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# Energy innovation investment and renewable energy in OECD countries

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ABSTRACT

Achieving carbon neutrality by 2050 remains fundamental to limiting global warming to 1.5 °C this century and mitigating the catastrophic effects of climate change. Policymakers have indicated that the transition towards a renewable energy economy is the catalyst for achieving this. Transitioning towards a renewable energy economy requires substantial investment in renewable energy technologies. While most empirical studies have explored the linkage between investment in research and development (R&D) and carbon emissions, not much is known empirically about the effect of energy innovation R&D on renewable energy generation. This study, therefore, contributes to the literature by investigating the impact of energy innovation R&D on renewable energy generation using a comprehensive panel dataset of 26 OECD countries from 1974 to 2020. Using a battery of robust alternative estimation methods, the results indicate that energy innovation R&D generally does not increase total renewable energy generation in the panel of OECD countries. The results further show that energy innovation R&D has a heterogeneous effect on disaggregated renewable energy sources such as solar energy, wind energy, nuclear energy, and hydro energy generation.

## 1. Introduction

Energy use is a major threat to sustainable development (International Energy Agency (IEA), 2021). Hence, deliberations on the energy sector and the plausible energy transition are paramount to attaining the Sustainable Development Goals (SDGs). Despite the growth in renewable energy in recent years (rising about 10 % in 2020 [1], nonrenewable energy sources (fossil fuels) still account for about 80 % of the global energy supply [2]. Excluding hydropower, renewable energy technologies such as wind, solar, geothermal, and biomass account for just about 2.1 % of global electric power [3]. Since traditional fossil fuels cost considerably less than renewable energy sources, renewable energy technologies have contributed a small share of the total electricity generation [4]. Fossil fuels (such as coal and crude oil) are the primary source of carbon dioxide ($CO_2$) emissions, which is the major cause of climate change (Environmental Protection Agency (EPA), 2021a). Many $CO_2$ emission mitigation strategies - including engaging in energy efficiency strategies (use of appliances that consume less energy), energy conservation (conscious use of less energy), fuel switching, carbon capture and sequestration technologies,[1] changes in land use, and fuel switching [5]- are being advocated and implemented.

Among the $CO_2$ emission mitigation strategies, fuel switching—the production and use of energy from renewable sources— is upheld to be the most potent [6]; [3]. Renewable energy sources include biofuels, geothermal, hydrogen-based, solar, and wind energy. As the chief source of global emissions - accounting for about three-fourths of global greenhouse gas emissions [7] - the energy sector holds the solution to respond to the world's climate challenge [7]. The IEA, for example, estimates that the energy sector alone accounts for about 53 % of the efforts required to tackle the global climate challenges [8]. It argues that reaching net-zero emissions by 2050 will require a total revolution of the global energy system to a solely renewable energy system. The pathway to net-zero emission requires the demand for coal, gas, and oil to reduce by about 98 %, 55 %, and 75 %, respectively [8].

Energy innovation investment is the pathway to the net-zero emission economy, driving the world to a clean and renewable energy system

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[1] $CO_2$ capture and sequestration is a set of technologies that can decrease $CO_2$ emissions from new and existing coal- and gas-fired power plants, industrial processes, and other stationary sources of $CO_2$ [5].

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(Ma, Feng & Chang, 2024). This emphasizes the imperativeness of technological transformation of the energy system with a significant upgrade of research, development, and demonstration (RD&D) ([9]; Hu, Skea & Hannon, 2018 [4]). The extent and effectiveness of innovative activities in the energy sector have become vital for tackling fundamental challenges associated with environmental sustainability and safeguarding the sustainable utilization of natural resources [4,10]. The attainment of global SDG7— ensuring access to affordable, reliable, sustainable, and modern energy for all—warrants the transition from fossil fuels to renewable energy and promoting energy efficiency [11]. The goal hinges on five main targets, which can be divided into two parts. The first part is outcome-based targets, ensuring universal access to modern energy, significantly increasing the share of renewable energy in the global energy mix, and doubling the improvement in energy efficiency [12]. The second part has two targets and is "inputs/means"-based targets, which means achieving the three targets in the first part. These targets comprise i) promoting international cooperation to enhance clean energy research and technology access. This includes promoting renewable energy, energy efficiency, advanced and cleaner fossil-fuel technology, and investment in energy infrastructure and clean energy technology. ii) expanding infrastructure and upgrading technology to supply modern and sustainable energy services for all in developing countries [12].

It is obvious that the "inputs/means"-based targets are driven by investment and innovation in the energy sector [4]. Winskel & Radcliffe [13] note that 'accelerated energy innovation' has become a crux component of energy policymaking in response to the urgent quest for a drastic change in the energy sector. Similarly, the Global Energy Assessment (GEA) recommends that significant and faster innovation is vital to counter the sustainability challenges of energy systems in the 21st century [14]. All the GEA energy roadmaps to a more sustainable future suggest a systematic transition from today's energy systems. The GEA (2012) asserts that hefty, early, and sustained investments in innovative energy systems are required to fund this transition. The drive for innovation in the energy system to accelerate the required transition hinges on creating markets (with substantial government support) that facilitate investments in energy options, technologies, and systems.

Energy innovation and the energy transition agenda have attracted enormous academic interest ([15]; [10,11,16]; Ma, Feng & Chang, 2024)). However, investigations into the relationship between energy innovation and renewable energy have not received much attention in the literature. We believe that shifting attention to how energy innovation affects renewable energy generation and consumption is imperative, especially for the climate change mitigation agenda. As a result, in this study, we focus on the OECD countries and examine the relationship between energy innovation investment and renewable energy. This study focuses on OECD countries because they are significant contributors to global carbon emissions and have committed to achieving carbon neutrality through sustainable investment in clean energy technologies and climate-friendly activities. Focusing on OECD countries is analogous to evaluating global leading economies' contribution towards achieving carbon-neutrality in 2050 through investment in energy innovation investment and renewable energy generation. To fulfil our objective, we seek to answer the following research questions: i) What is the effect of energy innovation investment on renewable energy in OECD countries? ii) Which renewable energy source benefits mostly from energy innovation investment in OECD countries?

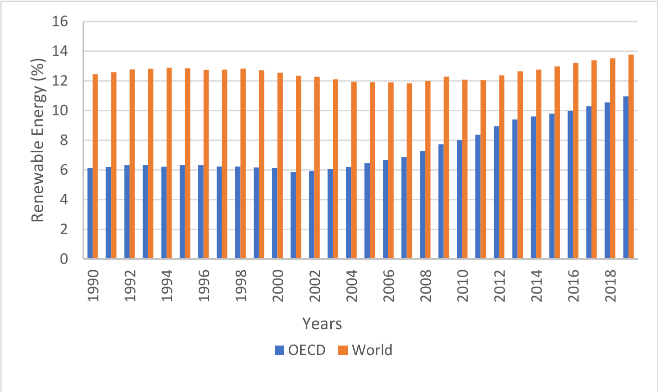

**Fig. 1.** Trend of total renewable energy (% of primary energy supply), 1990–2019.
Source: Used data from OECD [27].

Some of the studies related to the study include Liang & Fiorino (2013), Saygin et al. [17], Chakraborty & Mazzanti [18], and Jiang et al. [19]. Nevertheless, our study differs considerably in many strands. As we focus on the impact of energy innovation investment on renewable energy, Liang & Fiorino [16] examine the impact of federal R&D expenditures on renewable energy innovation. Saygin et al. [17] looked at the feasibility of renewable energy technologies and the role of innovation, doubling global renewable energy share from 18 % to 36 % between 2010 and 2030. Chakraborty & Mazzanti [18] study how green energy innovation activities affect energy intensity. The energy intensity there is not focused on renewable energy intensity. Jiang et al. [19] examined the effect of energy innovation and innovation transformation on energy consumption in China. Jiang et al. [19] do not focus specifically on renewable energy but total energy consumption. Khan et al. [20] looked at the relationship between technology innovations and renewable energy in Germany, and also Khan and Su [21] did similar for G10 countries. As these studies focus on technology innovation in general for a handful of countries, the present study specifically focuses on energy innovation investment for the OECD. More closely related to the present paper are Solarin, Bello and Tiwari [22], who look at the relationship between renewable energy innovation and renewable energy production. Our study, however, differs in the sense that as they have looked at aggregate renewable energy, we focus on disaggregated renewable energy sources. Also, we examine the renewable energy source that benefits the most from energy innovation investment. Furthermore, as they focus on BRICS countries (Brazil, Russia, India, China, and South Africa), we focus on the OECD.

In line with these, our paper contributes to the relevant literature along two main lines. Firstly, we look at how energy innovation investment impacts the various renewable energy sources. Although some other studies, such as Dzator and Acheampong [23] and Balsalobre-Lorente et al. [24], have probed the effect of energy innovation on carbon emissions, these studies do not provide a complete picture of the role of investment in energy innovation in achieving carbon neutrality. Achieving carbon neutrality by 2050 heavily relies on renewable energy. Therefore, our paper examining the contribution of energy innovation to renewable energy transition in achieving carbon neutrality is critical for informing policy. Second, our study adds to knowledge by examining the contribution of energy innovation investment to different renewable energy sources. This will help researchers and policymakers to understand whether there is a substitution or complementarity between various renewable energy sources given investment in energy innovation. In other words, understanding the effect of energy innovation investment on different renewable energy sources will help ascertain which renewable energy development sources benefit more from the investment in energy innovation. From a policy perspective, our study contributes to the discussions on the strategies and measures for achieving a carbon-neutral and renewable energy economy and addressing climate change. Innovation in the energy sector has become imperative in energy policy discourse, considering the race toward zero net emissions and the current challenges of climate change. As a result, initiatives leading to decarbonization and clean energy security for all are upheld high by policymakers. Hence, reducing $CO_2$ emissions via transition to renewable energy sources dominates environmental sustainability frameworks and discourses.

