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Do innovation and renewable energy transition play their role in environmental sustainability in Western Europe?

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Western European economies are among the top innovative countries in the globe and show a remarkable commitment to environmental sustainability through innovations and renewable energy targets. Particularly, renewable energy transition (RET) may shift Western European economies from unclean to clean energy sources and could reduce pollution. Therefore, we analyze the impact of RET and patents on CO_2 emissions in 25 Western Europe countries using a period 1995–2020 and cross-sectional dependence techniques. Moreover, the impact of economic growth is also analyzed to examine the Environmental Kuznets Curve (EKC). The results suggest the presence of EKC with a turning point at GDP per capita of 50,287 dollars and Denmark, Iceland, Sweden, Ireland, Norway, Luxembourg, and Switzerland are found at the second stage of the EKC in the long run. Moreover, RET reduces CO_2 emissions in the long and short run, Thus, RET helps to achieve environmental sustainability by reducing CO_2 emissions in Western European economies. However, patents have negative effects in the long run but do not affect emissions in the short run. Thus, innovation helps to sustain an environment in the long run.

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Introduction

CO_2 emissions are a major component of greenhouse gases (GHGs) around the globe, which has enhanced global warming (Lacis et al. 2010). The faster-growing technologies and a desire for higher economic development are putting further fuel on this fire. For instance, innovations and technological progress may lead to higher energy demand and pollution emissions (Saidi and Ben Mbarek 2016; Uddin et al. 2023), which may be termed a scale effect of innovations. In this regard, the United Nations (UN) has declared the Sustainable Development Goals (SDGs). Western European countries are striving to achieve the agenda of SDGs of the UN by reducing the CO_2 emissions per capita between 0.5% and 1.5% per year. But still, the performance of the entire region is not satisfactory to achieve the SDGs by the year 2030 (Barrera-Santana et al. 2021). To reduce GHGs emissions, Western European countries are trying to shift toward clean sources of energy. However, this adoption is slow and heterogeneous among the nations (Inglesi-Lotz 2016). Innovation should target technological progress in favor of a sustainable environment. Western Europe should focus on the technological progress to reduce energy intensity in the production process to achieve the SDGs in the whole region as this region is interlinked due to their trading and environmental agreements.

Western European countries have performed well in innovations in the recent years. As per most patents in force in the year 2020, 12 Western European economies are among the top 20 economies in the Globe (Statista 2021). In the year 2020, Germany stands at first position in Western Europe by filing 62,105 patent applications. Onwards, the UK, France, Italy, and Poland carry the next positions by filing 20,649, 14,313, 11,008, and 4098 patent applications, respectively (World Bank 2023). Moreover, the performance of Western Europe is pretty impressive in using Renewable Energy Consumption (REC) in 2021. Iceland holds the first position in Europe as 87% of Total Primary Energy Consumption (TPEC) is sourced from renewable sources. The major sources of REC are geothermal, hydropower, and wind power energy. Moreover, Iceland produces 99% of its electricity from renewable sources. Out of which, about 70% of electricity is produced from hydroelectric power. Fossil fuels are just used in the transportation sector in Iceland. Norway, Sweden, and Denmark hold the next positions in using REC about 72%, 51%, and 41% of TPEC, respectively. Moreover, Austria, Switzerland, Finland, and Portugal are using REC for more than 30% and Latvia, Spain, Slovenia, and Greece are using REC for more than 20% of TPEC. On average, the whole of Western Europe is using REC about 21% of TPEC (BP 2023). Hence, the REC carries a significant proportion of total primary energy consumption and can help in combating pollution in Western Europe.

Innovation and renewable energy transition (RET) would help achieve environmental sustainability in Western Europe. Some Western European economies have shown remarkable progress in RET while others have low levels of RET. Thus, there is a pressing need to investigate the environmental effect of RET in the whole of Western Europe as the whole region shares the same landscape. Moreover, the most of economies in this region are well-connected due to trading and environmental agreements. Therefore, we aim to analyze the roles of RET and innovation in fostering environmental sustainability within the Western European context. Particularly, the innovations would reduce energy intensity and pollution emissions in an economy and Western European literature has investigated this issue using a limited sample of countries (Apergis et al. 2013; Shahbaz et al. 2020). However, comprehensive research to gauge the environmental effect of patents in a maximum sample of Western Union countries is missing in the European literature. Moreover, the European literature has investigated the effects of REC on pollution (Pham et al. 2020; Jonek-Kowalska 2022; Altıntaş and Kassouri 2020; Bekun et al. 2019; Sulaiman et al. 2020; Dogan and Seker 2016; Neves et al. 2020; Barrera-Santana et al. 2021). However, the investigation of the effect of RET on emissions is missing in Western European literature. Therefore, the present study contributes to the Western European literature by developing the RET variable by using a ratio of REC to the sum of non-REC from oil, gas, and coal and by testing the effect of RET on CO_2 emissions. Thus, the objective of this research is to find the effects of patents, RET, and income growth on CO_2 emissions in 25 Western European countries from 1995–2020. Western European countries are members of the European Union and active partners in many environmental treaties to achieve some environmental goals. Because of trading and environmental agreements, Cross-sectional Dependence (CD) is expected in the model (Eberhardt 2012). Thus, the present research has applied CD techniques to care for the CD issue in the Western European panel.

Literature review

On the positive environmental side of technological progress, technological innovation may enhance energy efficiency and renewable energy (Zhou et al. 2010; Saqib et al. 2023), which would change the overall energy mix of the economy. Further, technological progress would decrease fossil energy share in an economy (Tang and Tan 2013). In addition, innovation may accelerate the productivity of inputs, and an economy may have a greater amount of output using a lesser amount of energy (Mensah et al. 2018). Thus, innovation may help in supporting the climate by using less energy. Moreover, technical innovation would generate effective technologies (Maranville 1992; Sharif et al. 2022) and would shift the economy toward less-polluted industries. Thus, innovation would help to achieve the technique and composition effects. Consequently, technological progress can help in promoting the environmental profile of the economies.

Literature has been conducted to explore the environmental effects of innovation variables and REC. For instance, Uche (2022) investigated 21 top remittance economies from 1990–2019 by using dynamic estimation techniques. The results exposed that REC and human capital helped in raising environmental quality. However, urbanization and structural transition reduced environmental quality. Obiakor and Uche (2022) examined African and Latin American economies from 1990–2018 and found that clean energy helped to enhance environmental quality. Moreover, the economic transition could support these economies' environment in the short run. Comparatively, the agricultural transition had better environmental effects than the manufacturing and mining sectors. Onuoha et al. (2023) investigated 29 Sub-Saharan African economies and found that FMD, CO_2 emissions, public debt, and economic growth reduced REC. However, urbanization enhanced REC. In a similar sample, Okere et al. (2023) originated that public debt raised many indicators of energy poverty. Uche et al. (2023a) analyzed BRICS economies and found that FDI's interaction with environmental innovation helped to mitigate pollution. Moreover, REC and human capital also reduced pollution. Uche et al. (2023b) explored G10 from 1985–2021 and substantiated that public R&D on green technology and REC helped to achieve environmental sustainability by reducing energy-induced emissions and temperature. Moreover, energy tax reduced emissions, and fossil fuels enhanced emissions. Uche et al. (2023d) analyzed India from 1980–2018 by using multiple threshold nonlinear Autoregressive Distributive Lag (ARDL) technique and substantiated the EKC. However, environmental-control technologies and trade openness could not support a clean environment, and energy consumption and urbanization enhanced pollution. Uche et al. (2023c) investigated India from 1997Q1–2021Q4 and found that carbon intensity and green technologies reduced emissions in the long run. Moreover, the EKC was validated. Muoneke et al. (2022) examined the Philippines and substantiated the EKC. However, agricultural development was lower than the threshold level. Moreover, de jure financial and trade globalization aggravated and reduced ecological footprint, respectively. Moreover, urbanization, economic growth, and fossil fuels enhanced the ecological footprint.

