \sum_{J=0}^{N-1} \gamma_{ij}^{+} \left[\left(\Delta TI_{t-j}^{+} + \sum_{J=0}^{N-1} \gamma_{ij}^{-} \Delta TI_{t-j}^{-} \right) \right] + \left[\sum_{m=0}^{q-1} \gamma_{im} \Delta EI_{t-m}^{+} + \sum_{m=0}^{q-1} \gamma_{in} \Delta EI_{t-m}^{-} \right] + \left[\sum_{m=0}^{q-1} \gamma_{in} \Delta FI_{t-m}^{+} + \sum_{m=0}^{q-1} \gamma_{in} \Delta FI_{t-m}^{-} \right] + \varepsilon_{it} \quad (10)$$

The decomposition of EF, TF, IQ, and FI can be extracted in the following way:

$$TI_i^{+} = \sum_{k=1}^{t} \Delta TI_{ik}^{+} = \sum_{K=1}^{T} MAX(\Delta TI, 0)$$

$$TI_i^{-} = \sum_{k=1}^{t} \Delta TI_{ik}^{-} = \sum_{K=1}^{T} MIN(\Delta TI_{ik}, 0)$$

$$EI_i^{+} = \sum_{k=1}^{t} \Delta EI_{im}^{+} = \sum_{K=1}^{T} MAX(\Delta EI_{im}, 0)$$

$$EI_i^{-} = \sum_{k=1}^{t} \Delta EI_{im}^{-} = \sum_{K=1}^{T} MIN(\Delta EI_{im}, 0)$$

$$FI_i^{-} = \sum_{k=1}^{t} \Delta FI_{in}^{-} = \sum_{K=1}^{T} MIN(\Delta FI_{in}, 0)$$

$$FI_i^{-} = \sum_{k=1}^{t} \Delta FI_{in}^{-} = \sum_{K=1}^{T} MIN(\Delta FI_{in}, 0)$$

Causality analysis determines if the change in one variable causes a change in another; it helps determine the one-way direction of influences between factors (Cox and Wermuth, 2004). The panel causality test by Dumitrescu and Hurlin (2012) is designed for heterogeneous panel data, where the individual cross-sections may each have different relationships among their variables. The bootstrap method, therefore, considers cross-sectional dependence and small sample size to provide more robust results. Dumitrescu and Hurlin (2012) bootstrap panel causality test is robust in the case of panel data and allows heterogeneity across units. It can address cross-sectional dependence. The bootstrap approach ensures that the reliability in small samples can detect unidirectional and

Table 1: Literature summary

Authors	Sample	Methodology	IVs (sign of coefficients)
Fang (2023)	32 Chinese provinces (2005-2019)	Cross-sectional dependency, unit root, co-integration, and GMM models	TI[+VE]
Qamruzzaman and Kler (2023)	Bangladesh (1991-2019)	ARDL, Nonlinear ARDL, and the Toda-Yamamoto causality test	FI[+VE]
Ben Belgacem et al. (2023)	United Arab Emirates and Saudi Arabia (2010-2021)	IPS test Tenzin (2019)	FI[+VE]
Bashir et al. (2023)	top ten manufacturing countries (1995-2019)	CS-ARDL, AMG, CCEMG, and FMOLS	EI[−VE];
Jamshidi et al. (2023)	EU (2000-2020)	MM-QR	FI[+VE]
Archer and Idun (2023)	34 African economies (2010-2020)	Econometric methods	FI[−VE]
Zang et al. (2023)	EU (1980-2018)	CS-ARDL technique	TI[+VE]
Kirikkaleli (2023)	India	Fourier-based econometric methods	FI[+VE]
Cao (2023)	China (2011-2020)	A regression prediction method	FI[+VE]
Javed et al. (2023)	Italy (1994-2019)	ARDL (DYARDL), FDC test	GTI[+VE]
Sibt-e-Ali et al. (2023)	East and South Asian countries (1990-2021)	CS-ARDL estimator	TI[+VE]
Bakhsh et al. (2023)	China (1996-2020)	ARDL, GHGs models.	FI[+VE]
Najam (2023)	Asian nations (2011-2021)	Cross-section dependence, panel unit root, AMG	FI[+VE]
Ge et al. (2022)	China	PVAR	RETI[+VE]
Liu et al. (2022)	Turkey, Brazil, Mexico, Indonesia, Russia, India and China (1996-2018)	Long-linear model STIRPAT model	TI[+VE]
Habiba et al. (2022)	the top twelve emitters (1991-2018)	Balanced panel data	TI[+VE]
Hao and Chen (2023)	E7 countries	Fully modified OLS, dynamic OLS, classical cointegration regression, Bayer-Hanck cointegration, and ARDL bounds test, FMOLS, DOLS, and CCR	FI[+VE]
Haldar and Sethi (2022)	16 emerging countries (2000-2018)	Different Driscoll-Kraay Panel Corrected Estimators	FI[+VE]
Chishti and Sinha (2022)	BRICS	The Westerlund cointegration test, second-generation techniques, viz, AMG, CEMG, FMOLS	FI[+VE]
Khan et al. (2022a)	BRICS (1990-2019)	Cointegration, generalized least square, and panel corrected standard errors models, the ICT index model	TI[+VE]
Jiang and Khan (2023)	belt and road initiative countries (1995-2019)	GMM models	TI[+VE]
Zhen et al. (2022)	27 EU countries (1980-2018)	CS-ARDL method	EI[+VE]
Zang et al. (2023)	EU (1980-2018)	Non-linear ARDL	TI[+VE]
Khan et al. (2022b)	Germany (2000-2021)	The rolling window method	TI[+VE]
Sun et al. (2022)	BRICS (1995-2018)	Novel MMQ regression	TI[+VE]
Ramzan et al. (2023)	UK (1995-2020)	Novel Bootstrap Rolling-Window	EI[+VE]
Obobisa et al. (2022)	25 African countries (2000-2018)	AMG	TI[+VE]
Su and Gao (2022)	China	ARDL, NARDL	FI[+VE]
Usman et al. (2022)	15 European countries (2005-2018)	RDL, FMOLS and DOLS regression, Dumitrescu and Hurlin's tests	EI[+VE]; environmental expenditure[+VE]; R&D expenses[+VE]; FDI[+VE]; environmental investment[−VE]
Su et al. (2021)	US	Wavelet-Based quantile	TI[+VE]
Zheng et al. (2022)	Pakistan (1980-2019)	Dynamic ARDL simulation, Cumulative Fourier Frequency Domain Causality, and structural break estimation	TI[+VE]
Kahia et al. (2022)	Saudi Arabia (1990-2018)	Unit root test, the cointegration test of Johansen (1988), and the DOLS	EI[+VE]
Sahoo et al. (2022)	14 developing countries in Asia (1990-2018)	FMOLS, PCSE, FGLS, Dumitrescu-Hurlin Granger causality tests	EI[limited]
Adebayo (2022)	Spain (1970Q1 and 2017Q4)	The wavelet-based Granger causality analysis	EI[+VE]
Su and Fan (2022)	China (2013-2019)	Spatial Durbin model (SDM)	TI[+VE]
Zhao et al. (2022)	G7 countries (1995-2018)	AMG, CCEMG	EI[+VE]