**Table 1**
Descriptive statistics and data summary.

| Variable | Definition | Units of measurement | Obs | Mean | Std. Dev. | Min | Max | Sources |
|---|---|---|---|---|---|---|---|---|
| Renewable | Total renewable energy production | Exajoules | 1069 | −3.666 | 2.261 | −11.513 | 1.816 | BP |
| Wind | Wind energy generation | Terrawatt-hour | 781 | −0.65 | 3.171 | −8.21 | 5.832 | BP |
| Solar | Solar energy generation | Terrawatt-hour | 633 | −2.561 | 3.285 | −11.513 | 4.898 | BP |
| Nuclear | Nuclear energy generation | Terrawatt-hour | 703 | 3.709 | 1.538 | −3.963 | 6.748 | BP |
| Hydro | Hydro energy generation | Terrawatt-hour | 1211 | 2.188 | 2.413 | −6.908 | 5.978 | BP |
| Gas | Gas energy production | Exajoules | 457 | 0.168 | 1.497 | −4.744 | 3.511 | BP |
| Real GDP | Economic development | GDP per capita (cons. 2015 US$) | 1139 | 10.193 | 0.64 | 7.916 | 11.39 | WDI |
| CO2 | Carbon emissions | CO2 emissions (kt) | 1138 | 11.907 | 1.31 | 9.71 | 15.573 | WDI |
| FDI | Foreign direct investment | FDI, net inflows (% of GDP) | 1086 | 0.209 | 1.531 | −7.198 | 4.686 | WDI |
| Trade | Trade openness | Trade (% of GDP) | 1162 | 4.121 | 0.524 | 2.208 | 5.531 | WDI |
| Energy_RD | Energy Innovation | Energy technology RD&D budgets per thousand units of GDP | 888 | −1.364 | 1.088 | −6.215 | 0.395 | IEA |

NB: The values are logged. BP]BP Statistical Review; WDI= World Development Indicators of the World Bank; IEA=International Energy Agency.

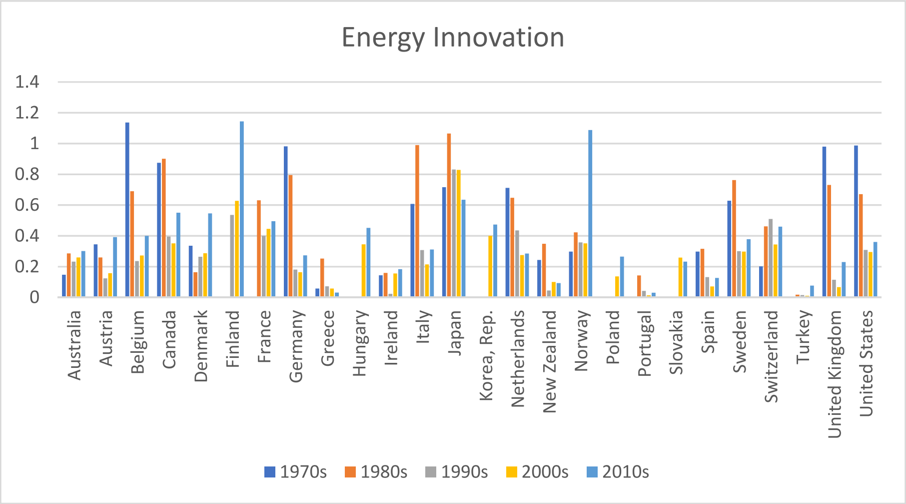

**Fig. 2.** Energy Innovation (Energy technology RD&D budgets per thousand units of GDP)
NB: 1970s, 1980s, 1990s, 2000s, and 2010s, respectively, represent the average of data from 1974 to 1979, 1980–1989, 1990–1999, 2000–2009, and 2010–2020.

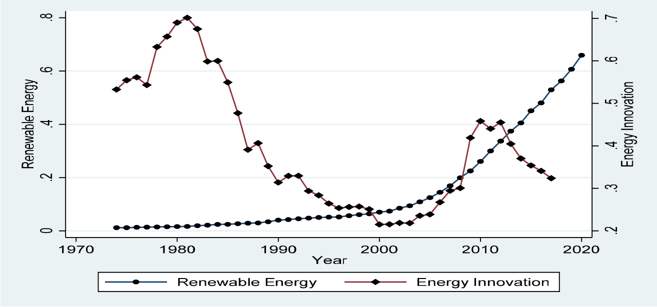

**Fig. 3.** Plot of renewable energy generation and energy innovation investment across years.

The rest of the paper proceeds as follows: Sections two and three, respectively, present the literature review and methodology. Section four presents the results and discussions. Section five presents the conclusion of the study.

## 2. Literature review

### *2.1. Stylized facts on renewable energy and energy innovation in the OECD*

In 2018, the 36 nations that made up the OECD attained a milestone for the first time by slightly generating more electricity from renewable energy sources than fossil fuels (coals) [25]. Renewable energy sources generated 2896 TW-hours of electricity, while burning coal generated 2863 TW-hours [25]. The growing interest in renewable energy is not limited to developed countries; energy from wind and solar sources is growing incessantly across the world. Since 2012, renewable power capacity installations globally have outstripped nonrenewables, amounting to about 60 % of all new power-generating capacity added globally in 2016 [26]. In 2019, the amount of new renewable power capacity installations (except large hydropower) was the largest ever (184 GW (GW)), 20GW more than in 2018. This included 118GW of new solar systems and 61GW of wind turbines (FS-UNEP Centre/BNEF, 2020). In 2019, renewable energy (excluding large hydro dams) generated 13.4 % of global electricity, up from 12.4 % in 2018 (FS-UNEP Centre/BNEF, 2020). Fig. 1 displays the pattern of total renewable energy (as a percentage of total primary energy supply) of OECD countries relative to the world. The Figure shows that since 2001, the proportion of total primary energy renewable energy has been increasing. However, the world average shows some fluctuations, and in 2010, it shows an upward trend.

Renewable energy investments have increased in developed and developing countries in the last couple of years. In 2016, OECD countries spent nearly $16.6 billion on energy RD&D, rising from $10 billion in 2000 [28]. Global investment in renewable energy has also increased in recent years. For example, for the first time, investment in renewable energy surpassed investment in fossil fuels in 2015, reaching $285.9

billion, equivalent to 147 GW (GW) (REN21, 2016). The total investment in renewable energy in 2020 was $303.5 billion (REN21, 2021). Though investment in renewable energy rose by 13 % in developed countries relative to a reduction of 7 % in developing and emerging countries in 2020, the latter countries invested more in terms of value, $153.4 billion (REN21, 2021). Solar energy takes a chunk of renewable energy investment, accounting for nearly half of global renewable energy investment in 2020 (REN21, 2021). Energy innovation investment in recent years has partly been enhanced by institutional investors' divestment of fossil fuel projects. For example, in 2020, more than 1300 such investors committed to divesting nearly $15 trillion from fossil fuel projects (REN21, 2021). Institutional commitments were also seen at the COP26 in 2021. For example, 30 CEOs of financial institutions with over $8.7 trillion in asset value committed to contributing to activities to phase out deforestation to reduce emissions. The pace of renewable energy innovation is enhanced if many more countries and institutions are engaged in R&D and invention activities (Costantini, Crespi & Palma, 2017; et al. Kijek, 2021).

Note: Renewable energy is the percentage of the contribution of renewables to the total primary energy supply. Renewables include the primary energy equivalent of hydro (excluding pumped storage), geothermal, solar, wind, tide, and wave sources [27].

The interest in renewable energy investment is driven by the commitment of countries to cut emissions. Over 130 countries (together with some cities, financial institutions, and companies) have set or are contemplating emission targets to transition them to net-zero emissions by 2050 [29]. The IEA re-echoes that the path to net-zero by 2050 necessitates quantum leaps in clean/renewable energy innovation. Net-zero emission in 2050 will require that nearly 90 % of global electricity generation emanate from renewable sources, with solar PV and wind energy amounting to about 70 % [7].

The drive to net-zero emissions also requires drastic measures such as stopping the production and sales of internal combustion engine (ICE) vehicles by 2035 and eliminating coal and oil power plants by 2040. The use of electronic vehicles (EVs) should be the way forward. To achieve this, global clean energy innovative investment will be required to triple by 2030 to $4 trillion yearly [7]. With this, the IEA projects that millions of jobs would be created, and universal access to electricity and clean cooking technologies worldwide would be attainable by the end of 2030. This will substantially enhance global economic growth. The IEA (2021) argues that despite the alley to a net-zero emission world being narrow, it is not an unattainable goal. With a commitment to and increasing levels of energy innovation investment, it is feasible to attain a net-zero emission world and limit global warming to 1.5 °C in this century.

Despite the general rise in renewable energy generation and energy innovation investment in OECD countries, considerable heterogeneities exist when individual countries are considered. Table A1 presents the average across years of renewable energy generation measured in exajoules (see bottom of Table A1 for a description of the averages) for the sampled OECD countries. Table A1 shows that over the years, the United States has taken a massive lead in renewable energy generation right from the 1970s to date. Despite the noticeable differences between countries, the last decade (average of 2010–2020) has seen many countries (see, for example, Australia, France, Germany, Italy, Japan, and Spain) significantly increase renewable energy generation (see the last column of Table 1A).

Similar to renewable energy generation, heterogeneities also exist in energy innovation investment. Fig. 2 presents a graph showing the average energy innovation investment. Unlike renewable energy generation, the last decade has seen an average growth; Fig. 2 shows that in countries such as Belgium, Canada, France, Germany, Italy, Japan, Netherlands, and the United States, generally, average energy innovation investment has fallen in the last decade (2010–2020) relative to previous periods (1974–1979, 1980–1989, 1990–1999, 2000–2009). For a handful of countries, such as Australia, Austria, Denmark, and Ireland, average energy innovation investment has only slightly increased in the last decade compared to the previous. Finland and Norway are probably the only countries with an enormous increase in energy innovation investment in the last decade (2010–2020).

The discussion above shows heterogeneous levels of renewable energy generation and energy innovation investment across the OECD countries and time (years). Fig. 3 presents trends of renewable energy generation and energy innovation averaged across the sampled countries of the study (26 OECD countries) over the years 1974–2020. The Figure shows that though renewable energy generation has generally been trending upwards over the years, energy innovation shows some fluctuations. For example, energy innovation investment rose in 1974 and peaked around 1980, then fell sharply till about 2000 (attained minimum ever around this period). It, however, starts to increase after 2000/2001 thereabout and falls around 2010/2011.

