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Achieving carbon neutrality goal in European countries: the role of green technology innovation, renewable energy, and financial development

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Abstract

Carbon dioxide (CO_2) emissions reduction in European countries has become an important topic with the implementation of national carbon neutrality objectives as part of the global agenda to halt climate change. The European Union (EU) has adopted sustainable finance and the "Green Deal" as a novel economic strategy and established intermediate goals for 2030 to ensure that consumed energy is generated from renewable sources to set the EU on the pathway to carbon neutrality. Herein, the study scrutinizes the impact of green technology innovation, renewable energy usage, and financial development on CO_2 emissions in 21 European countries with human capital and gross domestic product (GDP) as control variables. The empirical results from cross-sectional autoregressive distributed lags model (CS-ARDL) reveal that green technology innovation, human capital, and renewable energy usage mitigate CO_2 emissions. Financial development and GDP heighten CO_2 emissions. The causality test reveal a two-way causal affiliation among green technology innovation, renewable energy usage, financial development, human capital, and CO_2 emissions and a one-way causal link from GDP to CO_2 emissions. Also, results from the impulse-response and variance decomposition analysis indicate that a decrease in CO_2 emissions will be greatly aided by green technology innovation, usage of renewable energy, and human capital, whereas financial development and GDP will show higher variations of CO_2 emissions in the next decade. Policies are further suggested for achieving carbon neutrality based on the findings.

Keywords Green technology innovation · Renewable energy · Financial development · Carbon neutrality · Europe

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1 Introduction

The atmospheric concentration of carbon dioxide (CO_2) emissions caused by human activities and economic expansion have contributed massively to global warming. Due to global warming, extreme floods, and weather events have become more frequent and intense in recent years. With the mounting threat of global warming, countries globally have pledged to attain net zero CO_2 emissions by 2050,[1] which largely adheres to the 1.5 °C limits set out by the Intergovernmental Panel on Climate Change (IPCC).[2] Addressing climate change thus requires sustainable factors. For years, clean energy sources that have a low environmental effect have been prioritized in the fight against environmental pollution.[3] The International Energy Agency (IEA) has outlined steps to cut emissions by 35% by 2030, including expanding clean energy, enhancing energy efficiency, and promoting electrification by retiring or repurposing coal-fired plants (IEA, 2021). Scientists have also shown that the world needs to evolve from natural fossil fuels to renewable energy to keep global temperatures from rising.[4] Renewable energy sources such as geothermal, thermal winds, solar, hydropower, biomass, and biofuels are eco-friendly as they generate long-term negative CO_2 emissions while producing electricity (Yuan et al., 2022). Also, since these sources are based on organic substances that generate energy by absorbing CO2 or heat, using renewable energy resources, sustainable sources of energy during production processes do not release CO_2 (Kalak, 2023) pursuit.

Moreover, renewable energy development is different from conventional energy resources in that large-scale production and deployment of renewable energy need substantial capital investment as well as technology research and development (Obobisa, 2023). According to the IEA report, by 2050, 90% of the world's power will come from renewable sources to realize net-zero emissions targets (IEA, 2021). Thus, the importance of renewable energies result in a low-carbon energy system, and this is a fact that cannot be embroidered and the surge in renewable energy utilization specifies a rise in the use of clean electricity production, which could be a result of enhancements in accessing energy infrastructure and technological advances. However, it has also come to light that using renewable energy does not result in the desired ecological sustainability (Pata & Kartal, 2023). Also, such an energy transition approach may not be sufficient to achieve the carbon-reduction target (Ehsanullah et al., 2021).

More recently, scholars have emphasized the significance of green technologies in lessening CO_2 emissions globally.[5] Green technological innovation, originally advocated by Braun and Wield (1994), refers to the manufacture of green products that use technological approaches to reduce raw material usage, energy consumption, and environmental

[1] National pledges to attain net zero have surged as a result of global efforts to tackle climate change; several economies, including the United Kingdom, EU, US, Japan, are aiming for 2050 (Dafnomilis, den Elzen, and van Vuuren 2023).

[2] The IPCC report underscores the narrowing path to dampen global temperature to 1.5 °C, citing record temperatures and frequent climate disasters as signs of the pressing need for action (Intergovernmental Panel on Climate 2022).

[3] Renewable energy resources have been proposed as the key potential to reduce environmental pollution (Lin and Okoye 2023). The world is rapidly transitioning to renewable energy sources, spurred by concerns about global warming and energy security (De La Peña et al., 2022).

[4] See Cerqueira, Soukiazis, and Proença (2021).