Considering the positive role of innovation in the environment, European literature has investigated this issue using a proxy of R&D. For example, Škrinjarić (2020) compared the sustainable development of European economies and found that countries with higher R&D, Gross Domestic Product (GDP) per capita, and education had better performance in sustainable development. Literature has also focused on particular Western European countries. Apergis et al. (2013) explored Germany, France, and the UK from 1998–2011 and found that R&D after following international financial standards encouraged innovations and reduced CO_2 emissions. Later on, literature realized the role of R&D in shaping the Environmental Kuznets Curve (EKC) hypothesis in European countries. For example, Lapinskienė et al. (2015) examined 20 European Union (EU) economies from 1995–2011 and validated that R&D, nuclear energy, and energy taxes reduced GHGs emissions. The EKC was also corroborated. However, agriculture, industry, and construction sectors and solid fuels had positive effects on GHGs emissions. The same findings were shared by Lapinskienė et al. (2017) using a sample of 22 EU economies from 1995–2014.

Auci and Trovato (2018) investigated and verified the EKC in 25 EU economies from 1997–2005. The results of the composition effect showed that CO_2 emissions from dirty industries decreased with increasing economic growth. Moreover, the technique effect was corroborated by a reduction in emissions with increasing private R&D activities. However, public R&D increased emissions. By increasing the sample size of the EU, Nepal et al. (2021) investigated 28 EU countries from 1980–2018 and validated that energy efficiency and R&D reduced environmental degradation. Moreover, the EKC was also validated. Particularly, they claimed that energy efficiency would reduce petroleum consumption, which could reduce energy imports. Shahbaz et al. (2020) examined the UK from 1870–2017 and found that R&D reduced CO_2 emissions. Moreover, the EKC was also substantiated. However, energy consumption increased CO_2 emissions.

Another strand of literature utilized a proxy of patents for innovation in ecological studies of Europe. For instance, Khurshid et al. (2023) investigated 15 European economies and found that green innovations and ecological policies reduced emissions. de Araújo et al. (2020) investigated EU economies and found that technological advancement reduced CO_2 emissions. However, exports increased emissions and outweighed the pleasant role of technological advancement. Mongo et al. (2021) explored 15 EU countries and found that environmental innovations decreased CO_2 emissions.

Ignoring innovation in analyses, European literature has also examined the REC and emissions nexus. For instance, Pham et al. (2020) probed 28 EU economies from 1990 to 2014 and found that REC reduced CO_2 emissions. Moreover, the EKC hypothesis was also corroborated. However, FDI, income, urbanization, population, and trade had positive effects on emissions. Moutinho et al. (2015) claimed that CO_2 emissions in different European regions significantly declined due to switching to cleaner energy and reducing dependency on fossil fuels in end-user energy production. In the same way, Jonek-Kowalska (2022) found that replacing coal with REC and nuclear energy reduced CO_2 emissions in Europe. Salahodjaev et al. (2022) investigated Europe and Central Asia from 1990–2015 and substantiated the EKC. Further, REC mitigated emissions, and tourism increased CO_2 emissions. Altıntaş and Kassouri (2020) investigated 14 European economies from 1990–2014 and REC improved the environment. The EKC was also found in the ecological footprint model but not in the CO_2 emissions model. Moreover, fossil fuels damage the environment.

Sulaiman et al. (2020) investigated 27 EU countries from 1990–2017 and realized that wood biomass energy usage reduced emissions. However, fossil fuels, income growth, and trade openness increased CO_2 emissions. Dogan and Seker (2016) investigated 15 EU economies from 1980–2012 and corroborated the EKC. REC and trade openness reduced CO_2 emissions and non-REC increased emissions. Neves et al. (2020) examined 17 EU countries and environmental laws regarding REC and FDI decreased CO_2 emissions. Thus, the European Union economies had attracted innovative investment. Rodrigues et al. (2020) examined 28 EU economies from 2000–2015 and found that REC and efficiency gains reduced emissions from electricity production.

Bekun et al. (2019) investigated 16 EU economies and found that non-REC increased carbon emission flaring and REC decreased CO_2 emissions. Lee (2019) investigated EU economies from 1961–2012. The author found that exports and REC had negative effects, and economic growth and industrialization had positive effects on CO_2 emissions. Acaroğlu and Güllü (2022) investigated Turkey from 1980–2019. REC reduced temperature and non-REC increased precipitation. Marques et al. (2011) probed the drivers of RET in the EU and found that industrial lobbying was a hurdle in the way of the RET. Particularly, this lobbying effect was more prominent at the earlier stage of this transition. Apostu et al. (2022) examined and compared forty-two EU and non-EU countries from 1990–2018 and concluded that RET with allocated funds for transition was more in the EU compared to non-EU countries. In the particular case of Western Europe, Barrera-Santana et al. (2021) investigated 16 Western European countries from 1980–2019 and found that the countries' growth depending on energy-intensive sectors had adverse environmental consequences. However, REC decreased emissions by reducing energy intensity. Nwani et al. (2023) examined 20 European economies from 1995–2019 and found that REC helped to reduce consumption-based energy and carbon intensities. Moreover, the EKC was also validated in both environmental proxies. Alola et al. (2023) examined France, Germany, Italy, and Spain from 1995–2020 and found that REC helped to achieve carbon-neutrality targets. Moreover, the EKC was also substantiated.

Some studies applied spatial econometrics in the relationship between pollution emissions and REC in Europe. For instance, Wang et al. (2022) investigated 36 European economies from 2000–2018 using spatial econometrics and substantiated the EKC. Geothermal energy, hydropower, and FDI reduced local emissions. Nevertheless, solar, wind, and bioenergy had positive or insignificant effects on local CO_2 emissions and energy intensity increased local and neighboring economies' CO_2 emissions. Furthermore, solar and bioenergy generation in neighboring economies increased domestic pollution. Shahnazi and Shabani (2021) examined Europe from 2000–2017 and exposed the negative effect of REC on CO_2 emissions. Moreover, the EKC was substantiated and the spillovers of CO_2 emissions in neighboring economies were found statistically significant.