Many factors account for the heterogeneities of energy innovation investment across the OECD countries. Macroeconomic shocks may help explain some of the fluctuations in energy innovation investment. For example, the rise in energy innovation in the 1970s may have been necessitated by the Arab-Israeli War of 1973. The war led to temporary oil shortages imposed by the Organization of the Petroleum Exporting Countries (OPEC), which caused energy prices to increase and destabilized global economies. However, the crisis made many countries rethink the heavy reliance on crude oil, and this stimulated the development of new science and technology policies that inspired innovations in alternative energy sources (nuclear, solar, wind, and geothermal) and fuel-efficient automobiles. Oil is one of the world's essential commodities, and it amounts to nearly 3 % of the global GDP [30]. The impact of oil price fluctuations on global inflation cannot be ignored. Ley, Stucki & Woerter [31] show that energy prices and green innovation activities are positively related and that energy prices positively impact the ratio of green innovations to non-green innovations. Others, such as Aghion et al. (2012), Lanzi and Sue Wing (2011) and Popp [32], have found similar results. Popp [32] asserts that higher energy prices make energy-efficient inventions/innovations more valuable due to either larger energy savings (in monetary terms) or a greater market for energy-efficient inventions.

Following the 1970s episode, there was reduced demand for oil in the 1980s; however, increased production leading to an oversupply of oil in the 1980s led to a drastic drop in the price of oil [33]. Increased production by non-OPEC countries also necessitated the oversupply and drop in the price of oil and OPEC's decision to maintain high production levels in an attempt to maintain market share [33]. The price drop might have had an adverse effect on the rise of energy innovation experienced in the 1980s through to the 1990s. The 2000s boom in oil prices might again explain the rise in energy innovation investment (see Fig. 3) to offset dependence and increased prices of oil. During the 2000s, there was a heightened focus on energy security and the promotion of sustainable economic development through environmentally-friendly technological solutions, which led to a shift in energy innovation policies. However, this was hit by the global economic recession in 2008. The reduction in energy innovation investment after this may be attributed to the impact of the recession, which affected many industries, including the energy sector. The drastic drop in oil prices from 2014 to 2016 [34] may also have led to a reduction in energy innovation investment during this period and beyond.

Many studies have also explained factors that could lead to fluctuations in energy innovation investment. For example, Kijek et al. [10] argue that intrinsic structural weaknesses in some of these countries are apt to impede the demand for new technologies/innovations and the business prospects of these technologies. Some of the factors they identify as hindering the growth of energy innovation in these countries are i) the large initial financial outlay to invest in these technologies. Vazquez et al. [35] also emphasize the financing challenges that affect investment in energy innovation in these countries. ii) the high cost of new technologies with no guarantees that they will outperform existing technologies, iii) energy innovations encounter enormous entry barriers, including a mismatch of existing network infrastructure, the far-reaching market power of major competitors, price controls, and unstable regulatory frameworks. iv) energy innovation policy involving multiple stakeholders with sometimes conflicting interests. The OECD [36] asserts that though technology costs may be falling over the years, policy and market obstacles in various OECD countries impede the overall growth in energy innovation. The OECD [36] identifies that trade and investment policies that are not in line with climate change goals present challenges to cross-border trade and investment in renewable energy generation and innovation. The enforcement of local-content policy in solar PV and wind energy sectors in some OECD countries slows foreign investments in these sectors and threatens the optimization of the global renewable energy value chains [36]. Ang, Röttgers, and Burli [37] also identify the differences in the overall ease of doing business in different OECD countries as one of the major factors accounting for disparities in energy innovation. In talking about the ease of doing business, they emphasize investment policy (property registration, corruption perception, and regulatory quality of the renewable energy sector), investment facilitation (permit systems in the renewable energy sector), competition policy (the extent to which government controls businesses); trade policy (ease of trading across borders); and financial market policy (the ease of accessing credit domestically, sovereign credit rating, etc.).

Disincentives to energy innovation investment, such as fossil fuel subsidies and non-pricing of carbon emissions in some OECD countries, also account for the disparities in energy innovation [38]. These propel the incumbency of fossil fuels and work against the measures to reduce reliance on these energy sources. The reduction in demand for fossil fuels was emphasized at the 2021 COP26, where countries were entreated to halt the financing of fossil fuels abroad and rather focus on investing in clean energy. These would include fossil fuel projects that are “unabated,” that is, the combustion of fossil fuels without any technology to absorb the consequential emissions [39]. The United States, Canada, and 18 other countries committed to doing this by 2022.[2] Signed by 46 countries, a major global clean power transition statement was also made at the COP26; this was a pledge to halt coal investments, ramp up clean power, and get rid of coal by the 2030s in major economies and other economies by the 2040s [39]. Energy innovation that generates renewable energy technologies will play a pivotal role in transitioning to a sustainable energy system [4].

No single country can lead the energy innovation needed to change the energy sector and reduce its impact on emissions/climate change. The pace of energy innovation is faster if all or most of the countries in the OECD are engaged in renewable energy R&D; however, innovative capacity is not the same across the countries, leading to tremendous disparities in knowledge creation and the effect of R&D across countries [10]. An empirical study by Kijek et al. [10] finds that 25 of the 27 European sampled countries have converged into three clubs with significant heterogeneities in energy innovation (patent intensity, measured by the number of energy patent applications). Analysis of the convergence clubs led to the identification of some countries that are prone to free-riding on energy innovation efforts by other countries.

### 2.2. Energy innovation and renewable energy generation nexus

Technological innovations have long driven the energy sector to reduce the risks and increase the benefits associated with energy (Ma, Feng & Chang, 2024). Innovations have increased energy supplies, improved energy quality, and minimized the environmental consequences of energy extraction, production, and consumption [40]. Energy innovation investments drive technological innovations in the energy sector. Energy innovation investments are mainly green and environmentally sustainable investments in the energy sector. Hence, energy innovation investments are investments in renewable energy sources, and these innovations are new or improved procedures, methods, schemes, and products to elude or minimize environmental damage [41]; [4]. Miremadi et al. [4] posit that the main difference between such innovation (green innovation) and non-green innovation is that the former is more complex, particularly regarding cleaner technologies. In recent decades, the major economies have increased their RD&D budget to enhance innovation in the energy sector to reduce environmental damage [40,42]. With this, the cost of electricity from solar PV and onshore wind turbines has started reducing in some places, even to levels comparable with electricity generated from fossil fuels (Popp, 2020).

Hu et al. [42] assert that energy innovation results from RD&D, deployment, and diffusion activities. The energy technology system is developed in response to some of the features specific to the energy system that together result in a comparatively slow process of technology innovation and diffusion. Some of these features include [42] (1) capital intensiveness of energy technology investments. (2) lengthy time required to advance technology from invention to innovation, and (3) lengthy time for technology clustering and spillover impacts to be realized. The energy innovation process generally has three indicators-inputs, outputs, and outcomes [42]. The input indicators comprise the resources (both tangible and intangible) invested in the energy innovation process (R&D expenditure and personnel). The output indicators comprise the anticipated output produced from the inputs committed to the innovation process. These include factors such as publications (and patents) and technological achievement. Lastly, the outcome indicators are the broader socio-economic intended goals of the innovation process, such as the environmental impact (reduction in $CO_2$), upsurge in renewable energy consumption, mitigation of climate change effects, job creation, economic growth, and total installed capacity [42].

Watson [43] posits that innovation comprises numerous distinctive but connected stages - from R&D to prototyping, demonstration, commercialization, and deployment. The earlier notion of innovation was characterized by a simple linear path of moving from R&D to deployment [43]. Rothwell [44], however, shows that innovation has changed over time. Rothwell [44] characterized five distinctive models of innovation. The first model is the ‘technology push’ model in which, in the post-second world war, new product and process innovations were ‘pushed’ into the market. In the 1960s, the understanding of innovation was modified, and the second model, ‘the demand-pull’ model, was characterized by market and customer-focused innovation. The third model of innovation prevalent in the 1970s was the ‘coupled’ model in which both ‘technology’ push and ‘demand-pull’ models played roles. In this era, feedback loops connected R&D and marketing roles, underscoring mutual learning between them. The fourth model started somewhat in the late 1980s and was characterized by strong connections with supply chains and important ‘lead customers’ for new products. The last model observed from the 1990s is a networked model of innovation. Rothwell [44] asserts that this hinges on the fourth model’s basics, with more activities’ assimilation. A significant characteristic of this innovation model is incorporating feedback, which could also be referred to as ‘learning-by-doing’ [43]. With this, knowledge/feedback acquired from prototyping, demonstration, and the commercial deployment of new technologies is used to support further innovation.

The concept of energy innovation and technology development results from a complicated set of interactions between several entities (including firms, universities, and government institutions) targeted at producing and spreading new energy technologies [45]. The role of government and public policy in energy innovation investment cannot be over-emphasized. Government essence is mainly required due to the hefty financial outlay required for energy innovation investment (Nesta,

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[2] These countries invested about $18 billion annually from 2016 to 2020 in a number of international fossil fuel projects (Reuters, 2021) https://www.reuters.com/business/cop/19-countries-plan-cop26-deal-end-financing-fossil-fuels-abroad-sources-2021-11-03/.

**Table 2**
The impact of energy innovation on renewable energy [DOLS results].

| | Model 1 | Model 2 | Model 3 | Model 4 | Model 5 | Model 6 |
|---|---|---|---|---|---|---|
| | Total RE | Wind | Solar | Nuclear | Hydro | Gas |
| Real GDP | 1.296*** | 2.238*** | 1.198** | 0.879* | 1.075 | 1.560** |
| | (0.361) | (0.629) | (0.497) | (0.511) | (0.748) | (0.653) |
| CO2 | 0.882*** | 1.402*** | 1.672*** | 0.361 | −0.103 | 0.625*** |
| | (0.154) | (0.251) | (0.179) | (0.227) | (0.323) | (0.223) |
| FDI | 0.205 | 0.002 | −0.615*** | 0.074 | 0.026 | 0.426* |
| | (0.159) | (0.265) | (0.194) | (0.212) | (0.334) | (0.240) |
| Trade | 0.231 | 2.306*** | 3.017*** | −1.104 | −3.091*** | −0.345 |
| | (0.503) | (0.842) | (0.596) | (0.674) | (1.071) | (0.703) |
| Energy_RD | −0.158 | −0.912*** | −0.281 | −0.221 | −0.128 | 0.677** |
| | (0.184) | (0.309) | (0.230) | (0.310) | (0.385) | (0.291) |
| Constant | −28.745*** | −51.964*** | −48.578*** | −5.448 | 5.053 | −21.992** |
| | (5.625) | (10.022) | (7.703) | (7.626) | (11.443) | (10.642) |
| Observations | 728 | 564 | 465 | 458 | 776 | 311 |
| r2 | 0.392 | 0.343 | 0.326 | 0.525 | 0.354 | 0.651 |

Standard errors in parentheses. $^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$.