[5] See (Ahakwa et al., 2023; Chen et al., 2023a, 2023b; Obobisa, Chen, and Mensah 2022; Xu, Abbas, et al., 2023a, 2023b) for a review.

pollution. Compared to traditional innovations, green technology innovation is established on the core concepts of energy efficiency, ecological optimization, and sustainable development, and its outcomes are primarily showcased in technological development that leads to emissions reduction, energy efficiency, and conservation (Wang et al., 2021). Theoretically, green technologies are more sustainable for the environment and may be a viable solution for reducing carbon emissions while undertaking economic activities.[6] Shao et al. (2021) accentuated that advances in green technology innovations dampen emanations, and further improvement will help to achieve carbon neutrality. This suggests that increased green technology innovation would provide the best opportunities to develop greener economies and accelerate the transition to sustainable energy and carbon neutrality. Nevertheless, a well-functioning financial system is required to accelerate technological innovation and clean energy sources (Aluko & Obalade, 2020). Thus, expanding the financial sector's size and structure offers critical cash for green technology and clean energy investments while lowering financial costs.

In the context of financial sectors, great efforts have been made to examine how financial policymaking affects the environment, with a particular focus on green credit, financial development, financial structure, and financial agglomeration (Amin et al., 2020; Umar et al., 2021; Xu et al., 2023a, 2023b). Financial development, nevertheless, is widely recognized as a thorough assessment of the accessibility and effectiveness of an economy's financial system. It has also garnered scholarly interest in scrutinizing its influence on the environment (Bayar et al., 2020). Some researchers assert that expanding financial inclusion will increase access to financial services and firm financing, encouraging low-carbon, clean energy, and sustainable economic development activities that improve environmental quality (Chen et al., 2023; Mensah et al., 2021). Thus, in order to help high-polluting companies become low-polluting companies, money might be directed through the financial sectors, resulting in low carbon emissions (Lahiani et al., 2021).

Moreover, by offering businesses and people financial incentives to adopt energy-conserving or sustainable technologies, the developed financial sectors can encourage governmental expenditures on environmental preservation (Musah et al., 2023). However, other researchers caution against the potentially harmful effect of financial development, which could give firms more access to financial resources such as bank loans and increase economic activities and carbon emissions. Therefore, financial development may extend production activities in addition to increasing enterprises' spending on low-carbon technology adoption, manufacturing, and research, with equivocal implications on CO_2 emissions (Lahiani, 2020). Also, more credit products are often available to customers in an evolved financial system, which could lead to a rise in their spending on high energy-consuming goods (Wang et al., 2020). Additionally, financial inclusion may increase domestic trade and production as well as foreign investment, which could increase CO_2 emissions (Anwar et al., 2022) (Fig. 1).

In particular, Europe has considered a wide range of elements; the current policy mix is centered on changing the composition of technologies in their consumption structure. A resolution on climate change passed by the European Parliament in 2019 endorsed a goal of net-zero emissions by 2050 and urged Member States to achieve the same as part

[6] The theoretical approach on green technological innovation is given by (Feng, Wang, and Liang 2021; Obobisa, Chen, and Mensah 2023; Razzaq et al., 2021; Sahoo, Kumar, and Upadhyay 2023).These studies has summarized the theoretical basis of the concept of green technological innovation and ecological performance.

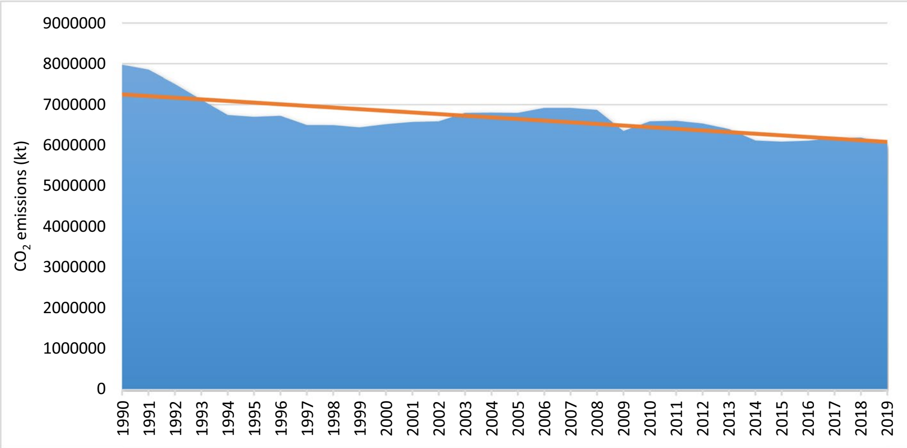

Fig. 1 CO_2 emissions measured in kilotons (kt) in Europe from 1990 to 2019 *Source*: Authors calculation from World Development Indicators