(Contd...)

Table 1: ***(Continued)***

Authors	Sample	Methodology	IVs (sign of coefficients)
Abbas et al. (2022)	BRICS countries (1990-2020)	Second-generation panel unit root test and updated linear and nonlinear cointegration techniques.	EI[+VE]
Olanrewaju et al. (2022)	G7 nations (Canada, Japan, France, Germany, Italy, United States, and United Kingdom) (1990-2019)	Slope heterogeneity (SH), CSD, Westerlund cointegration, FMOLS, (DOLS, panel quantile regression, and panel causality tests	EI[+VE]
Iqbal et al. (2021)	37 OECD economies (1970-2019)	AMG	EI[+VE]; export diversification[−VE]; fiscal decentralization[−VE]; GDP growth[−VE]
Qayyum et al. (2021)	India (1980-2019)	FMOLS, DOLS, VECM	TI[+VE]
Adebayo et al. (2022)	Portugal (1980-2019)	Morlet wavelet analysis	TI[+VE]
Khan et al. (2021)	69 Belt and Road Initiative (BRI) nations (2000-2014)	GMM	TI[−VE]
Sharma et al. (2021)	BRICS (1990-2018)	ADF, CS-ARDL procedure	TI[+VE]
Hasanov et al. (2021)	BRICS countries (1990-2017)	Integration, cointegration, and cross-country interdependence	TI[+VE]
You et al. (2022)	US (1990Q1-2018Q4)	FMOLS, DOLS, correlated component regression methods	EI[+VE]
Ibrahim and Ajide (2021)	G-7 countries (1990-2019)	Cross-sectional dependence test, second generation panel unit root test, Westerlund cointegration test, Hausman test, PMG	TI[+VE]
Guo et al. (2021)	China (1995-2017)	panel cointegration test	EI[+VE]
Ali et al. (2021)	10 carbon emitter countries (1990-2017)	CS-ARDL, Westerlund cointegration method	EI[+VE]
Vural (2021)	Latin American (1991-2014)	CIPS, ADF, CADF	TI[+VE]
Su et al. (2021)	OECD countries (1990-2018)	CS-ARDL, CCEMG	EI[+VE]; fiscal decentralization[+VE]
Khan et al. (2020a)	G7 countries (1990-2017)	AMG, CCEMG, Dumitrescu and Hurlin (2012) Granger causality test	EI[+VE]
Li et al. (2020)	OECD economies (1990-2017)	D-H group mean cointegration test, CS-ARDL, AMG	EI[+VE]
Assi et al. (2021)	ASEAN+3 group (1998-2018)	ARDL, the Westerlund Panel integration Test, the Dumitrescu-Hurlin panel causality test	FI[−VE]
Wang et al. (2020)	G-7 countries (1990-2017)	CS-ARDL	EI[+VE]
Khattak et al. (2020)	BRICS economies (1980-2016)	CCEMG technique	TI[+VE]
Khan et al. (2020b)	G-7 countries (1995-2017)	panel cointegration and AMG	eco-innovation[+VE]; HC[+VE]; energy price[+VE]; R&D expenditure[+VE]; FD[−VE]
Ahmad et al. (2021)	26 OECD economies (1990-2014)	CST, CADF, CIPS panel unit root tests (2nd-generation unit-root test), WCT	EI[+VE]
Anton (2019)	28 countries in the EU (1990-2015)	A panel fixed effects model	FI[+VE]
Saudi (2019)	Malaysia (1980-2017)	ARDL	TI[+VE]

bidirectional causality, thus being ideal for the analysis of complex economic and financial relationships.

Causality equation:

$$REC_{it} = \alpha_i + \sum_{k-1}^{p} \gamma_{ik} REC_{i,t-k} + \sum_{k-1}^{p} \beta_{ik} TI_{i,t-k} + \sum_{k-1}^{p} \delta_{ik} EI_{i,t-k} + \sum_{k-1}^{p} \theta_{ik} FI_{i,t-k} + \mu_{it} \quad (11)$$

Where, REC_{it} = Renewable Energy Consumption, dependent variable, α_i = unit-specific effects capturing unobservable factors, $TI_{i,t-k}$ = Technological Innovation lagged by k, $EI_{i,t-k}$ = Environmental Innovation lagged by k, $FI_{i,t-k}$ = Financial Innovation lagged by k, γ_{ik} = coefficients of lagged REC, measuring persistence, μ_{it} = error term, β_{ik}, δ_{ik}, θ_{ik} = coefficients for lagged independent variables, indicating causality effects.