**Table 3**
The impact of energy innovation on renewable energy [FMOLS results].

| | Model 1 | Model 2 | Model 3 | Model 4 | Model 5 | Model 6 |
|---|---|---|---|---|---|---|
| | Total RE | Wind | Solar | Nuclear | Hydro | Gas |
| Real GDP | 1.253*** | 2.066*** | 1.083 | 0.999** | 1.104* | 1.604*** |
| | (0.367) | (0.542) | (0.659) | (0.435) | (0.638) | (0.598) |
| CO2 | 0.752*** | 1.279*** | 1.555*** | 0.323* | −0.251 | 0.644*** |
| | (0.160) | (0.222) | (0.250) | (0.195) | (0.278) | (0.213) |
| FDI | 0.194 | 0.005 | −0.411* | 0.103 | 0.033 | 0.397** |
| | (0.139) | (0.190) | (0.214) | (0.156) | (0.243) | (0.187) |
| Trade | −0.176 | 1.786** | 1.965** | −1.161** | −3.150*** | −0.282 |
| | (0.493) | (0.693) | (0.775) | (0.555) | (0.875) | (0.644) |
| Energy_RD | −0.083 | −0.887*** | −0.440 | −0.205 | −0.143 | 0.689*** |
| | (0.180) | (0.257) | (0.295) | (0.246) | (0.312) | (0.262) |
| Constant | −24.961*** | −46.483*** | −41.914*** | −5.978 | 6.696 | −22.928** |
| | (5.451) | (8.255) | (10.019) | (6.329) | (9.310) | (9.593) |
| Observations | 730 | 566 | 467 | 460 | 778 | 313 |
| r2 | 0.253 | 0.210 | 0.186 | 0.056 | 0.030 | 0.010 |

Standard errors in parentheses. $^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$.

Vona & Nicolli, 2014). Rhodes et al. [46] assert that the massive elements of natural monopolies that still exist in the energy sector also make policymakers play a significant role in maintaining, altering, and regulating energy markets. This makes government support and commitment important to developing alternative energy technologies and sources [16]. In recent decades, Rhodes et al. [46] note that public R&D on energy has focused mainly on renewable technologies and energy efficiency. Considerable advancements made in reducing the cost of renewable energy emanate from the activities of policymakers to assist the development and expansion of renewable energy technology through either government-funded R&D or by regulations (such as feed-in tariffs) that support the production and consumption of renewable energy [3]. It is argued that safe environmental regulations push firms/people to cut CO$_2$ emissions from fossil fuel consumption through activities such as the introduction of a carbon tax (making emissions costly) incentive (subsidizing of renewable energy sources) to use renewable energy will be minimal [3]. This emphasizes the essence of policymakers in driving the renewable energy agenda. Popp (2020) opines that innovation is a vital component of energy policy, and pushing for clean energy innovation is often a goal of policymakers. Policymakers promote clean energy innovation to mitigate the effects of climate change, attain sustainable development, and promote the local economy (Popp, 2020). Despite the necessary involvement of the government, significant private investment is required if the public policy agenda of raising the share of renewable energy in the global energy mix comes to fruition [15].

The advantage of increasing investment in energy innovation or renewable energy technologies coupled with energy efficiency measures is that they can help meet future energy exigencies while reducing the risks associated with reliance on fossil fuels [15]. Many empirical studies have attempted to examine the patterns and impact of energy innovation technologies. In what follows, we review some of these studies. Gielen et al. [11] show that energy efficiency and renewable energy technologies are the main elements that drive the energy transition, and the synergies between the two (energy efficiency and renewable energy technologies) are salient in achieving the energy transition that will ensure global temperature rise below 2 °C between now and 2050. Kijek et al. [10] examined patterns in energy innovation convergence in 27 European countries from 2000 to 2018 using a nonlinear time-varying factor model; they did not find an overall convergence of energy innovation performance in the sample countries. However, they identified three convergence clubs by differences in energy patent intensity: Club 1 (the lowest energy patent intensity)- Bulgaria, Czech Republic, Greece, Hungary, Latvia, Lithuania, Luxembourg, and Poland, and Club 2 (medium energy patent active countries)- Belgium Estonia, Ireland, Italy, Netherlands, Norway, Portugal, Slovak Republic, Slovenia, Spain, and United Kingdom, Club 3 (the highest energy patent intensity)- Austria, Finland, France, Germany, Sweden, and Switzerland. Furthermore, an ordered logit estimation indicates that initial differences in environmental R&D expenditure (per capita), human resources in science and technology, and environmental policy stringency may explain the different convergence clubs.

On the empirical front, using data from 26 OECD countries over the period 1991–2004, Popp et al. [3] evaluate the effect of technological

**Table 4**

The impact of energy innovation on renewable energy in a panel of OECD countries.

| Variables | Model 1 | Model 2 | Model 3 | Model 4 | Model 5 | Model 6 |
|---|---|---|---|---|---|---|
| | Total RE | Wind | Solar | Nuclear | Hydro | Gas |
| Panel A: IV-GMM estimates | | | | | | |
| Energy_RD | −0.228*** | −1.076*** | −0.314* | −0.243*** | −0.142* | 0.592*** |
| | (0.078) | (0.137) | (0.169) | (0.062) | (0.074) | (0.094) |
| Real GDP | 1.384*** | 2.637*** | 1.324*** | 0.805*** | 1.145*** | 1.763*** |
| | (0.163) | (0.315) | (0.338) | (0.112) | (0.162) | (0.157) |
| CO2 | 0.970*** | 1.503*** | 1.663*** | 0.376*** | −0.065 | 0.649*** |
| | (0.067) | (0.092) | (0.107) | (0.050) | (0.064) | (0.076) |
| FDI | 0.148** | 0.015 | −0.400*** | 0.055 | 0.049 | 0.259*** |
| | (0.061) | (0.097) | (0.113) | (0.041) | (0.073) | (0.055) |
| Trade | 0.491** | 2.704*** | 2.805*** | −1.046*** | −3.032*** | −0.217 |
| | (0.214) | (0.330) | (0.391) | (0.175) | (0.229) | (0.254) |
| Constant | −31.782*** | −59.170*** | −49.069*** | −5.082*** | 3.674* | −24.958*** |
| | (2.493) | (3.944) | (4.833) | (1.941) | (2.173) | (3.266) |
| Observations | 663 | 530 | 444 | 428 | 700 | 283 |
| R2 | 0.388 | 0.327 | 0.292 | 0.518 | 0.337 | 0.622 |
| j | 4.083 | 6.189 | 0.341 | 0.095 | 1.327 | 3.998 |
| jp | 0.043 | 0.013 | 0.560 | 0.758 | 0.249 | 0.046 |
| F-statistics | 1556.251 | 1172.016 | 927.095 | 608.030 | 1446.107 | 524.572 |
| | **Total RE** | **Wind** | **Solar** | **Nuclear** | **Hydro** | **Gas** |
| **Panel B: Lewbel 2SLS estimates** | | | | | | |
| Energy_RD | −0.120 | −1.168*** | −0.882*** | −0.159 | −0.583*** | −0.110 |
| | (0.117) | (0.223) | (0.215) | (0.121) | (0.105) | (0.174) |
| Real GDP | 1.300*** | 2.691*** | 1.957*** | 0.835*** | 1.529*** | 1.643*** |
| | (0.185) | (0.388) | (0.370) | (0.118) | (0.181) | (0.149) |
| CO2 | 0.919*** | 1.524*** | 1.770*** | 0.401*** | 0.055 | 0.656*** |
| | (0.071) | (0.100) | (0.105) | (0.048) | (0.066) | (0.075) |
| FDI | 0.163*** | −0.042 | −0.494*** | 0.087 | −0.106 | 0.125** |
| | (0.062) | (0.096) | (0.120) | (0.055) | (0.068) | (0.063) |
| Trade | 0.428** | 2.801*** | 3.081*** | −0.993*** | −2.698*** | −0.100 |
| | (0.217) | (0.326) | (0.381) | (0.174) | (0.215) | (0.241) |
| Constant | −29.984*** | −60.610*** | −58.937*** | −5.891*** | −3.758 | −25.001*** |
| | (3.055) | (5.237) | (5.316) | (1.996) | (2.569) | (2.894) |
| Observations | 731 | 567 | 468 | 461 | 779 | 314 |
| R2 | 0.382 | 0.310 | 0.267 | 0.495 | 0.308 | 0.519 |
| | **Total RE** | **Wind** | **Solar** | **Nuclear** | **Hydro** | **Gas** |
| **Panel C: Driscol-Kraay estimates** | | | | | | |
| Energy_RD | −0.215* | −0.877*** | −0.276 | −0.263** | −0.093* | 0.550*** |
| | (0.123) | (0.294) | (0.339) | (0.121) | (0.055) | (0.145) |
| Real GDP | 1.397*** | 2.351*** | 1.324*** | 0.863** | 1.043*** | 1.672*** |
| | (0.172) | (0.542) | (0.440) | (0.370) | (0.171) | (0.216) |
| CO2 | 0.940*** | 1.459*** | 1.655*** | 0.396*** | −0.049 | 0.684*** |
| | (0.124) | (0.119) | (0.174) | (0.071) | (0.080) | (0.138) |
| FDI | 0.137 | 0.014 | −0.366* | 0.061 | 0.024 | 0.235*** |
| | (0.094) | (0.069) | (0.206) | (0.054) | (0.053) | (0.083) |
| Trade | 0.483 | 2.613*** | 2.774*** | −0.982*** | −2.947*** | −0.089 |
| | (0.567) | (0.734) | (0.681) | (0.327) | (0.287) | (0.488) |
| Constant | −31.587*** | −55.079*** | −48.855*** | −6.261 | 4.185** | −25.008*** |
| | (4.032) | (10.567) | (9.017) | (4.662) | (1.985) | (5.635) |
| Observations | 731 | 567 | 468 | 461 | 779 | 314 |
| R2 | 0.384 | 0.316 | 0.291 | 0.497 | 0.340 | 0.622 |