of the Future of Europe (Dafnomilis et al., 2023). In addition, the EU has set intermediate targets for 2030 that will improve energy efficiency and guarantee that 32% of the energy consumed comes from renewable resources. Also, the EU has put regulations for carbon pricing into place and established an ambitious agenda for sustainable financing. The Net Zero Industry Act, which aims to expedite green initiatives (Kleimann et al., 2023), is another component of the strategy, and the Critical Raw Materials Act, which seeks to guarantee the EU's supply of rare earth minerals necessary for the advancement of net-zero technology development. Therefore, there is a need for substantial study on how green technology innovation, renewable energy, and financial development may aid European nations in reducing CO_2 emissions (Fig. 2).

Although several studies have scrutinized the determinants of CO_2 emissions, there are still compelling grounds for further study in this field. The significance of renewable energies, green technologies, and financial inclusion in the direction of carbon neutrality in European economies is not well analyzed. Innovation in energy can be renewed, and green technologies are important to generate processes and energy to minimize emissions that other technologies emit. The financial sector has enormous leverage in terms of funding and raising awareness about sustainability issues. For example, it may support companies that follow ethical and sustainable business practices and research and development of clean energy technologies. Thus, investment verdicts that consider ESG aspects of an economic activity or project are critical and warrant further study.

Nevertheless, there is a dearth of literature scrutinizing the effect of these factors on CO_2 emissions in European economies. Therefore, this study focuses on the effect of green technology innovation, usage of renewable energies, and financial growth on CO_2 emissions in Europe, with human capital and GDP as additional variables. The current analysis aims to build consensus on policy pathways toward achieving Europe 2050 net zero targets and provide policymakers with empirical indication to improve or design apt outlines to address the threat of CO_2 emissions. This inceptive study adds to the extant literature in numerous ways. Firstly, this current study assesses European countries' race to carbon neutrality in different areas, including green investment, financial inclusion, human development, and economic growth. Second, the study innovatively