Ignoring REC and innovation variables, some European literature has investigated pollution emissions models. For instance, Mohsin et al. (2022) investigated European and Central Asian economies and found the causality from FDI and income level to CO_2 emissions. Xu et al. (2022) examined 34 European countries from 2000–2020 and found that lending rates decreased and domestic credit increased emissions from the transport industry. Clora and Yu (2022) investigated 31 European economies and found that decarbonization ambitions reduced GHGs emissions. However, it reduced competitiveness by damaging the trade balance in the supply-side mitigation measures. However, the demand-side mitigation measures improved both the trade balance and the environment. Akdag and Yildirim (2020) investigated 29 European economies from 1995–2016 and concluded that energy efficiency reduced GHGs emissions.

Li et al. (2016) explored 18 European economies and found that decreasing energy intensity reduced CO_2 emissions. Moreover, 7 Western European countries showed the highest potential to reduce emissions. Zhang et al. (2021) did efficiency analyses in Central and Western European economies to compare energy and environmental efficiencies. The authors found the UK and Ireland in first and second position in getting sustainable development. Wu et al. (2022) examined European economies and corroborated that energy prices reduced domestic and neighboring emissions. Christoforidis, Katrakilidis (2021) investigated Central and Eastern Europe from 1995–2014 and found that energy usage increased CO_2 emissions.

Mulatu et al. (2010) investigated manufacturing firms in 16 European economies and found that environmental regulations shifted the dirty industry to lower-regulated countries. Jamel and Maktouf (2017) investigated forty European countries from 1985–2014 and found bidirectional causality between income and pollution. Koengkan and Fuinhas (2021) investigated 14 EU economies and found that the gender gap increased emissions. However, income, globalization, and urbanization did not affect CO_2 emissions. Alonso et al. (2014) investigated and mentioned that two-thirds of EU flights landed in the UK, Spain, France, Italy, and Germany, which increased CO_2 emissions. Frodyma et al. (2022) investigated the EU from 1970–2017 and the EKC was validated in panel models of production and consumption-based emissions. However, the EKC could not be validated in country-specific analyses of most analyzed economies.

Munir (2023) investigated 21 EU countries from 1990–2018 in nonlinear settings. The author found that increasing and decreasing coal, electricity, and oil consumption increased and decreased CO_2 emissions, respectively. Acaravci and Ozturk (2010) investigated European economies and found that energy usage increased emissions in some Western European economies. Moreover, the EKC was substantiated. Kauppi and Tomppo (1993) investigated Western Europe and found that forests helped to reduce carbon in the atmosphere. Ali et al. (2018) investigated some Western European countries and found that the transport sector contributed to CO_2 emissions in France, Italy, Germany, and the UK. Németh-Durkó (2021) examined Hungary from 1974–2014 and found that electricity consumption and urbanization increased carbon emissions.

Muoneke et al. (2023a) investigated Med-9 economies from Europe and found that government effectiveness helped to raise the pleasant effects of public debt, migration, and unemployment on environmental sustainability. However, urbanization's interaction with government effectiveness harmed environmental sustainability. Okolo et al. (2023) investigated EU27 economies from 2006–2019 and found that credit from private and government sectors to small and medium enterprises improves environmental sustainability. Muoneke et al. (2023b) examined and found that coal consumption had a dampening effect on CO_2 emissions. Moreover, bureaucracy amplified this effect and socioeconomic factors mitigated it.

The reviewed literature sheds light on the role of innovation in combating pollution emissions. The patents are the direct source of innovations and are not tested on CO_2 emissions in a particular case of Western Europe. Moreover, the effect of RET is tested on CO_2 emissions. Thus, this present study is motivated to fill this literature gap by investigating the impact of patents, RET, and economic growth on CO_2 emissions in 25 Western European countries.

Methods

While testing the growth and emissions nexus, we cannot ignore the EKC hypothesis. Economic growth could have different environmental effects at different stages of growth. For instance, the environment may be sacrificed in achieving initial growth and it may be protected at a later stage. Thus, Grossman and Krueger (1991) advocated testing a nonlinear impact of economic growth on emissions. Therefore, we hypothesize the quadratic effect of economic growth on CO_2 emissions. Innovation would play an effective role in reducing pollution. For instance, innovation could develop environmentally friendly technologies to mitigate pollution and achieve a sustainable environment. Albino et al. (2014) suggested a proxy of patents for innovation to develop low-carbon technology. Similarly, Raiser et al. (2017) also suggested that patents would mitigate climate change. Patents would help an economy to transform from fossil fuels to clean technologies and/or cleaner sources of energy. Thus, we hypothesize a negative effect of patents on CO_2 emissions. Moreover, literature suggested that REC would mitigate pollution in an economy (Gessinger 1997; Khan et al. 2020). In addition, Chiu and Chang (2009) claimed that a high percentage of REC in the energy mix is required to combat pollution. Hence, an economy should reduce non-REC and enhance the REC in the energy mix to combat pollution. Moreover, a balance between REC and non-REC is required to meet the environmental challenges. Therefore, we use the renewable energy transition (RET) variable, which is captured through a ratio of REC to non-REC. Thus, RET may reduce pollution and we hypothesize a negative effect of RET on CO_2 emissions. RET and patents are included in the model of the EKC in Western Europe in the following way:

$$\mathrm{CO2}_{it} = f\left(Y_{it}, Y_{it}^2, \mathrm{RET}_{it}, \mathrm{PAT}_{it}\right) \tag{1}$$

Y_{it} is the natural logarithm of GDP per capita in constant US dollars and ${Y_{it}}^2$ is the square of Y_{it}. PAT_{it} reflects the thousands of filed patent applications. GDP data and patents are obtained from the World Bank (2023). RET_{it} is a ratio of REC in exajoule to the sum of energy consumption from oil, gas, and coal in exajoule. These variables are sourced from BP (2023). RET_{it} and PAT_{it} are not taken in the natural logarithm because of the presence of zero values in some sample years. $\mathrm{CO2}_{it}$ is per capita tCO_2 in the natural logarithm form and sourced from the Global Carbon Atlas (2023). All series are taken for the period 1995–2020 and from 25 Western European countries, i.e., Austria, Belgium, Cyprus, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Luxembourg, Netherlands, Norway, Poland, Portugal, Slovakia, Slovenia, Spain, Sweden, Switzerland, and the UK. Some small economies in Western Europe are ignored in the analysis due to data unavailability.