Heteroscedasticity robust standard errors in parentheses. Note for IV-GMM: J is Hansen J-statistics; jp is the p-value of Hansen J-statistics. F-statistics is the Cragg-Donald/Kleibergen-Paap F-statistics for weak instrument identification. The probability value for the Hansen J-statistics suggests that instruments are not over-identified, while the F-statistics also suggests the instruments are not weak. *$p < 0.10$, **$p < 0.05$, ***$p < 0.01$. Note: The estimates presented in Model 6 apply to 10 countries (Australia, Canada, Denmark, Germany, Italy, Netherlands, Norway, Poland, the United Kingdom, and the United States) that have data on gas generation.

change (increases in global technology stock) on investment in renewable energy capacity (wind, solar PV, geothermal, and electricity from biomass). They find that technological advancement increases (though with a small effect) investment in renewable energy capacity. Investments in other carbon-free energy sources (hydropower and nuclear power) were also found to increase with technology. Liang & Fiorino [16] examine the impact of the stability and size of federal R&D expenditures on renewable energy innovation (i.e., solar, wind, hydropower, geothermal, and bioenergy) from 1974 to 2009 in the United States. They find both the stability and size of government financial commitment to affect technology innovation, hence renewable energy innovation. Besides, the findings indicate that national-level R&D expenditures, policies pertaining to technology commercialization, and marketization are critical determinants of innovation activities. Using OECD data from the 1970s, Nesta et al. [47] find that environmental and renewable energy policies are essential in driving green innovation in countries with liberalized (competitive) energy markets. Saygin et al. [17] examine the potential of renewable energy technologies and the role of innovation in doubling the global renewable energy share from 18 % to 36 % between 2010 and 2030. Using national energy plans of 26 countries, they found that the renewable energy share could increase to 21 % by 2030. By accumulating country capabilities, they reveal that the global renewable energy share could double to 36 % by 2030. Miremadi et al. [4] assess the effect of public R&D and knowledge spillovers on developing renewable energy innovation in the Nordic countries. They find that cumulative knowledge stock in the Nordic countries will rise to

$2.4 billion by 2030, focusing on biofuels, solar, and wind energy. Jiang et al. [19] examine the effect of energy innovation and innovation transformation on energy consumption in China from 2009 to 2016. Using the fixed effect and Generalized Method of Moments (GMM) Vector Autoregressive (VAR) models, they find that green innovation transformation can reduce energy consumption.

Khan et al. [48] found that whereas eco-innovation negatively affects nonrenewable energy consumption, it enhances the consumption of renewable energy in G7 countries over the period 1995–2017. Li et al. [49] found results suggesting that eco-innovation drives renewable energy consumption for OECD economies over the period from 1990 to 2017. Using a sample of 25 OECD countries, Alam and Murad [50] show the mixed impact of technology progress on renewable energy, especially in the short run. Among other variables, Khan, Chenggang, Hussain and Kui [51] examine the technological innovation and renewable innovation for 69 Belt and Road Initiative countries for the period 2000–2014 and find a negative relationship. Ahmed et al. [52], for the period 1985–2018, found that public R&D investments in renewable energy increased renewable energy supply in G7 countries. Chen, Shi and Zhao [53] find that investment in renewable energy resources enhances energy efficiency in the USA (from 1990 to 2020). Solarin, Bello and Tiwari [22] examine the relationship between technological innovation and renewable energy for the period 1993 to 2018 for BRICS countries and find a positive relationship. Khan et al. [20] looked at the relationship between technology innovations and renewable energy in Germany for the period 2000 to 2021. They find that technology innovation enhances renewable energy positively for the full sample and negatively across multiple sub-samples (2005:03–2006:02; 2007:02–2008:10; 2010; 10–2011:09, 2012:01–2014:05, 2015, 01–2017:05, 2018:10–2020-04). Khan and Su [21] examine similar G10 countries for the same period and find that technology innovation has a significant impact on renewable energy in countries such as Germany, the Netherlands, Sweden, the UK, and the USA.

The reviewed studies have largely found a positive relationship; however, while innovation investment in energy can generally promote the development of renewable energy, there are scenarios where the innovation could have no adverse impact, particularly in the short term. For example, companies may focus on short-term gains rather than long-term horizons and may invest in innovation that does not have a longer-term effect on renewable energy. The heavy and longtime dependence on fossil fuels can also affect the effect of innovation investment in renewable energy. It will, therefore, take a long time for energy innovation investment and adoption strategies to have the full benefits of the investment. Also, some of the innovations may be specifically targeted at particular energy sources like solar energy and may not have a significant effect on other energy sources or renewable energy as a whole.

Innovation investment could also lead to the establishment of new technologies that could compete with renewable energy production and adoption. For example, the creation of new types of fossil fuels and more sustainable extraction of these fuels reduce environmental impact. This may have a negative effect on renewable energy. Also, an increase in fossil fuel investment may offset the effect of energy innovation investment on renewable energy. The IEA, for example, shows that notwithstanding a rise in renewable energy investment between 2004 and 2011, there was no apparent reduction in fossil fuel investment for that period and periods before and after (IEA, 2024). Besides, the high risk and complexity of eco-innovation can affect the creation and use of renewable energy. For example, investment in energy innovation is highly costly and has to do with the development of new and untested technologies. This makes it highly risky as it may not fully serve its intended purpose or may end up having a negative effect. The innovation can also lead to unintended environmental impacts that may counteract the effect of renewable energy.

As some of the reviewed studies focus on technology innovation in general for a handful of countries, the present study specifically focuses on energy innovation investment for the OECD. The present study also differs in the sense that as they have looked at aggregate renewable energy, we focus on disaggregated renewable energy sources. Also, we examine the renewable energy source that benefits the most from energy innovation investment. The largest part of the literature on energy innovation investment has actually looked at its impact on the environment (Wang& Zhu, 2020; [24,54]). Hence, we contribute to its impact on renewable energy generation.

## 3. Methodology and data

### 3.1. Empirical model and estimation strategies

To estimate the effect of energy innovation investment on renewable energy generation/production in the OECD countries, this paper augments the renewable energy empirical model used in the work of Rafiq, Bloch, and Salim [55], Acheampong, Dzator, and Savage [56] and da Silva, Cerqueira, and Ogbe [57] with energy innovation investment. Eq. (1) is the reduced form empirical model;

$$ln\ RE_{it} = \alpha_0 + \beta_1 lnENERGY_{RDit} + \beta_j X_{it} + \varepsilon_{it} \tag{1}$$

Where $lnRE_{it}$ is the natural logarithm of renewable energy production (including disaggregated renewable energy sources such as wind, solar, nuclear, hydro, and gas) in country $i$ at time $t$.[3] $lnENERGY\_RD_{it}$ is the natural logarithm of energy innovation (investment), $X_{it}$ is a set of control variables. $\alpha_0$ is a constant parameter to be estimated, $\beta_1$ is the coefficient of energy innovation investment to be estimated, $\beta_j$ is the coefficient of the control variables to be estimated and $\varepsilon_{it}$ is the stochastic error term.

Before estimating the empirical model, several pre-estimation tests such as cross-sectional dependency (CSD), stationarity and cointegration tests were conducted. As observed by De Hoyos & Sarafidis [58], due to the presence of common shocks and unobserved components that are often contained in the error term of panel data, CSDs can hardly be ruled out in panel estimations. The Persaran (2004; 2006) CSD test was used to test for CSD in the variables. The test reveals the presence of CSD in the data (see Table A2). Given the presence of CSD in the data, we proceed to implement Pesaran's cross-sectionally Augmented Dickey-Fuller (CADF) test and the cross-sectionally augmented panel unit root test (CIPS) to test for the stationarity of our variables. We noticed that for both tests in levels, seven variables out of the eleven are stationary for the CADF test and six variables for the CIPS test (see Table A3). As a robustness check, we also employ the Augmented Dickey-Fuller (ADF) and Phillips Perron (PP) panel unit root tests, confirming the stationarity of all variables at the first difference (see Table A4). We also test cointegration among the variables using the Westerlund [59] panel cointegration test. The application of the Westerlund [59] panel cointegration test is to account for structural break possibilities within the variables and offers impartial estimates in the presence of heteroscedasticity and CSD. Westerlund's [59] panel cointegration test reveals a cointegration among our variables (see Table A5), suggesting the long-run relationship among the variables.

Having achieved these preliminary results, we proceed by first estimating the empirical model with the fully modified OLS (FMOLS) and the dynamic OLS (DOLS). We employ the FMOLS and DOLS estimators methods for several reasons. FMOLS, according to Phillips and Hansen [60], is capable of controlling for endogeneity and serial correlation in the explanatory variables and has high parametric efficiency in small samples. DOLS by Stock and Watson [61] is also capable of producing

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[3] Noted that here we capture gas as part of the renewable energy sources, however strictly speaking it is not a renewable source. Nevertheless, relative to other non-renewable energy sources it is regarded a more reliable and greener alternative. In essence, it is more benign to the environment than other fossil sources like coal and crude oil.