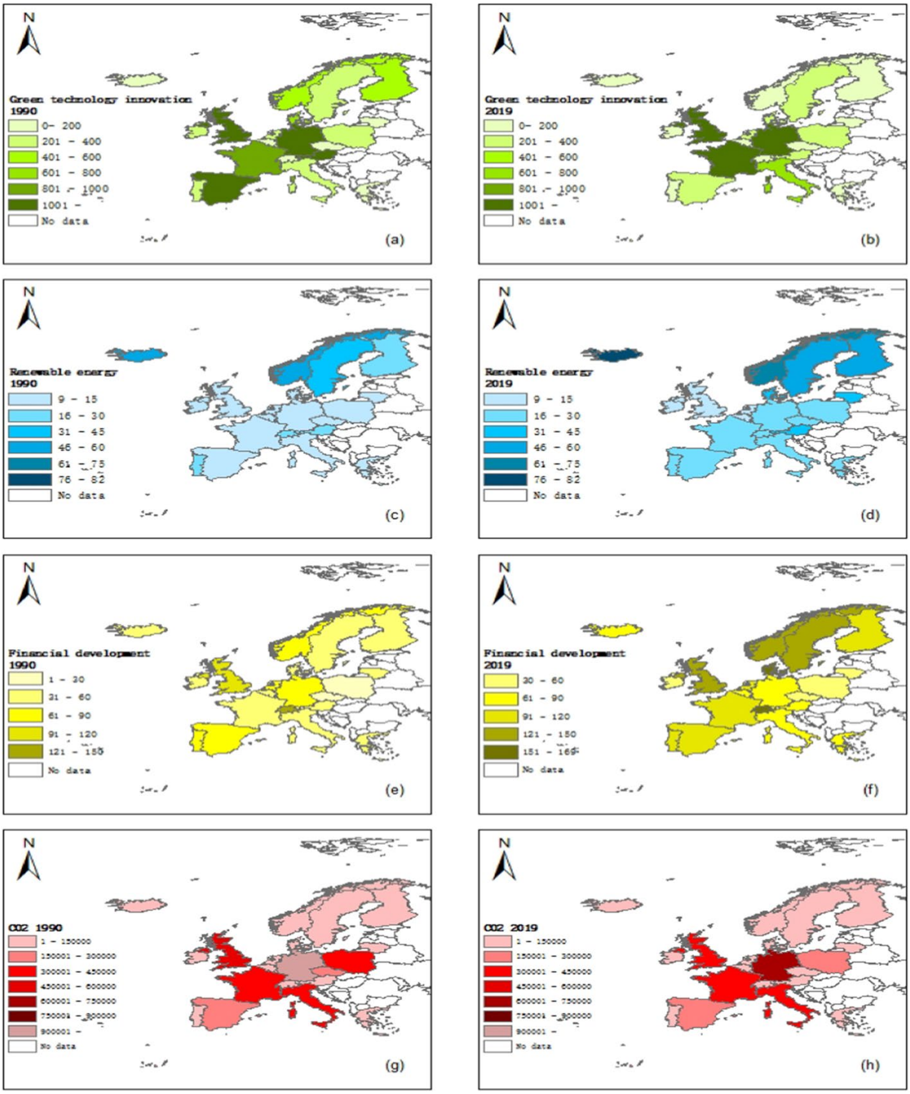

Fig. 2 Green technology innovation, renewable energy, financial development, and CO_2 emissions across 21 European economies in 1990 and 2019

forecasted the CO_2 emissions of the European countries for the next decade with the predominant predictors (green technology innovation, human capital, GDP, and renewable energy usage). Third, the study employs robust advanced estimators that address cross-sectional reliance and slope heterogeneity issues. By using advanced models, this study will help to clarify whether these variables can help to achieve carbon–neutral targets in European countries.

A review of relevant research is exhibited in the second section. The empirical methodology and study data are reported in the third section. The study results are reported and deliberated in the fourth section. The conclusion and suggestions are presented in the fifth section.

2 Review of related literature

2.1 Green technology innovation and CO_2 emissions

Green technology refers to technological innovation that minimizes pollution while also boosting the economy (Wang et al., 2021). Environmental or eco-innovation is an effective way of reducing pollution that can positively contribute to economic development (Sun et al., 2021). Also, the UN Sustainable Development Goals (SDGs) prioritize clean technology to avert global warming and keep global temperatures below 1.5 °C. Many countries have thus increased funding for the deployment and development of green technology innovations, which has attracted prominent scholars' attention in the environmental literature as a measure of ecological pollution. For instance, analyzing the role of green technological innovation and utilization of renewable energy toward carbon neutrality in N-11 nations, Shao et al. (2021) argued that green technological innovation can help dampen ecological degradation and achieve carbon neutrality. Shan et al. (2021) discovered that increased green technology innovation negatively impacted CO2 emissions in Turkey from 1990 to 2018. The research concludes that ecological sustainability can be improved through innovation in green technologies. According to Lin and Ma (2022), the adoption of green technological innovation is crucial in deterring the usage of nonrenewable energies and promoting the utilization of clean energies, hence reducing China's carbon emissions. Likewise, Kuang et al. (2022), found that green technology innovations dampen carbon emissions in China. Green innovation, according to Sun et al. (2019), promotes energy efficiency and lowers the use of polluting energies, both of which contribute to environmental sustainability. Moreover, Obobisa et al. (2022) emphasize that green technological innovations play an imperative role in stimulating green economic development and accelerating the sustainable energy transition to attain low CO_2 emissions. Dong et al. (2022) highlight that green technology innovations have considerably increased carbon emission efficiency in industrialized countries. According to Habiba et al. (2022), one key source of mitigating CO2 emissions is green technology innovation. However, Du et al. (2019) realized green technology innovation does not decrease carbon emissions in low-income nations. Alataş (2022) found that the influence of ecological technologies on the decrease of CO_2 emissions from the transportation industry in the EU is statistically insignificant. Similarly, Khan et al. (2020) highlight that the deployment and development of green technology innovations lead to an upsurge in energy usage and drive the adoption of efficient and new products, which results in a rebound impact on CO_2 emissions in G7 countries. Thus, green technology innovation increases the amount of energy consumed in the manufacturing process, increasing CO_2 emissions level, implying that the initial positive effect of a technological innovation improvement results in an upsurge in energy usage and CO_2 concentration in the atmosphere. From the empirical evidence, the study hypothesized that:

Hypothesis 1 Green technology innovation mitigates CO_2 emissions in European countries.