Most Western Europe countries are members of the EU. Due to trading and environmental agreements, we may expect the CD in the model, and CD should be considered in the estimations to have unbiased results (Eberhardt 2012). Breusch and Pagan (1980) suggested LM statistic to test the CD in each individual variable of the model and the residual. Moreover, Pesaran et al. (2008)

and Pesaran (2021) provided unbiased versions of LM tests, which are utilized to verify the presence of CD in each individual variable and the residual of a model. If the CD is validated, then the CD unit root tests of Pesaran (2007) will be applied to check the unit root problem in the panel series. The Cross-sectional Augmented-Dickey-Fuller (CADF) test equation is as follows:

$$\Delta y_{it} = \mu_0 + \mu_{1i} y_{it-1} + \mu_{2i}\overline{y_{t-1}} + \mu_{3i}\overline{\Delta Y_t} + \pi_{it} \quad (2)$$

$\overline{y_{t-1}}$ and $\overline{\Delta Y_t}$ are the cross-sections' average. The unit root may be tested with a null hypothesis of $\mu_{1i} = 0$. Moreover, Cross-sectional Im-Pesaran-Shin (CIPS) statistics may be calculated with estimated CADF statistics in the following way:

$$\mathrm{CIPS} = N^{-1}\sum_{i=1}^{N} \mathrm{CADF}_i \quad (3)$$

After inquiring about the unit root in series, Westerlund's (2007) CD procedure is used to verify a cointegration in the hypothesized relationships in Eq. (1) with the following test statistics:

$$G_t = N^{-1}\sum_{i=1}^{N} \frac{\Omega_i}{\mathrm{SE}\left(\widehat{\Omega_i}\right)} \quad (4)$$

$$G_a = N^{-1}\sum_{i=1}^{N} \frac{T\Omega_i}{\overset{,}{\Omega}(1)} \quad (5)$$

$$P_t = \frac{\widehat{\Omega}_i}{\mathrm{SE}\left(\widehat{\Omega_i}\right)} \quad (6)$$

$$P_a = T\hat{\Omega} \quad (7)$$

$\hat{\Omega}$ is a parameter, which is calculated from the error correction model. Afterward, we apply the procedure of Pesaran and Yamagata (2008). This procedure helps us to verify the possibility of slope-heterogeneity in the model using Δ-statistic and Δ_{adj}-statistic. The presence of slope-heterogeneity would lead us toward the methodology of Pesaran and Smith (1995), which does not care about the issue of CD in estimations (Eberhardt 2012). Caring the CD in analysis, Chudik et al. (2017) suggested efficient estimators in the following way:

$$\begin{aligned} \mathrm{CO2}_{it} = {} & a_i + \sum_{j=1}^{k} g_{ij}\mathrm{CO2}_{it-j} + \sum_{j=0}^{k} b_{1ij} Y_{it-j} + \sum_{j=0}^{k} b_{2ij} Y_{it-j}^2 \\ & + \sum_{j=j}^{k} b_{3ij}\mathrm{RET}_{it-j} + \sum_{j=1}^{k} b_{4ij}\mathrm{PAT}_{it-j} + \sum_{j=0}^{k} c_{1j}\overline{\mathrm{CO2}_{it}} \\ & + \sum_{j=0}^{k} c_{2j}\overline{Y_{it}} + \sum_{j=0}^{k} c_{3j}\overline{Y_{it}^2} + \sum_{j=0}^{k} c_{4j}\overline{\mathrm{RET}_{it}} + \sum_{j=0}^{k} c_{5j}\overline{\mathrm{PAT}_{it}} + e_{it} \end{aligned} \quad (8)$$

Equation 8 represents the CD-ARDL model. The estimates can be obtained by normalizing the coefficients after averaging the variables, $\hat{\beta} = \sum_{j=0}^{k}\hat{b}_{ij}/1 - \sum_{j=0}^{k}\hat{g}_{ij}$. Moreover, short-run effects can be estimated by c_{ij} after incorporating the error correction term (ECT_{t-1}) in Eq. (8).

Data analyses

Table 1 displays descriptive statistics and the mean values of all series are more than the standard deviation (SD) except PAT_{it}. Thus, all variables are under-diverse except PAT_{it}. The PAT_{it} is over-diverse, which explains that all Western European countries show a diverse performance in terms of patents. Moreover, the minimum values of PAT_{it} and RET_{it} are zero, which explains that some countries have zero performance in terms of RET and patents in some years.

Table 1 Descriptive statistics.

Series	Mean	Maximum	Minimum	SD
$\mathrm{CO2}_{it}$	2.0798	3.2733	1.0886	0.3684
Y_{it}	10.3158	11.6295	8.5109	0.6587
${Y_{it}}^2$	106.8491	135.2470	72.4356	13.4282
RET_{it}	0.3127	3.5899	0.0000	0.5231
PAT_{it}	5.6458	67.8990	0.0000	12.7274

Table 2 CD and slope heterogeneity tests.

	CD tests			Slope heterogeneity	
Series	Breusch-Pagan LM	Pesaran scaled LM	Pesaran	Δ	Δ_{adj}
$\mathrm{CO2}_{it}$	4292.7130	163.0018	54.7311		
	(0.0000)	(0.0000)	(0.0000)		
Y_{it}	5921.8240	229.5100	74.1801		
	(0.0000)	(0.0000)	(0.0000)		
${Y_{it}}^2$	5903.4560	228.7601	74.0151		
	(0.0000)	(0.0000)	(0.0000)		
RET_{it}	6939.1010	271.0402	83.2196		
	(0.0000)	(0.0000)	(0.0000)		
PAT_{it}	1972.8230	68.2927	3.5446		
	(0.0000)	(0.0000)	(0.0004)		
Residual	4733.5550	180.9991	60.5991	21.5860	24.5950
	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.000)

CD tests are applied for individual variables and the residual of regression in Table 2. All the CD tests show the existence of CD in all the tested series and the residual of regression. Thus, all tests suggest incorporating CD in further econometric analyses. Moreover, the slope heterogeneity is also corroborated by statistically significant Δ and Δ_{adj} statistics.

Table 3 displays the results of CADF and CIPS tests to confirm stationarity. All series at the level are non-stationary. Further, all series at first difference are stationary. Thus, the order of integration is one.

In Table 4, we apply the Westerlund cointegration technique, which verifies a cointegration in the model with significant Gt and Pa statistics at 10% level of significance. Thus, the hypothesized model is suitable for further long and short run analyses.

The long run results in Table 5 show the positive parameter of Y_{it} and the negative parameter of ${Y_{it}}^2$, which corroborated the EKC hypothesis in the panel of Western Europe. Thus, the hypothesis of an inverted U-shaped (quadratic) association between GDP per capita and CO_2 emissions is substantiated. The estimated turning point is found at GDP per capita of 50,287 US dollars [exponent of $-(11.2477)/2(-0.5195)$]. As per the last sample year 2020, Denmark, Iceland, Sweden, Ireland, Norway, Luxembourg, and Switzerland are found in the 2nd phase of the EKC with a GDP per capita of more than 50,287 US dollars. Thus, the economic growth of these countries is reducing CO_2 emissions. The rest analyzed Western European economies are in the first phase in the long run and have ecological consequences of growth. In the European EKC literature, some studies verified the existence of the EKC in 25 EU countries (Auci and Trovato 2018), in 20 EU economies (Lapinskienė et al. 2015), in 22 EU countries (Lapinskienė et al. 2017), in 28 EU countries (Pham et al. 2020), in 14 European economies (Altıntaş and Kassouri 2020), in 17 EU countries (Neves et al. 2020), and in all EU economies (Frodyma et al. 2022). However, the mentioned studies could not verify the EKC in the particular Western European region. Thus, the present study exploits this opportunity to validate the EKC in 25 Western European countries.

Table 3 Panel unit root analyses.