**Table 5**
The impact of energy innovation on renewable energy by controlling for the effect of oil price [FMOLS and DOLS results].

| | Model 1 | Model 2 | Model 3 | Model 4 | Model 5 | Model 6 |
|---|---|---|---|---|---|---|
| | Total RE | Wind | Solar | Nuclear | Hydro | Gas |
| **Panel A: FMOLS estimates** | | | | | | |
| Real GDP | 1.755*** | 3.520*** | 1.699* | 1.103 | 0.640 | 1.462** |
| | (0.266) | (0.737) | (0.933) | (1.386) | (0.919) | (0.690) |
| CO2 | 0.799*** | 1.217*** | 1.367*** | 0.397 | −0.152 | 0.891*** |
| | (0.099) | (0.238) | (0.276) | (0.484) | (0.343) | (0.202) |
| FDI | 0.007 | −0.218 | −0.360 | −0.088 | 0.039 | 0.248 |
| | (0.092) | (0.209) | (0.234) | (0.250) | (0.319) | (0.173) |
| Trade | 0.063 | 2.266*** | 1.896** | −0.879 | −3.443*** | −0.073 |
| | (0.309) | (0.737) | (0.812) | (0.974) | (1.106) | (0.568) |
| Energy_RD | −0.594*** | −1.400*** | −0.206 | −0.383 | −0.188 | 0.829*** |
| | (0.120) | (0.307) | (0.340) | (0.397) | (0.412) | (0.242) |
| Oil Price | 0.479*** | 0.269 | 0.170 | 0.322 | −0.043 | −0.350** |
| | (0.079) | (0.183) | (0.202) | (0.217) | (0.276) | (0.160) |
| Constant | −34.759*** | −64.921*** | −46.316*** | −11.064 | 11.489 | −23.402** |
| | (3.754) | (10.516) | (12.922) | (14.706) | (12.991) | (9.898) |
| Observations | 523 | 398 | 332 | 296 | 545 | 303 |
| R2 | 0.146 | 0.167 | 0.123 | 0.051 | 0.065 | 0.079 |
| **Panel B: DOLS estimates** | | | | | | |
| Real GDP | 1.705*** | 3.473*** | 1.587 | 0.904 | 0.533 | 1.168 |
| | (0.376) | (0.808) | (1.264) | (1.866) | (1.078) | (0.856) |
| CO2 | 0.754*** | 1.226*** | 1.428*** | 0.549 | −0.045 | 0.783*** |
| | (0.132) | (0.247) | (0.346) | (0.591) | (0.387) | (0.248) |
| FDI | 0.065 | −0.158 | −0.493 | −0.071 | 0.096 | 0.327 |
| | (0.151) | (0.275) | (0.385) | (0.382) | (0.432) | (0.258) |
| Trade | −0.104 | 2.594*** | 2.562** | −0.723 | −3.636*** | −0.238 |
| | (0.436) | (0.806) | (1.089) | (1.273) | (1.306) | (0.714) |
| Energy_RD | −0.571*** | −1.243*** | −0.119 | −0.370 | −0.225 | 0.726** |
| | (0.173) | (0.340) | (0.461) | (0.493) | (0.496) | (0.291) |
| Oil Price | 0.480*** | 0.367* | 0.389 | 0.284 | −0.002 | −0.328* |
| | (0.106) | (0.188) | (0.248) | (0.280) | (0.312) | (0.192) |
| Constant | −33.050*** | −66.159*** | −49.592*** | −11.395 | 11.799 | −18.529 |
| | (5.552) | (12.056) | (18.265) | (20.637) | (16.000) | (12.587) |
| Observations rowhead | 521 | 396 | 330 | 294 | 543 | 301 |
| R2 rowhead | 0.541 | 0.448 | 0.360 | 0.567 | 0.388 | 0.669 |

Standard errors in parentheses. $*p < 0.10$, $**p < 0.05$, $***p < 0.01$.

robust estimates in small samples and corrects for regressor endogeneity by incorporating leads and lags of the first difference of the regressors. Stock and Watson [61] explain that the inclusion of the leads and lags removes the bias of simultaneity within the sample. We also deploy the Baum et al. (2002) instrumental variable generalized method of moment (IV-GMM) technique and the Lewbel (2012) two-stage least squares estimator to address endogeneity. Furthermore, given the CSD among the variables, this study further applied the Driscoll and Kraay (1998) estimator as an additional estimator for the robustness check.

## 4. Results and discussion

We first run the estimations with DOLS and FMOLS (respectively in Tables 2–3). Tables 2–3 present 6 models with the dependent variables being, respectively, total RE, Wind, Solar, Nuclear, Hydro, and Gas.[4] Both estimation methods suggest that energy innovation has a negative coefficient but is only statistically significant for the models that use wind and gas as the dependent variables. This outcome suggests that holding all other things constant, generally, energy innovation investments have not been favourable to renewable energy generation in OECD countries. To account for endogeneity and CSD (as found in the data), we further employ the Baum et al. (2002) IV-GMM technique.[5] This estimation technique enables us to account for potential endogeneity. In addition, the estimator allows consistent estimations in the presence of AR (1) autocorrelation within panels and heteroscedasticity (Baum et al., 2002). Also, the IV-GMM estimator is consistent with Driscoll and Kraay's (1998) standard errors that are robust to 'spatial' and temporal CSD (Baum et al., 2002). Considering that the IV-GMM accounts for endogeneity and CSD, we focus the discussion on this method.

The IV-GMM results are reported in Panel A of Table 4. Based on the results in Table 4 (Panel A), we observe that energy innovation expenditure has negative and statistically significant (at 1 % and 10 % levels) coefficients with all the estimated models but has a significant positive effect on gas generation (see Model 6). At a glance, this finding might seem puzzling, given that one would expect an increase in energy innovation to lead to an increase in total renewable energy production and consumption. However, the results reveal that such investments may be more targeted (such as towards gas production in our case) mainly at the types of energy needs in each country based on accessibility and availability. Gas is the only energy source found to be positively associated with renewable energy investment; hence, it is not far-fetched that energy innovation may have a positive impact on gas production. In the midst of the Russia-Ukraine war, gas was the major energy concern for most OECD countries, especially for those in Europe. What this result seems to communicate is that renewable energy investment has benefited gas generation the most. Even though it is not an explicitly renewable energy source, it is often considered an environmentally benign energy type relative to other fossil fuels and constitutes a considerable share of the OECD countries' energy mix.

Indeed, Beise & Rennings [41] and Miremadi et al. [4] noted that energy innovation investments could be for new/clean energy or to

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[4] The estimations using gas as the dependent variable should be interpreted with caution as they are based on only 10 countries and may not be representative of the whole of OECD but only the countries in the sample. Again, we emphasize that due to data availability issues we employed aggregate R&D expenditures on energy innovation to represent energy innovation investment.

[5] We employ the first and second lags of the energy innovation variable as instruments.

**Table 6**

The lag impact of energy innovation on renewable energy [FMOLS results].

| | Total RE | | Wind | | Solar | | Nuclear | | Hydro | | Gas | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| L.Energy_RD | −0.597*** | | −1.383*** | | −0.341 | | −0.386 | | −0.222 | | 0.820*** | |
| | (0.122) | | (0.295) | | (0.365) | | (0.388) | | (0.410) | | (0.253) | |
| L2.Energy_RD | | −0.630*** | | −1.551*** | | −0.394 | | −0.351 | | −0.270 | | 0.763*** |
| | | (0.124) | | (0.293) | | (0.366) | | (0.388) | | (0.412) | | (0.253) |
| Controls | YES | YES | YES | YES | YES | YES | YES | YES | YES | YES | YES | YES |
| | (0.080) | | (0.178) | | (0.217) | | (0.213) | | (0.274) | | (0.165) | |
| Constant | −35.569*** | −36.727*** | −64.758*** | −67.589*** | −45.821*** | −45.418*** | −8.401 | −6.200 | 11.155 | 10.338 | −23.630** | −24.001** |
| | (3.860) | (3.982) | (10.105) | (10.050) | (13.864) | (13.907) | (14.849) | (15.565) | (13.069) | (13.294) | (10.478) | (10.653) |
| Observations | 526 | 519 | 408 | 409 | 341 | 342 | 294 | 288 | 544 | 535 | 304 | 299 |
| R2 | 0.189 | 0.206 | 0.309 | 0.271 | 0.109 | 0.101 | 0.065 | 0.070 | 0.048 | 0.045 | 0.151 | 0.098 |

Standard errors in parentheses.*$p < 0.10$, **$p < 0.05$, ***$p < 0.01$.

improve procedures, methods, schemes, and products to minimize environmental damage. In addition, as observed by Papież et al. [62], energy policy decisions are often pragmatic and tend to be centred around the needs of local reality, including the individual country's energy security and labour market protections, rather than universal climate protection values. Although the negative effect of energy innovation on renewable energy seems to contradict such studies as Jiang et al. [19], who document that green innovation transformation can reduce energy consumption in China, our finding is suggestive that reduction in energy consumption may not necessarily translate into increment in total renewable energy generation and consumption. A plausible reason could also be that, on an aggregate level, energy innovation may not be sufficient to translate into complete uptake in total renewable energy as their production often involves huge and long-term capital investments ([16]; Nesta, Vona & Nicolli, 2014 [42]).

For the control variables, the results show that economic growth and $CO_2$ emissions generally have positive and statistically significant coefficients (Panel A of Table 4), whereas FDI and trade openness have both negative and positive statistically significant coefficients in some models. The implication of the economic growth variable results is that an increase in economic growth may stimulate renewable energy production and consumption. This finding is consistent with a host of other recent studies, including Przychodzen and Przychodzen [63], Salim & Rafiq [64], da Silva et al. [57]; Acheampong et al. [56], and Lu [65] which all document the positive linkage. Gan and Smith [66] opined that countries with higher GDP are more concerned with alternative energy supply, focusing their policies on developing renewable energy generation capacity, which is consistent with the Environmental Kuznets Curve hypothesis. The reason is that individuals in high-income countries (like in the sample) are often concerned about the environment and thus could urge their governments to implement policies and regulations in favour of cleaner energy (see, for instance, Omiri and Nguyen, 2014). With higher growth comes high income, which could foster renewable energy deployment by raising the financial resources that can be allocated to fund capital-intensive renewable energy projects or regulatory initiatives (see Ref. [67,68]). With regards to $CO_2$ emissions, the result is suggestive that the continuous upsurge in $CO_2$ emissions is a major driver behind the expansion of renewable energy production as societies seek to mitigate the harmful impact of climate change due to excessive pollution (see, inter alia [56,69,63]). This finding also corroborates the evidence by Omiri and Nguyen (2014) that rising $CO_2$ emissions levels, in turn, create the necessary pressure and public appetite for environmentally sustainable policies, including using renewable energies as alternative sources.