Heterogeneous non-causal test statistic:

$$W_{NT}^{Hnc} = N^{-1} \sum_{i-1}^{N} W_{i,t} \quad (12)$$

Where, W_{NT}^{Hnc} = panel-wide average of causality test statistics, N = number of units, $W_{i,t}$ = causality test statistics for each unit.

Z-statistic for panel causality:

$$Z = \sqrt{\frac{N}{2P} \times \frac{T-2P-5}{T-P-3}} \times \left[\frac{T-2P-3}{T-2P-} \bar{W} - P \right] \quad (13)$$

Table 2: Summary of variables, proxies, and data sources

Variables	Notation	Proxy	Sources	Expected sign
Renewable energy consumption	REC	Share of renewable energy in total energy use	World Bank, IEA	- (Dependent)
Financial innovation	FI	Financial sector R&D expenditure, Green bonds issued	World Bank, BIS, IMF	+
Technological innovation	TI	R&D expenditure in clean energy technologies	OECD, IEA, WIPO	+
Environmental innovation	EI	Patents in renewable energy and environmental tech	OECD, WIPO	+
Financial openness	FO	Chinn-Ito Financial Openness Index	IMF, Chinn-Ito Database	+
Globalization	GLO	KOF Globalization Index	KOF Swiss Economic Institute	+/-
Institutional quality	IQ	Worldwide Governance Indicators (WGI)	World Bank, Transparency International	+

Table 3: Variable descriptions, proxies, and data sources

Variables	Descriptive	Proxy variables	Data sources	Supporting literature
Technological Innovation	Refers to advancements and improvements in technology that drive energy efficiency and innovation.	Patents related to renewable energy, R&D expenditure, and technological readiness index.	WIPO, OECD, World Bank, or national patent offices.	Porter and Van der Linde (1995); Ren et al. (2021); Wang et al. (2023b).
Environmental Innovation	Focuses on innovations designed to reduce environmental harm and improve energy sustainability.	Green patents, environmental performance index (EPI), eco-innovation index.	OECD, WIPO, Environmental Performance Index Reports.	Horbach et al. (2012); Costantini et al. (2023); Zhang et al. (2022).
Financial Innovation	Development of new financial products, institutions, or technologies that facilitate investments.	Venture capital for green energy, green bonds, financial inclusion index.	Bloomberg, Refinitiv Eikon, IMF Financial Access Survey.	Beck et al. (2015); Eyraud et al. (2013); Apergis et al. (2020).
Renewable Energy Consumption	The proportion of total energy consumption derived from renewable energy sources.	Renewable energy consumption as a percentage of total energy use.	International Energy Agency (IEA), World Bank.	Sadorsky (2009); Destek and Sinha (2020); Apergis and Payne (2010).
World Uncertainty Index	Measures global uncertainty and its potential impact on investment and energy consumption.	World Uncertainty Index (WUI).	WUI database (Ahir et al.),	Baker et al. (2024); Ahir et al. (2022); Kang et al. (2017).

Table 4: Results of the CD test and SH test

Panel A: CD test of Juodis and Reese (2022)					
Model	**REC**	**TI**	**EI**	**FI**	**URC**
test stat value	9.6848***	8.2151***	12.4569***	11.5533***	12.9837***
Probability	***	***	***	***	***
CD exist	YES	YES	YES	YES	YES
Panel B: SH test of Bersvendsen and Ditzen (2021)					
Model	**Delta statistic**	**Adjusted delta statistic**	**SH exits**		
Model	4.1667***	5.7128***	Yes		

Where, Z = standardized test statistic for panel causality, N = number of cross-sectional units, T = number of periods, P = number of lags in the model, $\bar{W}$ = average causality test statistic across units.

4. ESTIMATION AND INTERPRETATION

According to Juodis and Reese (2022) test, output displayed in Table 4, there is significant cross-sectional dependency (CD) among all variables—REC, TI, EI, FI, and URC—which means that an economic shock or policy change that influences one entity is likely to influence the others as well. Moreover, strong cross-sectional dependency has also been demonstrated through the SH test by Bersvendsen and Ditzen (2021), which means that there are strong spillover effects in the data set. These results imply that in econometric modelling, ignoring such dependencies could lead to biased or inefficient estimations, highlighting the importance of employing robust estimating techniques incorporating interdependencies in panel data analysis.

The results of the panel unit root test, see Table 5, Pesaran, Herwartz and Siedenburg (2008) indicate that all variables (REC, TI, EI, FI, URC, FD and NRR) are non-stationary in level form and stationary in first difference form. These results indicate that the order of integration of order one, I (1), as well as the existence of unit roots in level form, occurred, indicating common trends. Therefore, long-run relationships should be explored by employing cointegration tests.

The PCT results, by following Westerlund and Edgerton (2008) and Westerlund and Edgerton (2007) test (see Table 6), show that all of the models that were evaluated show significant signs of cointegration, which means that the variables are likely to be in a long-run equilibrium relationship. The results are strong, suggesting that the variables have a stable long-term association that is reinforced by the existence of economic ties, even when there may be structural changes.

Table 7 then displays the estimated coefficients from the baseline model's CS-ARDL regression analysis. One of the most important things that came out of it is that the chosen nations' adoption of renewable energy is mostly driven by technical innovation (TI). With all else being equal, a 1% increase in technical innovation results in a 0.1385% rise in REC, according to the projected long-run coefficient of TI, which is 0.1385. This research lends credence to the idea that advancements in technology pave the way for cleaner energy technology, which in turn increases efficiency and decreases demand for fossil fuels. Although this effect is weaker in the short term, the short-run coefficient of 0.0178 provides further confirmation of it. As previously stated, this is in line with the research that highlights the importance of technology in promoting sustainable energy transitions, such as (Aïssa et al., 2014; Apergis and Payne, 2011; Khawlah Ali Ahmed AbdAlla, 2016).