2.2 Renewable energy usage and CO_2 emissions

Renewable energy sources have long been recognized for their ability to dampen CO2 emissions and create a sustainable environment. According to Danish and Ulucak (2021), carbon emissions may be lowered by using renewable energy more efficiently while also enhancing energy security. Bilan et al. (2019) argued that establishing effective tools and processes to improve renewable energy adoption is needed to dampen the anthropogenic influence of CO_2 emissions in EU economies. Obobisa (2022) explored the impact of the utilization of renewable energy on CO_2 emissions and revealed that renewable energy usage dapmens CO_2 emissions in Asia–Pacific, Africa, America, European economies, and globally. The study clinched that increased usage of renewable energy could help to realize the global net-zero CO_2 emissions and 1.5 °C goals. Applying the OLS approach, Dogan and Seker (2016) demonstrate that an advanced share of renewable energy reduces CO_2 emissions in EU nations. By studying the affiliation that ensue between renewabl energy utilization and CO_2 emissions in the USA, Yuan et al. (2022) argued that renewable energies perform well in terms of realizing carbon neutrality ambitions. Similarly, Wolde-Rufael and Mulat-Weldemeskel (2022) analyzed the efficiency of renewable energies in reducing Latin America and Caribbean economies' share of CO_2 emissions and concluded that renewable energy sources are excellent tools for promoting environmental quality. Based on their findings, Mujtaba et al. (2022), suggest that OECD nations may lower their share of global CO_2 emissions and improve environmental conditions by consuming more renewable energy. Also, an empirical investigation by Ehigiamusoe (2020) on the effect of electricity on CO_2 emissions in African nations highlighted that replacing polluting gas, coal, and oil with renewable energies such as solar, biomass, geothermal heat, and wind would significantly reduce carbon emissions. An analysis of the usage of renewable energy and CO_2 emissions by Shahnazi and Dehghan Shabani (2021) showed that the usage of renewable energy resources in EU nations promotes environmental quality. The study acknowledged that renewable energy can be used to perform economic activities such as transportation (vehicles, boats, and aircraft) and production without emitting carbon emissions. Similarly, Mahmood et al. (2022) observed that the usage of renewable energies adds to CO_2 emissions reduction and encourages green growth in OECD economies. From the empirical observation, the study hypothesized that:

Hypothesis 2 Renewable energy helps curb CO_2 emissions in European economies.

2.3 Financial development and CO_2 emissions

Financial development is widely acknowledged as a comprehensive indicator of an economy's financial system depth, efficiency, and stability, and it has received extensive attention to investigate its influence on CO2 emissions. For instance, Aluko and Obalade (2020) documented that financial development dampens CO2 emissions by analyzing the effect of financial development on environmental quality in sub-Saharan Africa from 1985 to 2014. Zafar et al. (2019) recognized that financial development improves environmental sustainability in OECD countries by plummeting CO_2 emissions. The study also detected a one-way causal link from CO_2 emissions to financial development. Examining the USA's potential for carbon neutrality, Lahiani et al. (2021) discovered that financial sector development heightens the usage of renewed energy resources, which lowers CO_2 emissions. Abid (2017) highlighted that low carbon emissions and sustainable development are linked with financial inclusion in the EU and MEA countries. Musa et al. (2021) argued that an established robust financial system is one of the reliable means to promote a cleaner and more sustainable environment in EU countries. This implies that financial stability is a prerequisite for improving environmental performance. Using different financialization proxies on CO_2 emissions in top-ten emitter economies Amin et al. (2020) assert that expansion of financial institutions is required to increase the availability and accessibility of funds to individuals and companies which can stimulate investments in clean energies and reduce CO_2 emissions level. According to Musah et al. (2023), expanding financial sectors will improve access to firm finance and financial services, encouraging clean energy, low-carbon technologies, and sustainable economic activities that promote a clean environment. Also, Umar et al. (2021) accentuated that financial development is essential to boost carbon–neutral credit and promote clean environment in the Eurozone. Thus, for economies to be carbon-free, green financial intermediation mechanisms must be developed. However, other researchers emphasize that the expansion of financial sectors contributes to environmental pollution. For instance, Bayar et al. (2020), on financial development and carbon emission in post-transition EU economies, analytically discovered that development in financial sectors causes a rise in carbon emissions. The study, however, found no causality between development in financial sectors and carbon emissions. Also, investigating financial-related CO_2 emissions, Lahiani (2020) evidenced that the expansion of financial institutions generates more carbon in China. Khan et al. (2022) revealed that financial development encourages the purchase of polluting items, which increases energy utilization and CO_2 emissions globally. Similarly, Anwar et al. (2022) established that growth in financial sectors heightens CO_2 emissions in 15 Asian nations. From the empirical evidence, the study hypothesized that:

Hypothesis 3a Financial development mitigates CO2 emissions in European countries.