For the FDI variable, the result suggests that an increase in FDI bodes well for a rise in total renewable energy generation and gas production in particular. This finding is intuitive because successful acceleration in deploying renewable energy projects hinges on both strong policies and access to financial capital via FDI channels. In particular, FDI inflows supporting clean energy technologies bring financial capital, managerial expertise, know-how, and greater energy efficiency via the so-called technology leapfrogging, stimulating the development and dissemination of secure and clean energy resources. This is in line with Gallagher and Zarsky [70], Keeley and Ikeda [71], Kumar and Sinha [72], and Przychodzen and Przychodzen [63] that FDI positively influences renewable energy production. However, although the negative coefficient for solar generation contradicts the literature mentioned above, it is consistent with Przychodzen and Przychodzen [63], with plausible implications that not all renewable energy types benefit from FDI investments within our sample.

On the trade openness variable, the results suggest that greater openness can positively stimulate total renewable energy production and increase the generation of solar and wind energies. This finding is unsurprising and in line with the literature, as trade openness often brings about technology and knowledge transfers (see Ref. [67,73]). Indeed, increasing trade openness can promote the importation of clean

**Table 7**
The impact of energy innovation on renewable energy [FMOLS results].

| | Total RE | Wind | Solar | Nuclear | Hydro | Gas |
|---|---|---|---|---|---|---|
| Energy_RD | −0.587** | −0.069 | 0.765 | −1.668* | −0.172 | 2.127*** |
| | (0.284) | (0.654) | (0.788) | (0.899) | (0.948) | (0.500) |
| Energy_RD_Sq | −0.010 | 0.320** | 0.234 | −0.422 | 0.013 | 0.469*** |
| | (0.064) | (0.138) | (0.178) | (0.276) | (0.217) | (0.165) |
| Controls | YES | YES | YES | YES | YES | YES |
| Constant | −34.557*** | −74.140*** | −54.227*** | −1.192 | 10.341 | −30.650*** |
| | (4.067) | (10.239) | (12.997) | (14.725) | (13.748) | (8.728) |
| Observations | 523 | 398 | 332 | 296 | 545 | 303 |
| r2 | 0.219 | 0.176 | 0.088 | 0.053 | 0.065 | 0.173 |

Standard errors in parentheses. $^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$.

and energy-efficient technologies due to the so-called technology transfer [74]; [75,76], which could help in diffusing the adoption of production technologies using renewable energy while upscaling total renewable energy generation. However, similar to FDI, we conjecture that the negative effect of trade openness on hydro and nuclear generation may imply that technology and knowledge transfers via trade openness are renewable energy sources specific, with less incentives for nuclear and hydro generation. We hasten to add here that the mixed (positive and negative) coefficients of FDI and trade on renewable energy types/sources are rather consistent with Bourcet [77], who asserts that global studies fail to find clear proof regarding the direction of the relationship between the size of international flows (i.e., trade and/or FDIs) on renewable energy deployment.

Although the IV-GMM estimations have provided some meaningful insights, for further robustness of the results, the study also utilizes the Lewbel (2012) two-stage least squares (2SLS) as an alternative estimation technique. The Lewbel 2SLS estimator is applied when the sources of identification, such as having appropriate external instruments, are not available or weak. The estimator includes internally constructed heteroskedasticity-based instruments.

These are generated from the auxiliary equation's residuals, which are multiplied by each of the included exogenous variables in mean-centred form. For empirical estimation, this approach does not rely on satisfying standard exclusion restrictions. The estimations from the Lewbel 2SLS model are reported in Panel B of Table 4. The coefficients of the main explanatory variable are negative and statistically significant for models 2, 3, and 5. The negative coefficients are generally consistent with the previous estimation methods employed. Interestingly, the coefficients of energy innovation turn negative and statistically significant for model 6 (where gas is the dependent variable) but statistically insignificant for model 1 (with Total renewable energy as the dependent variable) and model 4 (with nuclear as the dependent variable). For all the control variables, the Lewbel 2SLS estimates did not show any surprises, as the estimates are largely consistent with the results from the IV-GMM models.

To further account for the presence of CSD, we employ the Driscoll-Kraay estimator. As Hoechle [78] observed, the Driscoll-Kraay estimator can produce heteroskedasticity- and autocorrelation-consistent standard errors that are robust to general spatial and temporal dependence forms. The Discroll-Kraay standard errors have been commonly used in the literature as one of the ways to handle cross-sectional dependence (see Ref. [58,78]). Consequently, we present the results based on the Driscoll-Kraay estimator in Panel C of Table 4. Similar to the IV-GMM estimations, the coefficients of the main explanatory variable are negative and statistically significant except in model 6, where the dependent variable is gas and comes with a positive coefficient. The only difference is that the coefficient for energy innovation investment in the Driscoll-Kraay results is statistically insignificant for model 4 (where nuclear generation is the dependent variable). Thus, holding other things constant, the Driscoll-Kraay estimator suggests that our earlier explanation holds for all models except for model 4.

In combining all the outcomes from the various estimation methods, the results generally indicate a negative effect of energy innovation investments on renewable energy, except in the case of gas, where the coefficient of energy innovation is generally positive. The results, hence, suggest that at an aggregated level, energy innovation may not be sufficient to stimulate total renewable energy in OECD countries except for gas production. Gas is often considered an environmentally benign energy type relative to other fossil fuels and constitutes a sustainable share of the OECD countries' energy mix (over 30.6 % of the total energy supply in 2020); it is not far-fetched that energy innovation may have a positive impact on gas production. In the midst of the Russia-Ukraine tension, gas has been the major energy concern for most OECD countries, especially those in Europe.

## 5. Extension of analysis

We run further analysis by testing the effect of oil prices, the lag effects of renewable energy innovation and the nonlinear effect of nonrenewable energy innovations on the energy sources.[6] Oil prices, which are proxies for crude oil or fossil energy prices, are obtained from the Energy Institute Statistical Review of World Energy. Given that the oil prices we used are international prices, we follow Doytch and Narayan [79] to compute energy price data for each country by deflating oil prices by each country's consumer price index, using 2015 as the base year (just as used for the real variables from the WDI). Data on crude oil prices, measured in US dollars per barrel, are obtained from the Energy Institute Statistical Review of World Energy.

Table 5 shows FMOLS (Panel A) and DOLS (Panel B) estimates on the effect of energy innovation on renewable energy while controlling for the effect of oil prices. From Panels A and B of Table 5, the impact of energy innovation consistently has a negative effect on total renewable energy, wind, solar, nuclear and hydro energy, but the impact is only significant in total renewable energy and wind energy models (see Models 1 and 2). As presented in Table 5, Models 6 of both Panels A and B show that energy innovation has a consistently significant positive effect on gas generation.

We also argue that energy innovation investment may have a lag effect on renewable energy. We, therefore, estimated the lags (lags 1 and 2) effect of energy innovation investment on renewable energy and the results are presented in Table 6.[7] From Table 6, the results remain similar to those found in the previous estimations using contemporaneous energy innovation investment as the explanatory variable.

We further fit a nonlinear estimation where we include the squared term of energy innovation investment as an additional explanatory variable (Table 7). The result for the linear term of energy innovation investment remains largely consistent with the previous results, except

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[6] We thank the anonymous reviewers for suggesting these to us.

[7] Considering that FMOLS and DOLS estimations produced similar results, we report those of the FMOLS only. Further lags produced similar results. We do not report those to save space and also considering we have a limited sample size.

that the coefficient turns statistically insignificant when wind energy is the dependent variable and turns slightly significant for nuclear energy as the dependent variable. At the same time, the coefficient of the squared term remains statistically insignificant, except when wind energy and gas are the dependent variables. In combining all the outcomes from the various estimation methods, the results generally indicate a negative effect of energy innovation investments on renewable energy, except in the case of gas, where the coefficient of energy innovation is generally positive. The results, hence, suggest that at an aggregated level, energy innovation may not be sufficient to stimulate total renewable energy in OECD countries except for gas production.

## 6. Conclusion

Greenhouse gas emissions, especially carbon emissions, have been a significant driver of global climate change. Over the past decades, climate change has posed a threat to the global economy. The Intergovernmental Panel for Climate Change has indicated that achieving carbon neutrality in 2050 remains fundamental for limiting global warming to 1.5°C and mitigating the catastrophic effects of climate change. Policymakers and scholars have indicated that the transition towards a renewable energy economy is the catalyst for achieving carbon neutrality in 2050. Transitioning towards a renewable energy economy requires substantial investment in renewable energy technologies. While most empirical studies have explored the linkage between investment in R&D and carbon emissions, few studies have examined the effect of R&D on renewable energy generation [80]. Our paper, therefore, extends and contributes to the literature by investigating the effect of energy innovation on renewable energy generation using a comprehensive panel dataset of 26 OECD countries from 1974 to 2020. Using a battery of estimation methods (including FMOLS, DOLS, IV-GMM, Lewbel 2SLS and the Driscoll and Kraay estimator) to control for cross-sectional dependence, heteroskedasticity, autocorrelation and potential endogeneity, the empirical findings that emerge suggest that energy innovation does not improve renewable energy generation in the panel of OECD countries. The results also showed that energy innovation has a heterogeneous effect on disaggregated renewable energy sources. Thus, energy innovation does not increase wind, nuclear, and hydro energy generation but may increase gas production.

The availability of data has limited this study. For example, the data had many missing observations due to access issues. Also, due to issues of data availability, we could not get specific investments going into the different energy sources to ascertain the specific impact. As a result, we employed aggregate R&D expenditures on energy innovation to represent energy innovation investment. With the availability of data, future studies could examine specific innovation investments, such as solar energy, to determine the effect of the investment on solar energy generation.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

Data will be made available on request.