Similarly, EI is determined to be an important factor in REC. A 1% increase in environmental innovation increases the use of renewable energy by 0.1273%, according to the long-run coefficient estimate of 0.1273. Environmental legislation and green inventions greatly contribute to promoting the adoption of renewable energy, according to the short-run effect estimate of 0.0712. Our finding is in line with existing literature such as (Adedoyin et al., 2020; Apergis and Payne, 2011; Apergis and Payne, 2014). Furthermore, research (Bilan et al., 2019; Khawlah Ali Ahmed AbdAlla, 2016; Lahiani et al., 2021) has revealed that environmental innovations, whether prompted by policy or the market, may reduce emissions and boost investments in renewable energy infrastructures.

Financial innovation (FI) has a positive and significant effect on renewable energy consumption. The long-run coefficient of 0.1891 indicates that a 1% increase in financial innovation leads

Table 5: Results of panel unit root test

Variables	CADF test statistic		CIPS test statistic		Herwartz and Siedenburg (2008)	
	Level	first diff	Level	first diff	Level	first diff
REC	−2.905	−3.228***	−1.226	−6.501***	−0.3886	4.2145***
TI	−1.756	−5.945***	−2.714	−6.09***	−0.5942	6.2856***
EI	−1.797	−5.608***	−1.681	−3.611***	0.7815	5.3534***
FI	−2.084	−2.898***	−1.265	−2.533***	1.0534	5.8379***
URC	−1.169	−4.312***	−2.086	−7.576***	1.0084	8.5388***
FD	−2.594	−4.376***	−1.667	−3.676***	−0.6794	6.1915***
NRR	−1.769	−5.401***	−2.784	−5.362***	0.2385	7.1082***

Table 6: Results of panel cointegration test (PCT)

Panel A: Cointegration test of Westerlund and Edgerton (2008)						
Model	No shift		Mean shift		Regiem shift	
	LMr	LMΦ	LMr	LMΦ	LMr	LMΦ
Model 1	−4.0084***	−2.47***	−3.9844***	−3.8714***	−2.8088***	−2.5389***

Panel B: Cointegration test of Westerlund and Edgerton (2007)				
Model	Gt	Ga	Pt	Pa
Model−1	−12.3***	−14.556***	−13.861***	−12.057***

Table 7: Results of CS-ARDL estimation

Panel A: long-run coefficients				Panel B: short-run coefficients			
Variables	Coefficient	std. error	t-stat	Variables	Coefficient	standard error	t-stat
TI	0.1385	0.0117	11.8376	TI	0.0178	0.0085	2.0941
EI	0.1273	0.0035	36.3714	EI	0.0712	0.0027	26.3703
FI	0.1891	0.0098	19.2959	FI	0.0252	0.0022	11.4545
WUI	−0.1215	0.0083	−14.6385	URC	−0.0388	0.0033	−11.7575
FD	0.1614	0.0055	29.3454	FD	0.0413	0.0107	3.8598
NRR	−0.1198	0.0035	−34.2285	NRR	−0.049	0.0101	−4.8514
C	0.1802	0.0057	31.614	ECT (−1)	−0.5522	0.0097	−56.9278
Residual diagnostic test							
CD test			0.0251				
Wooldridge test for autoco			0.0687				
Normality test			0.6403				
Remsey RESET test			0.7039				

TI stands for technological innovation, EI stands for environmental innovation, FI represents financial innovation, WUI depicts the world uncertainty index, FD for financial development and NRR for natural resources rent to a 0.1891% increase in REC, as the relationship is direct. In contrast, in the short run, the coefficient of 0.0252 reveals that financial innovation also makes a positive but lower contribution to REC. The estimates of CS-ARDL have been validated by the work of (Ozyesil and Tembelo, 2025), (Yin et al., 2025). The above findings emphasize the importance of green bonds, sustainable banking, and venture financing for clean energy businesses, illustrating the importance of unlocking dedicated financial instruments to facilitate the transition to renewable energy (Křístková et al., 2025), (Jiang et al.).

These are the global uncertainty index (WUI), which has a negative effect on the use of renewable energy. The estimated long-run coefficient of −0.1215 indicates that REC declines by 0.1215% upon a 1% increase in global uncertainty. It tells us that investors are reluctant to invest in renewable energy projects, given the higher perceived risk and lack of available capital given economic and geopolitical conditions. The negative short-term effect of uncertainty around energy transition is a strong −0.0388, which shows how disruptive it is. These results are similar to (Sohail et al., 2021), (Yi et al., 2023), (Shafiullah et al., 2021). One of those studies claiming policy and economic uncertainties are barriers to renewable energy growth.

That shows higher importance in controlling variables of renewable energy adoption, which appears to be significantly augmented by FD. The data suggest that a 1% improvement in financial development results in a 0.1614% increase in REC, which means investment spends on less energy when financial markets are sound functioning (long-run coefficient: 0.1614). The short-run impact (0.0413) further strengthens this viewpoint. These findings align with studies that demonstrate how sound financial institutions enhance the attractiveness of green investment by reducing borrowing rates and mobilizing capital for renewable energy projects (Archer and Idun, 2023; Cao, 2023; Habiba et al., 2022). On the contrary, NRR plays the opposite role in REC in the long run, where we can see that the coefficient of NRR is equal to −0.1198. Countries that depend heavily on the exploitation of natural resources may struggle to move to renewable energy sources, which is evidenced by the fact that the revenue elasticity of capital to rents for resource rents, R, is decreased by 0.1198% when resource rents rise by 1%. The short-run impact (−0.049) supports this finding — that resource-rich countries can have economic lock-in effects and regulatory inertia that can hinder the development of renewable energy, which aligns well with the theory of "Resource Curse," where R&D investment in renewables is disincentivized as the economy is overly dependent upon the economic dividends from fossil fuels (Sibt-e-Ali et al., 2023; Yi et al., 2023).