2.4 Human capital and CO_2 emissions

Investing in human capital has been proven to affect the environment. Hao et al. (2021) analytically noted that human capital reduces CO_2 emissions in G7 countries. According to Wang and Xu (2021), human capital is vital to the development of a low-carbon nation. Moreover, Sheraz et al. (2021) suggest that human development, such as environmental education, is critical in managing environmental degradation since people with a high level of education engage in ecologically friendly activities and adhere to environmental policies. In the manufacturing sector, highly educated individuals help to promote innovation and diffusion of technologies (Jahanger, 2022). Also, firms with significant human capital tend to be long term oriented, with a focus on sustainable development, suggesting that growth in human capital will aid in cutting ecological footprints and accelerating the net-zero emissions transition (Shujah ur et al., 2019). According to Yao et al. (2020), firms with a higher human capital stock tend to implement stricter pollution controls and are unlikely to breach external environmental standards. A recent analysis by Umar et al. (2022) accentuated that increased human capital efficiency dampens emissions of CO_2 and improves environmental quality. Thus, increasing human capital investment leads to inventive management techniques that aid in the transition to sustainable development (Bayar et al., 2022). However, analyzing the effect of human capital on the emissionsanations of CO_2, Haini (2021) found that industries with a high stock of human capital tend to increase CO_2 emissions. Also, Ganda (2021) accentuated that a high level of human capital leads to increased economic activities, which have the potential to add additional carbon emissions when environmental quality is not prioritized. Exploring the link between environmental pollution and human capital from 1994 through 2018 in EU countries, Çakar et al. (2021) revealed that human capital dampens CO_2 emissions in low-growth regimes but upsurge CO_2 emissions in high-growth regimes. The research further documented that human capital raises carbon emissions in low and high financial development regimes. From the empirical evidence, the study hypothesized that:

Hypothesis 4 Human capital mitigates CO_2 emissions in European countries.

2.5 GDP and CO_2 emissions

GDP is a crucial factor in economic growth. GDP targets can be attained through the improvement of production, industrialization, transportation, and energy consumption. In contrast, growth in the manufacture of products and services and industrial activities might have an impact on the environment. Therefore, there has been a shift in recent years from a strictly environmental construal of sustainable development to a more integrated strategy, examining the association between GDP and emissions. Mohsin et al. (2022) scrutinized the affiliation between carbon emissions and GDP in European and Asia countries and revealed that CO_2 emissions are significantly increased by economic activities. In OECD nations, Ganda (2019a), analytically documented a positive affiliation between GDP and emissions of CO_2. Also, Zaidi et al. (2019) established the validity of the EKC hypothesis in their research by showing that long-run GDP growth leads to fewer emissions of CO_2 in Asia Pacific Economic Cooperation (APEC) nations. Erdoğan et al. (2020), nevertheless, showed that the EKC is invalid in G20 nations. Khattak et al. (2020) discovered that increasing levels of income result in higher levels of carbon emissions for BRICS economies. In their study on the affiliation between GDP and CO_2 emissions, Zhang et al. (2020) recognized a positive affiliation between real income and carbon emanations in China and ASEAN countries. For EU countries, Radmehr et al. (2021) found that greater income levels are connected with higher levels of CO_2 emissions. Real income and carbon emissions in China and the USA are positively correlated, according to an empirical analysis by Mohmmed et al. (2019) concerning the connection between economic growth and forest resources. A recent analysis by Zhao et al. (2022) recognized that an upsurge in GDP is the main contributor to carbon emissions in nations that have declared carbon neutrality goals. The study noted that when GDP in nations rises, so do emissions of $CO_{2,}$ which degrades the quality of the environment. Economic actions such as transportation and production require conventional energy, which releases CO_2 and reduces ecological quality (Mensah et al., 2021). From the empirical evidence, the study hypothesized that:

Hypothesis 5 GDP increases CO_2 emissions in European countries.

3 Empirical methodology

3.1 Model specification

The Stochastic Impacts by Regression on Population, Affluence, and Technology (STIRPAT) model is a commonly used model in empirical research to identify factors contributing to changes in environmental quality (Dietz & Rosa, 1994). The STIRPAT model expands on the IPAT model proposed by (Ehrlich & Holdren, 1971).[7] It establishes a theoretical framework for comprehending the ecological consequences of population, affluence, and technology. The STIRPAT model has been extended in studies (Aluko & Obalade, 2020; Habiba et al., 2022) to account for the ecological impact of other factors. The STIRPAT model is specified as:

$$I_{it} = \alpha P_{it}^{e} A_{it}^{f} T_{it}^{g} \varepsilon_{it} \quad (1)$$

where I denote the ecological impact. The parameters e, f, and g denote estimated coefficients, and ε is the error term. By transforming Eq. (1) to a logarithmic form, the study specified Eq. (2) as:

$$lnI_{it} = ln\alpha + elnP_{it} + flnA_{it}, + glnT_{it} + \varepsilon_{it} \quad (2)$$

The STIRPAT has recently emerged as the most comprehensive model for scrutinizing the effect of elements on CO_2 emissions. Thus, the current study expands and adapts the STIRPAT theoretical model, as shown in Eq. (3).

$$lnCO_{2it} = \alpha_0 + \beta_1 lnGTI_{it} + \beta_2 lnREC_{it} + \beta_3 lnFD_{it} + \beta_4 HC + \beta_5 lnGDP_{it} + \varepsilon_{it} \quad (3)$$

where CO_2 denotes carbon dioxide emissions, GTI denotes green technology innovation, REC denotes renewable energy consumption, FD means financial development, HC signifies human capital, and GDP means economic growth.