## Appendix 1

Table A1Renewable Energy Generation (measured in Exajoules) in OECD countries

| Countries | 1970s | 1980s | 1990s | 2000s | 2010s |
|---|---|---|---|---|---|
| Australia | 0.004 | 0.005 | 0.009 | 0.045 | 0.224 |
| Austria | 0.000 | 0.004 | 0.015 | 0.044 | 0.114 |
| Belgium | 0.002 | 0.001 | 0.003 | 0.020 | 0.141 |
| Canada | 0.007 | 0.022 | 0.065 | 0.122 | 0.393 |
| Denmark | 0.000 | 0.002 | 0.022 | 0.082 | 0.175 |
| Finland | 0.000 | 0.000 | 0.066 | 0.094 | 0.147 |
| France | 0.014 | 0.016 | 0.029 | 0.096 | 0.451 |
| Germany | 0.012 | 0.017 | 0.041 | 0.477 | 1.586 |
| Greece | 0.000 | 0.000 | 0.000 | 0.015 | 0.084 |
| Hungary | 0.000 | 0.000 | 0.000 | 0.012 | 0.037 |
| Ireland | 0.000 | 0.000 | 0.001 | 0.014 | 0.069 |
| Italy | 0.039 | 0.035 | 0.041 | 0.129 | 0.579 |
| Japan | 0.006 | 0.110 | 0.139 | 0.217 | 0.631 |
| Korea, Rep. | 0.000 | 0.000 | 0.001 | 0.008 | 0.185 |
| Netherlands | 0.008 | 0.006 | 0.014 | 0.064 | 0.168 |
| New Zealand | 0.017 | 0.018 | 0.028 | 0.042 | 0.092 |
| Norway | 0.000 | 0.000 | 0.003 | 0.008 | 0.043 |
| Poland | 0.002 | 0.003 | 0.001 | 0.025 | 0.193 |
| Portugal | 0.002 | 0.005 | 0.010 | 0.043 | 0.155 |
| Slovakia | 0.000 | 0.000 | 0.000 | 0.004 | 0.022 |
| Spain | 0.002 | 0.005 | 0.016 | 0.227 | 0.680 |
| Sweden | 0.003 | 0.016 | 0.024 | 0.084 | 0.276 |
| Switzerland | 0.001 | 0.004 | 0.006 | 0.010 | 0.030 |
| Turkey | 0.002 | 0.001 | 0.002 | 0.006 | 0.200 |
| United Kingdom | 0.000 | 0.000 | 0.020 | 0.116 | 0.697 |
| United States | 0.228 | 0.357 | 0.772 | 1.363 | 4.371 |

NB: 1970, 1980, 1990, 2000, and 2010, respectively, represent the average of data from 1974 to 1979, 1980–1989, 1990–1999, 2000–2009, and 2010–2020.

Table A2Cross-sectional dependence test

| Variables | CD-test | *P*-value | Average joint T | mean (ρ) | mean abs(ρ) |
|---|---|---|---|---|---|
| Renewable | 98.086*** | 0.000 | 37.04 | 0.90 | 0.90 |
| Wind | 84.697*** | 0.000 | 26.60 | 0.91 | 0.91 |
| Solar | 70.205*** | 0.000 | 19.49 | 0.89 | 0.89 |
| Nuclear | 42.685*** | 0.000 | 40.96 | 0.21 | 0.22 |
| Hydro | 25.503*** | 0.000 | 46.15 | 0.21 | 0.31 |
| Gas | 1.494 | 0.135 | 44.47 | 0.01 | 0.07 |
| Real GDP | 107.772*** | 0.000 | 41.04 | 0.94 | 0.94 |
| CO2 | 17.669*** | 0.000 | 42.59 | 0.15 | 0.58 |
| FDI | 46.548*** | 0.000 | 37.28 | 0.42 | 0.46 |
| Trade | 75.639*** | 0.000 | 42.59 | 0.65 | 0.71 |
| Energy_RD | 30.455*** | 0.000 | 26.88 | 0.32 | 0.43 |

Notes: All variables are expressed in natural logarithms. The null hypothesis is that cross-sectional units are independent of each other in the panel. *** denotes statistical significance at a 1 % level. Under the null hypothesis of cross-section independence.

**Table A3**
CADF and IPS Unit roots test

| Variables | CADF<br>Z [t-bar] |  | CIPS<br>W-*t*-bar |  |
|---|---|---|---|---|
|  | Levels | 1st Difference | Levels | 1st Difference |
| Renewable | −2.679*** | −7.409*** | 4.781 | −24.694*** |
| Wind | −2.884*** | −6.265*** | −10.228*** | −15.043*** |
| Solar | −1.873** | −1.636** | 4.304 | −11.545*** |
| Nuclear | −3.429*** | −10.112*** | −18.396*** | −28.715*** |
| Hydro | −6.387*** | −17.766*** | −14.293*** | −45.848*** |
| Gas | 6.784 | −2.940*** | 4.161 | −17.844*** |
| Real GDP | 1.962 | −5.737*** | −1.895** | −15.017*** |
| CO2 | 0.208 | −9.445*** | −0.815 | −31.178*** |
| FDI | −3.211*** | −3.765*** | −8.602*** | −40.013*** |
| Trade | −1.594** | −10.224*** | 0.663 | −26.819*** |
| Energy_RD | 0.549 | −4.946*** | −4.222*** | −24.583*** |

The null hypothesis is that the series is nonstationary. All tests incorporate a constant and trend. The null hypothesis is that the series is nonstationary.

**Table A4**
ADF and PP Unit root test

| Variables | ADF |  |  |  | PP |  |  |  |
|---|---|---|---|---|---|---|---|---|
|  | Inverse chi-squared | Inverse normal | Inverse logit | Modified inv. chi-squared | Inverse chi-squared | Inverse normal | Inverse logit | Modified inv. chi-squared |
| Levels |  |  |  |  |  |  |  |  |
| Renewable | 69.935** | 3.104 | 2.696 | 1.759** | 69.935** | 3.104 | 2.696 | 1.759** |
| Wind | 335.185*** | −9.878*** | −16.931*** | 27.769*** | 335.185*** | −9.878*** | −16.931*** | 27.769*** |
| Solar | 87.990*** | 3.863 | 1.551 | 3.529*** | 87.9899*** | 3.8634 | 1.5508 | 3.5291*** |
| Nuclear | 470.681*** | −16.800*** | −32.464*** | 54.835*** | 470.681*** | −16.800*** | −32.464*** | 54.835*** |
| Hydro | 385.398*** | −14.683*** | −20.709*** | 32.692*** | 385.398*** | −14.683*** | −20.709*** | 32.692*** |
| Gas | 46.504*** | −1.113 | −2.300** | 4.191*** | 46.5038*** | −1.1125 | −2.3002 | 4.1906*** |
| Real GDP | 102.004*** | −2.006** | −2.767*** | 4.903*** | 102.004*** | −2.006** | −2.767*** | 4.903*** |
| CO2 | 73.874** | −0.879 | −1.101 | 2.145** | 73.8741** | −0.8792 | −1.1007 | 2.1449** |
| FDI | 219.322*** | −9.012*** | −11.176*** | 16.407*** | 219.322*** | −9.012*** | −11.176*** | 16.407*** |
| Trade | 44.652 | 0.850 | 0.624 | −0.721 | 44.652 | 0.850 | 0.624 | −0.721 |
| Energy_RD | 148.172*** | −3.513*** | −6.303*** | 9.430*** | 148.172*** | −3.513*** | −6.303*** | 9.430*** |
| 1st **Difference** |  |  |  |  |  |  |  |  |
| Renewable | 730.313*** | −22.906*** | −39.626*** | 66.514*** | 730.313*** | −22.906*** | −39.626*** | 66.514*** |
| Wind | 413.335*** | −15.797*** | −22.377*** | 35.432*** | 413.335*** | −15.797*** | −22.377*** | 35.432*** |
| Solar | 298.335*** | −9.767*** | −15.427*** | 24.155*** | 298.335*** | −9.767*** | −15.427*** | 24.155*** |
| Nuclear | 587.923*** | −20.619*** | −40.646*** | 69.490*** | 587.923*** | −20.619*** | −40.646*** | 69.490*** |
| Hydro | 1658.390*** | −38.474*** | −89.995*** | 157.520*** | 1658.390*** | −38.474*** | −89.995*** | 157.520*** |
| Gas | 284.734*** | −14.609*** | −25.057*** | 41.858*** | 284.734*** | −14.609*** | −25.057*** | 41.858*** |
| Real GDP | 392.788*** | −15.613*** | −21.212*** | 33.417*** | 392.788*** | −15.613*** | −21.212*** | 33.417*** |
| CO2 | 1079.169*** | −29.902*** | −58.562*** | 100.722*** | 1079.169*** | −29.902*** | −58.562*** | 100.722*** |
| FDI | 1426.664*** | −35.351*** | −77.420*** | 134.797*** | 1426.664*** | −35.351*** | −77.420*** | 134.797*** |
| Trade | 858.933*** | −26.533*** | −46.611*** | 79.126*** | 858.933*** | −26.533*** | −46.611*** | 79.126*** |
| Energy_RD | 805.167*** | −24.160*** | −43.626*** | 73.854*** | 805.167*** | −24.160*** | −43.626*** | 73.854*** |

**Table A5**
Westerlund Cointegration Test.

| | Model 1 | Model 2 | Model 3 | Model 4 | Model 5 | Model 6 |
|---|---|---|---|---|---|---|
| **Variance ratio** | −3.281*** | −3.645*** | −2.470*** | −2.500*** | −4.691*** | −2.064** |

Model 1: cointegration results for total renewable energy model; Model 2: cointegration results for wind energy model; Model 3: cointegration results for solar energy model; Model 4: cointegration results for nuclear energy model; Model 5: cointegration results for hydro energy model; Model 6: cointegration results for gas energy model.

### *3.2. Data description*

The study uses a comprehensive panel dataset of 26 OECD countries from 1974 to 2020.[8] Six renewable energy variables (including total renewable energy) were used. These include total renewable energy production, wind energy, nuclear energy, hydro energy, and gas energy production. All the renewable energy variables were obtained from the BP Statistical Review.[9] Energy innovation investment was measured using the energy technology RD&D budgets per thousand units of GDP. This was sourced from the International Energy Agency (IEA). Following the existing literature on renewable energy, variables such as carbon emissions, economic development/standard of living, foreign direct investment and trade openness have been indicated to affect renewable energy generation [55–57,69]. Therefore, these variables were included in the empirical model to prevent omission variable bias. These control variables were sourced from the World Development Indicator (WDI) database. The descriptive statistics, variables definitions, and measurements are presented in Table 1. For the empirical estimation, all the variables were transformed using natural logarithms. The variables are logged for the following reasons: they help reduce the influence of outliers, they make interpretation of the estimates easier, and they also help to reduce heteroscedasticity [81].

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