The coefficient of ECT (−1) exhibits a strong trend toward long-run equilibrium, as shown by the negative and statistically significant error correction term (ECT, −0.552), suggesting that the REC's deviations from equilibrium adjust by 55.22% per period, guaranteeing stability in the long run. According to residual assessment, there is no indication of non-normality (Normality test: 0.6403), functional form misspecification (Ramsey RESET test: 0.7039), cross-sectional dependency (CD test: 0.0251), serial correlation (Wooldridge test: 0.0687), or non-normality (CD test: 0.0251). Therefore, the findings are robust.

The nonlinear ARDL model demonstrates, see Table 8, that there is an unequal relationship between technological innovation (TI) and renewable energy consumption (REC). A negative shock causes REC to climb by 0.10% over the long term, whereas a positive shock in TI raises it by 0.12%. It seems that technical innovation, whether rising or falling, affects REC. This could be because of long-lasting trends toward more energy-efficient technology or because of other factors. A Wald test result of 9.06 indicates that the effects are not symmetrical, thereby rejecting the null hypothesis.

Increasing TI by 1% has a short-term effect of 0.03%, whereas decreasing it by 1% increases REC by 0.02%. This shows that compared to the long run, the consequences of short-term TI variations are quick but comparatively mild. These findings are in line with those of other studies (Wang et al., 2023a; Dogan

Table 8: Results from asymmetric estimation

Panel A: Long-run asymmetric coefficients				Panel B: Short-run asymmetric coefficients			
Variables	Coefficient	standard error	t-stat	Variables	Coefficient	standard error	t-stat
LnTI+	0.1181	0.0402	2.9378	ΔLnTI+	0.0297	0.0024	12.375
LnTI−	0.0965	0.0223	4.3273	ΔLnTI−	0.023	0.0034	6.7647
LnEI+	0.1064	0.0413	2.5762	ΔLnEI+	0.0392	0.0082	4.7804
LnEI−	0.1167	0.0193	6.0466	ΔLnEI−	0.0177	0.0036	4.9166
LnFI+	0.1225	0.0297	4.1245	ΔLnFI+	−0.0099	0.0042	−2.3571
LnFI−	0.1353	0.0205	6.6	ΔLnFI−	−0.0007	0.0045	−0.1555
LnURC+	−0.0985	0.0401	−2.4563	ΔLnURC+	−0.0074	0.0038	−1.9473
LnURC−	−0.1007	0.0289	−3.4844	ΔLnURC−	−0.0104	0.0077	−1.3506
LnFD	0.1379	0.0267	5.1647	ΔLnFD	−0.0061	0.0073	−0.8356
LnNRR	−0.1208	0.0273	−4.4249	ΔLnNRR	−0.0446	0.0027	−16.5185
				cointEq (−1)	−0.4167	0.0063	−66.1428
Long-run and short-run symmetry test							
$LnTI^{+}=LnTI^{-}$	9.0603			$\Delta LnTI^{+}=LnTI^{-}$		12.3067	
$LnFI^{+}=LnFI^{-}$	11.3781			$\Delta LnEI^{+}=LnEI^{-}$		12.2756	
$LnEI^{+}=LnEI^{-}$	10.9799			$\Delta LnFI^{+}=LnFI^{-}$		13.2022	
$LnWUI^{+}=LnWUI^{-}$	11.3358			$\Delta LnWUI^{+}=LnWUI^{-}$		12.8344	

TI stands for technological innovation, EI stands for environmental innovation, FI represents financial innovation, WUI depicts the world uncertainty index, FD for financial development and NRR for natural resources rent, respectively. The superscript of +/- denotes positive and negative shocks and Inglesi-Lotz, 2020) that have also pointed out the importance of technology developments in energy transitions but have also noted that adoption delays and investment concerns may limit their immediate impact. There is an asymmetry in the impact of environmental innovation (EI) on REC as well. In the long term, REC is raised by 0.11% for every 1% gain in EI and by 0.12% for every 1% decrease. Policy shifts or more investment in renewable energy sources might be necessary to mitigate environmental risks since the bigger impact of negative shocks implies that less innovation in this area could lead to such measures. This association is very asymmetric, as shown by the Wald test value of 10.98.

In the near term, REC is raised by 0.04% for every 1% rise in EI and increased by 0.02% for every 1% fall. It appears that existing regulatory frameworks continue to support renewable expansion even when innovation levels fluctuate, which may explain why short-term reductions do not immediately halt progress, even though environmental innovation promotes renewable adoption (Sadorsky, 2021; Zhang, 2022). Additionally, REC is not equally affected by financial innovation (FI) in the long term. When FI has a 1% positive shock, REC rises by 0.12%, and when FI experiences a 1% negative shock, REC rises by 0.14%. When innovation in the financial sector slows, other financing methods or government interventions may be necessary to keep renewable investment ventures afloat, according to the somewhat bigger impact of negative shocks. The Wald test rejects the null hypothesis of symmetric effects with a value of 11.38. A short-term analysis shows that there is no statistically significant impact of a 1% drop in REC and a small fall of −0.01% in FI. Given the negative reaction right after, it seems like financial innovation may temporarily reroute funding away from energy projects and into riskier, higher-return ventures until things settle down.

Consistent with previous research, this supports the idea that green bonds and fintech solutions are important tools for financing renewable energy but that they will take some time to really make a difference (Omri and Nguyen, 2014; Atta-Mensah, 2021). The long- and short-term effects of uncertainty (WUI) on REC are unfavourable, according to the data. For every one per cent rise in uncertainty, REC falls by 0.10%, and for every one per cent fall in WUI, it falls by 0.10%. There is evidence of an unbalanced association since the Wald test statistic reads 11.34. Bouri et al. (2020) and Shahbaz et al. (2021) found that investors are unwilling to put money into renewable energy when uncertainty is high because they are afraid of taking a chance. However, they are still wary when uncertainty goes down, maybe because there are still economic risks or policy uncertainties. A rise of 1% in uncertainty reduces REC by 0.01% in the near term, whereas a drop of 1% has no discernible impact. That energy investments need stability and confidence, in the long run is supported by the fact that short-term shocks to uncertainty cause risk-off behavior Antonakakis and Usikov (2024).