Variable	Level		Difference	
	Intercept	Intercept and trend	Intercept	Intercept and trend
CADF test				
$CO2_{it}$	−1.4980	−2.0103	−2.3833***	−2.7641***
Y_{it}	−1.7881	−2.3272	−2.6901**	−2.8256***
RET_{it}	−1.1780	−1.4411	−2.4286***	−2.8064***
PAT_{it}	−1.6572	−2.2122	−3.1043***	−3.3899***
CIPS test				
$CO2_{it}$	−1.8979	−2.4060	−3.6276***	−3.9236***
Y_{it}	−1.8411	−2.5713	−3.9291***	−4.2514***
RET_{it}	−1.3026	−1.7285	−2.4247***	−2.7873**
PAT_{it}	−1.6566	−2.2118	−3.1040***	−3.4178***

** and *** show the stationarity of the variables at 5% and 1% levels of significance, respectively.

Table 4 Westerlund cointegration test.

Test statistics	Value	Z-value	p value
Gt	−2.9823	−1.5952	0.0550
Ga	−4.8154	2.1654	0.9654
Pt	−9.6901	−1.2682	0.1025
Pa	−7.6541	−1.3684	0.0854

Table 5 Regression analyses.

Variable	Coefficient	S.E.	t-value	p value
CD-ARDL: long run results				
Y_{it}	11.2477	5.7264	1.9642	0.0508
Y_{it}^2	−0.5195	0.2727	−1.9051	0.0576
RET_{it}	−0.7503	0.2254	−3.3288	0.0011
PAT_{it}	−0.0136	0.0034	−4.0172	0.0000
CD-ARDL: short run results				
Y_{it}	19.5835	10.9587	1.7871	0.0740
Y_{it}^2	−0.8937	0.5151	−1.7351	0.0831
RET_{it}	−1.3039	0.3672	−3.5509	0.0000
PAT_{it}	−0.0193	0.0245	−0.7879	0.4314
ECT_{t-1}	−0.9059	0.0627	−14.4483	0.0000

RET_{it} has a negative parameter and the hypothesis of a negative relationship between RET and CO_2 emissions is substantiated. Thus, the renewable energy transition from non-REC to REC helps to lower emissions in Western Europe. The results substantiate that the renewable energy transition has helped Western European economies to reduce the environmental effects of energy consumption. This result is natural as a whole Western Europe has transited more than 20% of total energy need from REC (BP 2023), and this transition helped this region to reduce CO_2 emissions. The transition from non-renewable to REC reduces the dependence on fossil fuels and CO_2 emissions are reduced consequently. Using renewable energy consumption variable, Barrera-Santana et al. (2021) corroborated the negative impact of REC on CO_2 emissions in 16 Western European countries. Moreover, some other studies reported the negative effect of REC on pollution emissions in 28 EU countries (Pham et al. 2020; Rodrigues et al. 2020), in aggregated data of all EU countries (Lee 2019), and in 36 European countries (Wang et al. 2022). However, the mentioned studies worked on the REC variable. The result of RET in this present study suggests that RET can help in reducing CO_2 emissions, which might be achieved by reducing non-REC and/or increasing REC. Thus, both movements of energy usage can help in reducing CO_2 emissions.

The coefficient of PAT_{it} is negative and the hypothesis of a negative association between patents and emissions is proven. Thus, the increasing number of patents in Western Europe is helping to reduce CO_2 emissions. It shows that increasing patents are attached to the development of clean technologies in Western Europe and are thus helping in environmental sustainability. This finding is matched by the fact that 12 Western European economies are among the top 20 economies in producing patents (Statista 2021). Thus, patents are developing new clean technologies and reducing CO_2 emissions in the region. Using different proxies of innovation, the literature has substantiated the negative impact of innovation on pollution emissions. For instance, some studies revealed a negative effect of R&D on pollution in some Western European economies (Apergis et al. 2013), in the UK (Shahbaz et al. 2020), and in some EU economies (Nepal et al. 2021; Lapinskienė et al. 2017; Auci and Trovato 2018). Moreover, Khurshid et al. (2023) corroborated the negative effect of green innovation on pollution in 15 European countries, de Araújo et al. (2020) validated the negative impact of technological advancement on emissions in the EU, and Mongo et al. (2021) substantiated the negative effect of environmental innovations on pollution in 15 EU economies.

In the short run results, the parameter of ECT_{t-1} is negative, which shows the convergence of short run disequilibrium to long run equilibrium. Moreover, the EKC is also validated in the short run with a turning point at GDP per capita of 57,320 US dollars [exponent of $-(19.5835)/2(-0.8937)$], and Denmark, Iceland, Ireland, Norway, Luxembourg, and Switzerland are at 2nd stage of the EKC as per their GDP per capita in the last sample year 2020. Further, RET also helps to reduce emissions. However, patents have a negative but insignificant coefficient. Thus, patents do not affect CO_2 emissions in the short run. Patents need time to be generalized and come in the form of workable technologies, which could help in reducing pollution emissions. So, the short-run results could not validate the positive environmental impact of patents. However, Mongo et al. (2021) corroborated the short-run positive impact of ecological innovations on CO_2 emissions in 15 EU economies.

Conclusions

This research examines the effects of the RET, the number of patents, and economic growth on CO_2 emissions in 25 Western European countries from 1995–2020. The study utilizes CD techniques to investigate long and short run relationships. The results disclose the validity of the EKC in the long run with a turning point at GDP per capita of 50,287 dollars and Denmark, Iceland, Sweden, Ireland, Norway, Luxembourg, and Switzerland are at the 2nd stage of the EKC. Thus, these economies are enjoying the pleasant environmental effects of economic growth. However, the remaining Western European economies are found at an early phase of the EKC, and their economic growth has ecological concerns. Therefore, it is recommended to rest Western European countries to take immediate action to control pollution by devising environmentally friendly policies. Further, the EKC is corroborated in the short run with a turning point at GDP per capita of 57,320 dollars, and Norway, Luxembourg, and Switzerland are at 2nd stage of the EKC. RET reduces CO_2 emissions in the long and short run. Thus, RET helps mitigate the environmental degradation. Patents have negative effects on emissions in the long run but patents do not affect emissions in the short run. This result explains that patents need a long time to be generalized and to have pleasant effects on the environment.

The results suggest that RET helped reduce CO_2 emissions. Thus, switching to renewable in the transition of energy would reduce ecological problems. So, we strongly suggest Western European economies for a fast transition from non-REC to REC to attain a sustainable environment in the countries. This transition may be achieved by setting a target of a low proportion of non-REC in the energy mix, which would help these economies to control ecological problems. For this purpose, Western Union countries should invest in developing the infrastructure to enhance the production capacity of renewable energy. On the consumption side, the government should give subsidies to promote the REC and should tax the energy consumption from fossil fuels. Moreover, renewable energy standards should be improved. Governments may provide tax incentives and credits for renewable energy investments. We also find that patents could reduce CO_2 emissions in the long run. Thus, Western European economies should invest in R&D activities to generate further patents with environmentally friendly technologies to achieve a green environment. Moreover, governments should encourage collaboration between public and private research organizations for the development of clean technologies. Furthermore, governments should also spend on educational and training programs to develop manpower for high-level research and the application of such research in favor of a pleasant environment. In addition, Western European economies should foster research collaboration within the region to promote environmentally friendly technologies.