To estimate Eq. (3) parametrically, the study first conducted preliminary tests such as slope heterogeneity, cross-sectional dependency (CSD), and stationarity tests. The study's use of second-generation panel models will be contingent on homogeneity and CSD validations. This would clarify that avoiding these preliminary tests may result in some erroneous estimations (Obobisa et al., 2021a, 2021b). To validate the long-run correlations between the selected study variables, Westerlund (2007) cointegration approach is applied. Based on the cointegration test, CS-ARDL by Chudik and Pesaran (2015) is used to estimate the short-run and long-run relationship between the study variables. This panel estimator has a particular benefit over other approaches since it addresses variables with cross-sectional reliance, slope heterogeneity, endogeneity, and non-stationarity concerns. This study utilizes the CS-ARDL regression as:

$$InCO_{2it} = \alpha_o + \sum_{j=1}^{P} \lambda_{it} InCO_{2i,t-j} PC + \sum_{j=0}^{P} \underset{it}{\alpha} X_{t-j} + \sum_{j=0}^{3} \underset{it}{\ddot{v}} \overline{Z}_{t-j} + \mu_{it} \quad (4)$$

where $\overline{Z}_t = (\Delta\overline{InCO_{2t}}, \overline{X}_t\prime)\prime$ and $X_{it} = \left(InGTI_{it}, InREC_{it}, InFD_{it}, HC_{it}, InGDP_{it}\right)\prime$.$CO_2$ denotes the denotes the carbon emissions, and X signifies the explanatory variables such as green technology innovation, renewable energy usage, financial development, human capital

[7] For details on the limitations of IPAT model see Li and Lin (2015).

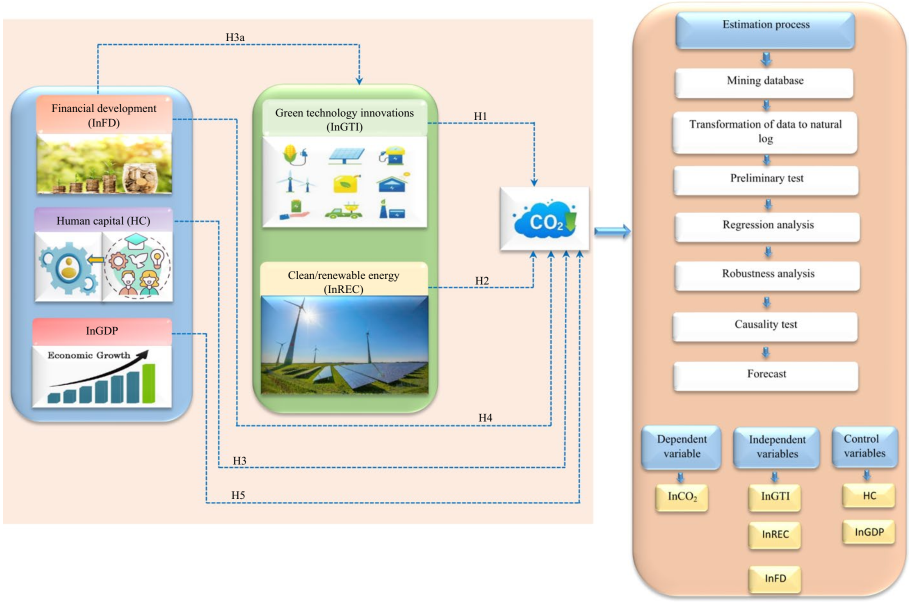

Fig. 3 Analysis framework

index, and GDP. The study further used AMG and CCEMG estimators for robustness checks. Also, a causality test using Dumitrescu and Hurlin (2012) technique is performed to ascertain the variables' causal affiliation. Accordingly, the study utilized Lanne and Nyberg (2016) variance decomposition and impulse response technique to scrutinize the response of CO_2 emissions to shocks in the explanatory variables. Figure 3 shows the analytical framework.