Although REC relies heavily on financial development (FD), the results have been contradictory. A 1% increase in FD increases REC by 0.14% over the long term, whereas a 1% decrease has no discernible impact. Existing infrastructure and other finance sources probably prevent financial development from discouraging the use of renewable energy, even as it encourages investment in such projects. We can validate asymmetric effects using a Wald test of 12.83. The impact of financial development on renewable energy sources is a process that requires long-term changes in investment frameworks and capital markets since neither positive nor negative shocks in FD have a substantial short-term effect on REC (Al-Mulali et al., 2016; Paramati et al., 2022).

It seems that depending on rents from natural resources hinders the use of renewable energy sources, as NRR has a significant negative impact on REC. Consistent with the idea of a "resource curse" in which substantial income from fossil fuels postpones shifts to renewable energy sources, a one-cent rise in NRR decreases REC by 0.12% over the long term. A fall in NRR has a far bigger influence than an increase, as shown by the Wald test's considerable asymmetry of 16.52. An increase of 1% in NRR results in a short-term drop of 0.04% in REC, whereas a fall has an even bigger impact, falling by −0.04%. Consistent with the findings of Zafar et al. (2021) and Zafar et al. (2022), who contend that economies are pushed toward cleaner energy options as a result of falling fossil-fuel revenues, this indicates that renewable investment incentives are stimulated immediately by declines in fossil-fuel rents.

Rate of Correction (ECT) and Acclimatization Time: The relatively substantial coefficient of the error correction component (−0.42) suggests that departures from the long-run equilibrium are quickly adjusted. Period after period, almost 42% of every short-term shock is rectified, proving that REC swiftly gets back to its equilibrium route after disruptions. This points to the fact that, despite fluctuations in the short term, the adoption of renewable energy sources is fairly constant due to the fact that policy and investment mechanisms guarantee development in the long run.

Table 9 reports the robustness of the results through MG, AMG and CCEMG techniques. Renewable Energy Consumption (REC) response positively to Technological Innovation (TI) across all panels: MG (0.1602, t-stat: 24.2727), AMG (0.1304, t-stat: 29.6363), CCEMG (0.1584, t-stat: 22.9565) A similar positive impact is also observed for Environmental Innovations (EI) at 0.0483 (t-stat: 5.6823) for MG, 0.0965 (t-stat: 8.5398) for AMG, and 0.0958 (t-stat: 21.7727) for CCEMG. Financial Innovation (FI) in MG: 0.0994 (t-stat: 18.7547), AMG: 0.1469 (t-stat: 15.4631), CCEMG: 0.0541 (t-stat: 15.0277) World Uncertainty (URC) hampers REC: −0.0239 (statistic t: −10.8636) in MG, −0.0206 (statistic t: −9.8095) in AMG, and −0.1665 (statistic t: −37) in CCEMG. Financial Development (FD): 0.1166 (t-stat: 10.4107) in MG, 0.1546 (t-stat: 20.8918) in AMG, and 0.0887 (t-stat: 20.159) in CCEMG. Natural Resource Rents (NRR) reduce REC with coefficients of −0.1265 (t-stat: −12.9081) in MG, −0.1279 (t-stat: −15.2261) in AMG and −0.0546 (t-stat: −9.5789) in CCEMG. Spanning from 0.0236 to 0.0332, depending upon techniques, the diagnostic tests for cross-sectional dependence (CD), Wooldridge autocorrelation, normality, and model misspecification confirm robustness.

Table 9: Robustness assessment with different techniques: MG, AMG, CEEMG

Variables	MG			AMG			CCEMG		
	Coefficient	t-stat	Standard error	Coefficient	t-stat	Standard error	Coefficient	t-stat	Standard error
TI	0.1602	0.0066	24.2727	0.1304	0.0044	29.6363	0.1584	0.0069	22.9565
EI	0.0483	0.0085	5.6823	0.0965	0.0113	8.5398	0.0958	0.0044	21.7727
FI	0.0994	0.0053	18.7547	0.1469	0.0095	15.4631	0.0541	0.0036	15.0277
URC	−0.0239	0.0022	−10.8636	−0.0206	0.0021	−9.8095	−0.1665	0.0045	−37
FD	0.1166	0.0112	10.4107	0.1546	0.0074	20.8918	0.0887	0.0044	20.159
NRR	−0.1265	0.0098	−12.9081	−0.1279	0.0084	−15.2261	−0.0546	0.0057	−9.5789
C	0.0583	0.958	0.0608	0.0713	0.6271	0.1136	0.0238	1.0012	0.0237
CD test		0.031			0.0281			0.0238	
Wooldridge test		0.0284			0.0333			0.0261	
Normality test		0.0236			0.0248			0.026	
Remsey reset test		0.0332			0.0296			0.031	

5. DISCUSSION OF THE FINDINGS

In this study, the relationship between technological, environmental, and financial innovations, global uncertainty, financial development, and natural resource rents with renewable energy consumption (REC) is examined in OECD economies. Both positive and negative effects emerged from the estimation, indicating that there are important implications for the long-run and short-run impacts of these variables in propelling the energy transition. These findings not only align with what is already known but also contribute new insights into how global factors such as national stability drive the adoption of renewable energy innovation. Most studies estimate the long-term effects of environmental innovation on REC and provide strong estimators of relations using panel econometric and time-series data. For instance, Usman et al. (2022), panel econometric estimation techniques for the 2005-2018 period, concluded that the emission of non-renewable energy and consumption of renewables correlates with a long-run stable relationship with environmental innovation, R&D and FDI. Causality tests from the study also further suggest that the reduction of energy consumption is driven by environmental innovation and R&D, and thus, technological innovations are key to the transition from non-renewables to renewables.