The present study could work on the RET from aggregated REC. However, future research may develop RET proxies from different sources of renewable energy to segregate the impact of each RET proxy on the environment. Moreover, the increasing sample of European countries could enhance the generalization power of the research for a wide region.

Data availability

The data generated during and/or analyzed during the current study are provided in Supplementary File "data".

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References

Acaravci A, Ozturk I (2010) On the relationship between energy consumption, CO_2 emissions and economic growth in Europe. Energy 35(12):5412–5420. https://doi.org/10.1016/j.energy.2010.07.009

Acaroğlu H, Güllü M (2022) Climate change caused by renewable and non-renewable energy consumption and economic growth: a time series ARDL analysis for Turkey. Renew Energy 193:434–447. https://doi.org/10.1016/j.renene.2022.04.138

Akdag S, Yildirim H (2020) Toward a sustainable mitigation approach of energy efficiency to greenhouse gas emissions in the European countries. Heliyon 6(3):e03396. https://doi.org/10.1016/j.heliyon.2020.e03396

Albino V, Ardito L, Dangelico RM, Petruzzelli AM (2014) Understanding the development trends of low-carbon energy technologies: a patent analysis. Appl Energy 135:836–854. https://doi.org/10.1016/j.apenergy.2014.08.012

Ali Y, Socci C, Pretaroli R et al. (2018) Economic and environmental impact of transport sector on Europe economy. Asia Pac J Reg Sci 2:361–397. https://doi.org/10.1007/s41685-017-0066-9

Alola AA, Muoneke OB, Okere KI, Obekpa HO (2023) Analysing the co-benefit of environmental tax amidst clean energy development in Europe's largest agrarian economies. J Environ Manag 326:116748. https://doi.org/10.1016/j.jenvman.2022.116748

Alonso G, Benito A, Lonza L, Kousoulidou M (2014) Investigations on the distribution of air transport traffic and CO_2 emissions within the European Union. J Air Transp Manag 36:85–93. https://doi.org/10.1016/j.jairtraman.2013.12.019

Altıntaş H, Kassouri Y (2020) Is the environmental Kuznets Curve in Europe related to the per-capita ecological footprint or CO_2 emissions? Ecol Indic 113:106187. https://doi.org/10.1016/j.ecolind.2020.106187

Apergis N, Eleftheriou S, Payne JE (2013) The relationship between international financial reporting standards, carbon emissions, and R&D expenditures: evidence from European manufacturing firms. Ecol Econ 88:57–66. https://doi.org/10.1016/j.ecolecon.2012.12.024

Apostu SA, Panait M, Vasile V (2022) The energy transition in Europe—a solution for net zero carbon? Environ Sci Pollut Res 29:71358–71379. https://doi.org/10.1007/s11356-022-20730-z

Auci S, Trovato G (2018) The environmental Kuznets curve within European countries and sectors: greenhouse emission, production function and technology. Econ Polit 35:895–915. https://doi.org/10.1007/s40888-018-0101-y

Barrera-Santana J, Marrero GA, Puch LA et al. (2021) CO_2 emissions and energy technologies in Western Europe. SERIEs 12:105–150. https://doi.org/10.1007/s13209-021-00234-8

Bekun FV, Alola AA, Sarkodie SA (2019) Toward a sustainable environment: nexus between CO_2 emissions, resource rent, renewable and nonrenewable energy in 16-EU countries. Sci Total Environ 657:1023–1029. https://doi.org/10.1016/j.scitotenv.2018.12.104

BP (2023) BP Statistical Review of World Energy. https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html

Breusch TS, Pagan AR (1980) The Lagrange multiplier test and its applications to model specification in econometrics. Rev Econ Stud 47:239–253. https://doi.org/10.2307/2297111

Chiu C-L, Chang T-H (2009) What proportion of renewable energy supplies is needed to initially mitigate CO2 emissions in OECD member countries? Renew Sustain Energy Rev 13(6):1669. https://doi.org/10.1016/j.rser.2008.09.026

Christoforidis T, Katrakilidis C (2021) Does foreign direct investment matter for environmental degradation? Empirical evidence from Central–Eastern European countries. J Knowl Econ 13:2665–2694. https://doi.org/10.1007/s13132-021-00820-y

Chudik A, Mohaddes K, Pesaran MH, Raissi M (2017) Is there a debt-threshold effect on output growth? Rev Econ Stat 99(1):135–150. https://doi.org/10.1162/REST_a_00593

Clora F, Yu W (2022) GHG emissions, trade balance, and carbon leakage: insights from modeling thirty-one European decarbonization pathways towards 2050. Energy Econ 113(1):106240. https://doi.org/10.1016/j.eneco.2022.106240

de Araújo IF, Jackson RW, Neto ABF, Perobelli S (2020) European Union membership and CO_2 emissions: a structural decomposition analysis. Struct Change Econ Dyn 55:190–203. https://doi.org/10.1016/j.strueco.2020.06.006

Dogan E, Seker F (2016) Determinants of CO_2 emissions in the European Union: the role of renewable and non-renewable energy. Renew Energy 94:429–439. https://doi.org/10.1016/j.renene.2016.03.078

Eberhardt M (2012) Estimating panel time-series models with heterogeneous slopes. Stata J 12:61–71. https://doi.org/10.1177/1536867x1201200105

Frodyma K, Papież M, Śmiech S (2022) Revisiting the environmental Kuznets curve in the European Union countries. Energy 241:122899. https://doi.org/10.1016/j.energy.2021.122899

Gessinger G (1997) Lower CO2 emissions through better technology. Energy Convers Manag 38:25–30. https://doi.org/10.1016/S0196-8904(96)00240-3

Global Carbon Atlas (2023) Global Carbon Atlas: Country Emissions. Available online: http://www.globalcarbonatlas.org/en/CO2-emissions Accessed 30 Feb 2023

Grossman GM, Krueger AB (1991) Environmental impacts of the North American Free Trade Agreement. NBER Working paper 3914. https://doi.org/10.3386/w3914

Inglesi-Lotz R (2016) The impact of renewable energy consumption to economic growth: a panel data Application. Energy Econ 53:58–63. https://doi.org/10.1016/j.eneco.2015.01.003

Jamel L, Maktouf S (2017) The nexus between economic growth, financial development, trade openness, and CO_2 emissions in European countries. Cogent Econ Financ 5(1):1341456. https://doi.org/10.1080/23322039.2017.1341456

Jonek-Kowalska I (2022) Towards the reduction of CO_2 emissions. Paths of pro-ecological transformation of energy mixes in European countries with an above-average share of coal in energy consumption. Resour Policy 77:102701. https://doi.org/10.1016/j.resourpol.2022.102701

Kauppi PE, Tomppo E (1993) Impact of forests on net national emissions of carbon dioxide in West Europe. Water Air Soil Pollut 70:187–196. https://doi.org/10.1007/BF01104996

Khan Z, Ali S, Umar M, Kirikkaleli D, Jiao Z (2020) Consumption-based carbon emissions and international trade in G7 countries: the role of environmental innovation and renewable energy. Sci Total Environ 730:138945. https://doi.org/10.1016/j.scitotenv.2020.138945

Khurshid A, Rauf A, Qayyum S et al. (2023) Green innovation and carbon emissions: the role of carbon pricing and environmental policies in attaining

sustainable development targets of carbon mitigation—evidence from Central-Eastern Europe. Environ Dev Sustain 25:8777–8798. https://doi.org/10.1007/s10668-022-02422-3
Koengkan M, Fuinhas JA (2021) Is gender inequality an essential driver in explaining environmental degradation? Some empirical answers from the CO_2 emissions in European Union countries. Environ Impact Assess Rev 90:106619. https://doi.org/10.1016/j.eiar.2021.106619
Lacis AA, Schmidt GA, Rind D, Ruedy R (2010) Atmospheric CO_2: principal control knob governing Earth's temperature. Science 330:356–359. https://doi.org/10.1126/science.1190653
Lapinskienė G, Peleckis K, Radavičius M (2015) Economic development and greenhouse gas emissions in the European Union countries. J Bus Econ Manag 16(6):1109–1123. https://doi.org/10.3846/16111699.2015.1112830
Lapinskienė G, Peleckis K, Slavinskaitė N (2017) Energy consumption, economic growth and greenhouse gas emissions in the European Union countries. J Bus Econ Manag 18(6):1082–1097. https://doi.org/10.3846/16111699.2017.1393457
Lee JW (2019) Long-run dynamics of renewable energy consumption on carbon emissions and economic growth in the European Union. Int J Sustain Dev World Ecol 26(1):69–78. https://doi.org/10.1080/13504509.2018.1492998
Li T, Baležentis T, Makutėnienė D, Streimikiene D, Kriščiukaitienė I (2016) Energy-related CO_2 emission in European Union agriculture: driving forces and possibilities for reduction. Appl Energy 180:682–694. https://doi.org/10.1016/j.apenergy.2016.08.031
Maranville S (1992) Entrepreneurship in the business curriculum. J Educ Bus 68(1):27–31. https://doi.org/10.1080/08832323.1992.10117582
Marques AC, Fuinhas JA, Manso JP (2011) A quantile approach to identify factors promoting renewable energy in European countries. Environ Resour Econ 49:351–366. https://doi.org/10.1007/s10640-010-9436-8
Mensah CN, Long X, Boamah KB, Bediako IA, Duada L, Salman M (2018) The effect of innovation on CO_2 emissions of OCED countries from 1990 to 2014. Environ Sci Pollut Res 25:29678–29698. https://doi.org/10.1007/s11356-018-2968-0
Mohsin M, Naseem S, Sarfraz M, Azam T (2022) Assessing the effects of fuel energy consumption, foreign direct investment and GDP on CO_2 emission: new data science evidence from Europe & Central Asia. Fuel 314:123098. https://doi.org/10.1016/j.fuel.2021.123098
Mongo M, Belaid F, Ramdani B (2021) The effects of environmental innovations on CO_2 emissions: empirical evidence from Europe. Environ Sci Policy 118:1–9. https://doi.org/10.1016/j.envsci.2020.12.004
Moutinho V, Moreira AC, Silva PM (2015) The driving forces of change in energy-related CO_2 emissions in Eastern, Western, Northern and Southern Europe: the LMDI approach to decomposition analysis. Renew Sust Energ Rev 50:1485–1499. https://doi.org/10.1016/j.rser.2015.05.072
Mulatu A, Gerlagh R, Rigby D et al. (2010) Environmental regulation and industry location in Europe. Environ Resour Econ 45:459–479. https://doi.org/10.1007/s10640-009-9323-3
Munir K (2023) Energy use and environmental degradation in Europe: evidence from panel nonlinear ARDL. Qual Quant 57:2529–2543. https://doi.org/10.1007/s11135-022-01473-y
Muoneke OB, Egbo OP, Okere KI (2023b) Coal–environmental quality nexus in EU-part of the Eastern Bloc: do socioeconomic factors and bureaucracy play a substantial role? Energy Environ. https://doi.org/10.1177/0958305X221149503
Muoneke OB, Okere KI, Alemayehu FK (2023a) Interplay between socio-economic challenges, environmental sustainability and the moderating role of government effectiveness in the Med-9 countries. Resour Policy 85:104017. https://doi.org/10.1016/j.resourpol.2023.104017
Muoneke OB, Okere KI, Nwaeze CN (2022) Agriculture, globalization, and ecological footprint: the role of agriculture beyond the tipping point in the Philippines. Environ Sci Pollut Res 29(36):54652–54676. https://doi.org/10.1007/s11356-022-19720-y
Németh-Durkó E (2021) Determinants of carbon emissions in a European emerging country: evidence from ARDL cointegration and Granger causality analysis. Int J Sustain Dev World Ecol 28(5):417–428. https://doi.org/10.1080/13504509.2020.1839808
Nepal R, Musibau HO, Jamasb T (2021) Energy consumption as an indicator of energy efficiency and emissions in the European Union: a GMM based quantile regression approach. Energy Policy 158:112572. https://doi.org/10.1016/j.enpol.2021.112572
Neves SA, Marques AC, Patrício M (2020) Determinants of CO_2 emissions in European Union countries: does environmental regulation reduce environmental pollution?. Econ Anal Policy 68:114–125. https://doi.org/10.1016/j.renene.2016.03.078
Nwani C, Usman O, Okere KI, Bekun FV (2023) Technological pathways to decarbonisation and the role of renewable energy: a study of European countries using consumption-based metrics. Resour Policy 83:103738. https://doi.org/10.1016/j.resourpol.2023.103738
Obiakor RT, Uche E (2022) Is structural innovativeness a panacea for healthier environments? Evidence from developing countries. Technol Soc 70:102033. https://doi.org/10.1016/j.techsoc.2022.102033
Okere KI, Dimnwobi SK, Ekesiobi C, Onuoha FC (2023) Turning the tide on energy poverty in sub-Saharan Africa: does public debt matter? Energy 282:128365. https://doi.org/10.1016/j.energy.2023.128365
Okolo VO, Ohanagorom MI, Okocha ER, Muoneke OB, Okere KI (2023) Does financing SMEs guarantee inclusive growth and environmental sustainability in the European Union? Heliyon 9(4):e15095. https://doi.org/10.1016/j.heliyon.2023.e15095
Onuoha FC, Dimnwobi SK, Okere KI, Ekesiobi C (2023) Sustainability burden or boost? examining the effect of public debt on renewable energy consumption in Sub-Saharan Africa. Energ Source Part B 18(1):2214917. https://doi.org/10.1080/15567249.2023.2214917
Pesaran MH (2007) A simple panel unit root test in the presence of cross-section dependence. J Appl Econ 22:265–312. https://doi.org/10.1002/jae.951
Pesaran MH (2021) General diagnostic tests for cross-sectional dependence in panels. Empir Econ 60:13–50. https://doi.org/10.1007/s00181-020-01875-7
Pesaran MH, Smith R (1995) Estimating long-run relationships from dynamic heterogeneous panels. J Econ 68:79–113. https://doi.org/10.1016/0304-4076(94)01644-F
Pesaran MH, Ullah A, Yamagata T (2008) A bias-adjusted LM test of error cross-section independence. Econ J 11:105–127. https://doi.org/10.1111/j.1368-423x.2007.00227.x
Pesaran MH, Yamagata T (2008) Testing slope homogeneity in large panels. J Econ 142:50–93. https://doi.org/10.1016/j.jeconom.2007.05.010
Pham NM, Huynh TLD, Nasir MA (2020) Environmental consequences of population, affluence and technological progress for European countries: a Malthusian view. J Environ Manag 260:110143. https://doi.org/10.1016/j.jenvman.2020.110143
Raiser K, Naims H, Bruhn T (2017) Corporatization of the climate? Innovation, intellectual property rights, and patents for climate change mitigation. Energy Res Soc Sci 27:1–8. https://doi.org/10.1016/j.erss.2017.01.020
Rodrigues JF, Wang J, Behrens P, de Boer P (2020) Drivers of CO_2 emissions from electricity generation in the European Union 2000–2015. Renew Sustain Energy Rev 133:110104. https://doi.org/10.1016/j.rser.2020.110104
Saidi K, Ben Mbarek M (2016) Nuclear energy, renewable energy, CO_2 emissions, and economic growth for nine developed countries: evidence from panel Granger causality tests. Prog Nucl Energy 88:364–374. https://doi.org/10.1016/j.enpol.2010.01.024
Salahodjaev R, Sharipov K, Rakhmanov N et al. (2022) Tourism, renewable energy and CO_2 emissions: evidence from Europe and Central Asia. Environ Dev Sustain 24:13282–13293. https://doi.org/10.1007/s10668-021-01993-x
Saqib N, Ozturk I, Usman M (2023) Investigating the implications of technological innovations, financial inclusion, and renewable energy in diminishing ecological footprints levels in emerging economies. Geosci Front 14(6):101667. https://doi.org/10.1016/j.gsf.2023.101667
Shahbaz M, Nasir MA, Hille E, Mahalik MK (2020) UK's net-zero carbon emissions target: investigating the potential role of economic growth, financial development, and R&D expenditures based on historical data (1870–2017). Technol Forecast Soc Change 161:120255. https://doi.org/10.1016/j.techfore.2020.120255
Shahnazi R, Shabani ZD (2021) The effects of renewable energy, spatial spillover of CO_2 emissions and economic freedom on CO_2 emissions in the EU. Renew Energy 169:293–307. https://doi.org/10.1016/j.renene.2021.01.016
Sharif A, Saqib N, Dong K, Khan SAR (2022) Nexus between green technology innovation, green financing, and CO_2 emissions in the G7 countries: the moderating role of social globalisation. Sustain Dev 30(6):1934–1946. https://doi.org/10.1002/sd.2360
Škrinjarić T (2020) Empirical assessment of the circular economy of selected European countries. J Clean Prod 255:120246. https://doi.org/10.1016/j.jclepro.2020.120246
Statista (2021) Ranking of the 20 national patent offices with the most patents in force in 2020. https://www.statista.com/statistics/257172/ranking-of-the-20-countries-with-the-most-patents-in-force/
Sulaiman C, Abdul-Rahim AS, Ofozor CA (2020) Does wood biomass energy use reduce CO_2 emissions in European Union member countries? Evidence from 27 members. J Clean Prod 253:119996. https://doi.org/10.1016/j.jclepro.2020.119996
Tang CF, Tan EC (2013) Exploring the nexus of electricity consumption, economic growth, energy prices and technology innovation in Malaysia. Appl Energy 104(4):297–305. https://doi.org/10.1016/j.apenergy.2012.10.061
Uche E (2022) Strategic pathways to combating remittance-induced carbon emissions; the imperatives of renewable energy, structural transformations, urbanization and human development. Energ Source Part B 17(1):2141375. https://doi.org/10.1080/15567249.2022.2141375