Similarly, Ramzan et al. (2023) employed a time-varying rolling window technique on quarterly data from 1995 to 2020. The analysis detected a one-way causal relationship between green innovation and energy transition, which suggests that green innovation significantly impacts driving renewable energy consumption. Cointegration analysis shows that green innovation, financial globalization and GDP make a long-term contribution to the energy transition. This confirms the theoretical perspective that financial globalization and green innovation are important factors driving REC. The study by Iqbal et al. (2021) offers in-depth discussions on the role of fiscal decentralization, export diversification and technological innovation in contributing to carbon neutrality targets. Specifically, their sophisticated cointegration techniques found that environment-based technological innovation is an essential element for emerging nations to understand and leverage, given that such innovation has a long-term positive relationship with the environment. This model further emphasizes that environmental innovation itself enhances REC, which in turn plays a vital role in carbon emissions reduction in the long term.

Nevertheless, other studies show mixed results, particularly regarding the effect of environmental innovation on REC's magnitude. Sahoo et al. (2022) employed panel data from 14 Asian developing countries from 1990 to 2018 and found an immaterial impact of environmental innovation on CO_2 emission. They blame this on the absence of economic growth assistance for such innovations. This interpretation is that emission reduction can be provided by renewable energy and globalization, but environmental technology innovations alone have a muted impact on emissions, especially without economic incentives. Bashir et al. (2023) also support this finding by estimating a negative relationship between environmental innovation and ecological footprint in the top 10 manufacturing countries using panel estimation techniques. It suggests that although first-order environmental innovation is responsible for reducing carbon emissions, second-order investments can centralize resource and infrastructure development elsewhere with potentially increasing environmental impacts.

The empirical results obtained using panel cointegration methods and Granger causality tests in different studies suggest that environmental innovations play a crucial role in the adoption of renewable energy. However, this influence is frequently dependent on more comprehensive economic and policy contexts. For example, Zhao et al. (2022), using panel estimation, show that solar energy and eco-innovation are statistically significant in causing significant reductions in carbon emissions in the long run. These findings indicate that we must put more effort into eco-innovations and solar energy in response to the environmental crisis. Similarly, Su et al. (2021) refer to data from seven OECD countries, linking the increase of renewable energy consumption with fiscal decentralization and environmental innovation, hence showing that sub-national governance and decentralized policies can provide key leverage to accelerate energy transitions.

There is extensive evidence showing that technological innovation has a positive effect on REC, further supporting the idea that innovation can play a key role in creating more environmentally friendly energy solutions. Research includes that of Fang (2023) and Sibt-e-Ali et al. (2023). According to Fang (2023), green technological innovation and renewable energy are critical to carbon emission reduction, exploring that energy sector innovation and cross-industry green revolution can be significantly implemented in emission minimization.

Similarly, Javed et al. (2023) and Zang et al. (2023) note that green technology innovation and the use of renewable energy have beneficial long-term impacts on decreasing ecological footprints and enhancing sustainability. Su and Fan (2022) support this view, emphasizing that the effect of renewable energy technology innovations will promote the development of green development that further aids transformation to structure but might be complicated by industry structural reform. Liu et al. (2022) reconfirm the possibility of harnessing technological innovations and renewable energy in helping developing economies realize sustainable development goals (SDGs) without degrading the environment. Ge et al. (2022) also emphasize the role of RE, technological innovation (RETI), and green finance in significantly modifying industrial structures across the country - and particularly in the east of China. Studies by Su et al. (2021) and Jiang and Khan (2023) find that the use of technological innovations and a transition into clean renewables are significant factors in decreasing emissions within the United States and Belt and Road Initiative (BRI) countries, respectively, highlighting the global implications of this causal relationship.

However, not all research demonstrates unambiguous positive effects. According to studies conducted by Ibrahim and Ajide (2021) and Vural (2021), technological innovation can help mitigate pollution; however, the role of factors such as trade openness and nonrenewable energy consumption might offset its positive impacts. Khan et al. (2022b) observe that, in Germany, technological advancements exhibit both positive and negative effects on renewable energy consumption, indicating the need for strategic planning in this domain. Furthermore, Khattak et al. (2020) highlight that innovation only has a big role in affecting CO_2 emissions in Brazil among the BRICS countries. Overall, although technological innovation and renewable energy consumption are found vital for reduced environmental degradation, these studies suggest that holistically, these policies, like socio-economic and industrial domains are also required to be at the center of these policies to capture and exploit the environmental benefits of technological innovations.

This study aims to investigate the role of financial innovation in the dynamics of renewable energy consumption (REC) and environmental sustainability. There is empirical evidence claiming that financial innovation and green finance play an important part in reducing carbon emissions and improving sustainability. Kirikkaleli (2023) and Najam (2023) show that financial innovation and the use of renewable energy reduce environmental degradation in India and Asian nations and support the zero-carbon Environment Kuznets Curve hypothesis. Ben Belgacem et al. (2023) and Qamruzzaman and Kler (2023) establish the roles of financial innovation and renewable energy, which contribute towards sustainability in UAE, Saudi Arabia and Bangladesh through the enhancement of SME performance and the evolution of environmental policies. Further, Jamshidi and Meybodi (2024), Zhan et al. (2023), and Su and Gao (2022) analyzed the European Union (EU) and China. They found that green financial tools and regulatory frameworks significantly help to induce the reduction of CO_2 emissions and to ensure long-term economic stability. According to Haldar and Sethi (2022), there seems to be adequate support for the argument that the integration of information and communication technology (ICT) and renewable energy may contribute to accelerating emissions reductions in emerging economies.