Uche E, Das N, Bera P (2023d) Re-examining the environmental Kuznets curve (EKC) for India via the multiple threshold NARDL procedure. Environ Sci Pollut Res 30(5):11913–11925. https://doi.org/10.1007/s11356-022-22912-1

Uche E, Das N, Bera P, Cifuentes-Faura J (2023a) Understanding the imperativeness of environmental-related technological innovations in the FDI–Environmental performance nexus. Renew Energ 206:285–294. https://doi.org/10.1016/j.renene.2023.02.060

Uche E, Ngepah N, Cifuentes-Faura J (2023b) Upholding the green agenda of COP27 through publicly funded R&D on energy efficiencies, renewables, nuclear and power storage technologies. Technol Soc 75:102380. https://doi.org/10.1016/j.techsoc.2023.102380

Uche E, Okere KI, Das N (2023c) Energy efficiency and carbon neutrality target in India: a wavelet quantile correlation perspective. Int J Sustain Energy 42(1):759–775. https://doi.org/10.1080/14786451.2023.2234051

Uddin I, Usman M, Saqib N, Makhdum MSA (2023) The impact of geopolitical risk, governance, technological innovations, energy use, and foreign direct investment on CO_2 emissions in the BRICS region. Environ Sci Pollut Res 30:73714–73729. https://doi.org/10.1007/s11356-023-27466-4

Wang JH, Mamkhezr J, Khezri M, Karimi MS, Khan YA (2022) Insights from European nations on the spatial impacts of renewable energy sources on CO_2 emissions. Energy Rep. 8:5620–5630. https://doi.org/10.1016/j.egyr.2022.04.005

Westerlund J (2007) Testing for error correction in panel data. Oxf Bull Econ Stat 69(6):709–748. https://doi.org/10.1111/j.1468-0084.2007.00477

World Bank (2023) World Development Indicators. The World Bank, Washington, DC. https://databank.worldbank.org/source/world-development-indicators

Wu J, Abban OJ, Boadi AD et al. (2022) The effects of energy price, spatial spillover of CO_2 emissions, and economic freedom on CO_2 emissions in Europe: a spatial econometrics approach. Environ Sci Pollut Res 29(42):63782–63798. https://doi.org/10.1007/s11356-022-20179-0

Xu B, Li S, Afzal A, Mirza N, Zhang M (2022) The impact of financial development on environmental sustainability: a European perspective. Resour Policy 78:102814. https://doi.org/10.1016/j.resourpol.2022.102814

Zhang J, Patwary AK, Sun H, Raza M, Taghizadeh-Hesary F, Iram R (2021) Measuring energy and environmental efficiency interactions towards CO_2 emissions reduction without slowing economic growth in central and western Europe. J Environ Manag 279:111704. https://doi.org/10.1016/j.jenvman.2020.111704

Zhou N, Levine MD, Price L (2010) Overview of current energy-efficiency policies in China. Energy Policy 38(11):6439–6452. https://doi.org/10.1016/j.enpol.2009.08.015

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Author contributions

Conceptualization: HM; Methodology: HM; Formal analysis and investigation: HM; Writing—original draft preparation: HM, AuRI, and MT; Writing—review and editing: AuRI and MT; Funding acquisition: HM; Supervision: HM; Data curation: MT.

Competing interests

The authors declare no competing interests.

Ethical approval

This article does not contain any studies with human participants performed by any of the authors.

Informed consent

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Additional information

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