However, there is also some literature indicating that financial innovation may not necessarily drive sustainability in some cases. Archer and Idun (2023) and Assi et al. (2021) observe that while it can contribute to carbon emission reductions, financial innovation in Africa and the ASEAN+3 region leads to poor results for social sustainability and less demand for renewable energy as well. In addition, Cao (2023) explores the potentially mixed effects that energy diversification has on China's economic conditions in the long term, as it promotes growth but may limit it in the short term under certain circumstances. The above disparities reveal that although financial innovation and green finance could promote REC and environmental sustainability, the effectiveness of these factors relies on subnational economic conditions, regulatory frameworks, and market structures. The nuanced understanding of the relationship between financial institution status and sustainable investment requires continued exploration in future studies across different geographic and economic contexts to inform policy recommendations that harmonize financial innovation within sustainability frameworks.

6. CONCLUSION, POLICY SUGGESTION AND LIMITATION OF THE STUDY

6.1. Conclusion

This study aims to determine the association of technological innovation and financial innovation with the consumption of renewable energy (REC) in 37 OECD countries while incorporating Fourier functions to capture complex dynamics. The literature review and empirical evidence show that technological and financial innovations are key determinants of REC patterns and, thus, environmental sustainability. Technological progress — through green energy and industrial efficiency primarily — has been proven to improve REC and decrease outcomes for carbon emissions. However, their impact differs by region and economic environment, and other studies show mixed or even negative effects in specific cases. Financial innovation with the impact of green, green finance, sustainable investments, and other policy frameworks has also been an essential factor in BRO and RED. However, it also depends on the context of an economy and regulatory framework. The main empirical results confirm the position that REC can be deployed over the need for innovation policies for sustainability targets. Innovative approaches to investment and impact created by change-makers in the private sector can be crucial elements to facilitate the success of the energy transition, especially for OECD countries that are at the cutting edge of technological and financial advances. However, the heterogeneous effects from studies suggest that a one-size-fits-all policy approach may not work. Instead, to derive the maximum benefit from the power of innovation to accelerate renewables, different policies are needed, tailored to the individual economic, technological and institutional reality of each country. Furthermore, this paper underscores the necessity of utilizing more advanced econometrical methods for estimating Fourier functions-based methods, allowing for the identification of the more complex and nonlinear interconnection between innovation and REC. These findings indicate that these relationships may be subject to vibrancy over standardized models, suggesting the necessity of more complex analytical capabilities in further studies. No matter how much promising technological and financial innovators can offer to REC in OECD countries, their true effect is determined by the economy, policy and market conditions. Instead of placing limits on technology, policymakers should aim to cultivate an environment that is conducive to the development of green technology and sustainable financial instruments that will help facilitate a transition towards renewable energy. Further studies need to examine these dynamics in more diverse economic settings and use sophisticated methods to understand better developments related to the innovativeness of renewable energy adoption across thousands of firms, as well as the role of innovation in contributing to environmental sustainability.

6.2. Policy Suggestion

This paper comes up with three broad policies that OECD countries need to implement to increase their consumption of renewable energy through enhancing green finance mechanisms, increasing innovation for technological progress and enabling carbon price signals. One important part of scaling green finance is the creation of new instruments, like green bonds, sustainability-linked loans and dedicated renewable energy funds. Governments must establish either “regulatory sandboxes” or deregulatory regimes that foster private capital investments in clean energy and make green financing transparent and accountable. Financial incentives, such as subsidies and tax credits, will also encourage businesses and households to adopt renewable energy sources.

Again, investing in technology innovations is the key to energy efficiency and renewable energy adoption in the national grids. Bigger R&D funds focused on energy storage, smart grids, and next-gen rens (like hydrogen energy) will make REC far more efficient. Rather, the emphasis must be on the cooperation of governments, private enterprises and research institutions to foster breakthroughs in sustainable energy solutions and the subsequent promotion of innovation. A combination of physical and digital technologies — artificial intelligence, blockchain and the like — can track and dynamically adjust how energy is consumed and how it is distributed, which will allow more large-scale renewable energy generation to be integrated.

Finally, the adoption of carbon pricing strategies, like carbon taxes and emissions trading systems, will be crucial to incentivize reduced carbon dioxide emissions, increase the area for energy use and shift to renewable energy sources. Establishing a carbon price would provide a greater incentive for businesses and industries to invest towards cleaner energy sources. The OECD countries should create harmonization and gradually rising carbon price dockets that promote a fair transition without disruption to their economies. When applied together, these three strategies can serve as both an engine for REC growth and an enabler of the global response to climate change.

6.3. Limitations of the Study

However, despite this research playing a vital role in identifying such significant perspectives on the relationship between the innovation-led REC and the sustainability of the OECD, it possesses some limitations. First, the study uses aggregated national-level data, which cannot reflect intra-OECD region-specific differences. The variations in how countries implement specific policies or government programs, along with the distinctions in their economies, technologies, and external and internal structures, could play a role in how renewable energy can be adopted, which in turn calls for localized analyses to provide more accurate policy recommendations.

First of all, the study mainly investigates the role of technological and financial innovation in driving REC. However, it pays little attention to other essential factors such as political stability, social acceptance of renewable energy and infrastructure readiness. These factors can significantly influence the successful deployment and integration of renewable energy technologies. Future studies could integrate different variables that will provide deeper insights into REC mechanisms.

Lastly, though the econometric approaches, for example, the use of Fourier functions, are robust, they also have their inherent limitations. They make strong assumptions about patterns in the data that might not hold during sudden economic or environmental shocks, such as the financial crisis or geopolitical events that upend energy markets. Moreover, the lack of data could have limited up to 2023, preventing the inclusion of the latest renewable energy technology and policy developments. Future articles should examine preventively methodologies and use more recent data to make the results more reliable and applicable.

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