3.2 Data

The panel is made up of a subset of 21 European countries[8] with yearly observations from 1990 to 2019. The study's dependent variable is CO_2 emssions, whereas the independent explanatory factors are GDP, green technology innovation, human capital, financial development, and renewable energy usage. The UN Sustainable Development Goals (SDGs) (Nations 2016) served as inspiration for the choice of the model variables. Thus, carbon emission, which is in line with climate change reduction (SDG-13), is the world's most urgent to minimize global emissions. Also, fostering green technology innovation (SDG 9) may aid in promoting sustainable economic growth (SDG- 8), production and consumption (SDG-11 and 12), and reducing CO_2 emissions. Renewable energy sources (SDG-7), which are cost-effective and environmentally friendly, play a vital role in increasing access to electricity while mitigating environmental pollution. Also, a higher degree of financial development suggests that people and enterprises are more likely to get bank loans to grow their manufacturing activity

[8] Due to data availability, the sample is limited to 21 European countries: Austria, Belgium, Czechia, Denmark, Finland, France, Germany, Greece, Iceland, Ireland, Italy, Lithuania, Luxembourg, Netherlands, Norway, Poland, Portugal, Spain, Sweden, Switzerland, United Kingdom.

and consume more energy, resulting in uncertain implications on CO_2 emissions. GDP, on the other hand, contributes to CO_2 emissions (Mohsin et al., 2022). Theoretically, economic activities such as production and transportation generate more demand for the consumption of energy, and energy use directly impacts environmental resources (Obobisa et al., 2021a, 2021b). Additionally, human capital such as environmental education (SDG- 4), training, and technical skills are assumed to be critical in managing environmental degradation since people with a high level of education engage in environmentally friendly activities and adhere to environmental policies (Wang et al., 2020; Yao et al., 2020).

Similarly, the endogenous growth theory established that human capital is a driving force behind technological advancement and a supplement to research and development (Romer 1990). As such, technological innovation enhances energy resource efficiency and helps the transition to cleaner energies and production, lowering CO_2 emissions. Hence, a comprehensive examination of these highlighted variables is timely in the achievement of carbon neutrality and SDGs.

The dataset is obtained from multiple authentic sources. Definitions for the variables and databases are exhibited in Table 1, while Table 2 presents the descriptive statistics. The boxplot analysis of the variables in Fig. 4 confirms the descriptive or summary statistics. Besides, all the study variables display VIF values of less than 5, signifying no multicollinearity amongst the study variables. The correlation test in Fig. 5 also reveals that all of the variables' correlation coefficients are less than 0.95, proving the absence of multicollinearity. Moreover, elucidating their one-to-one connection are scatter plots of the independent and dependent study variables (see Figs. 6, 7, 8, 9, 10). The correlation findings in Fig. 5 are supported by the analysis displayed in Figs. 6, 7, 8, 9, 10 below. Figure 6, 9, and 10 demonstrate the positive affiliation of green technology innovation, human capital, and GDP with CO_2 emissions. Thus, an upsurge in environmental-related technologies, human development, and economic growth activities will boost CO_2 emissions. However, Figs. 7 and 8 expose that renewable energy usage and financial development are negatively connected to CO_2 emissions, indicating that increased usage of renewed energy resources and financial inclusion curb CO_2 emissions.

4 Empirical analysis and discussion of results

4.1 Results of preliminary tests

Table 3 reports the CSD results by Pesaran (2004) and the heterogeneous slope coefficient of Pesaran et al. (2008). It was observed that at a 1% significance level, the selected study variables are cross-sectionally independent, confirming the interdependence of the European countries. This further clarifies why CO_2 emissions increase or decrease cannot be managed independently; other countries would have an impact on a nation's objectives. Moreover, the null hypothesis regarding slope coefficients for the selected variables is rejected, considering the homogeneity test outcomes. These findings thus highlight the heterogeneous nature of the variables and show that using traditional tests and cointegration techniques will produce biased results. Thus, applying the second-generation stationarity test is necessary since the panel dataset exhibits CSD.

The results of Pesaran (2007) stationarity test in Table 4 demonstrate the non-stationarity of the variables, with the exception of green technology innovation and renewable energy consumption, which is stationary at the level. Nevertheless, all the study variables stagnate stationarity in their first difference.

Table 1 Definition of variables and sources

Variables	Definition	Measure (unit)	Database
Dependent variable			
lnCO_2	Carbon dioxide emissions	Kiloton (kt)	World development Iindicators
Independent variables			
lnGTI	Green technology innovation	Number of environmental technology patents that are registered	OECD statistics
lnREC	Renewable energy consumptionusage	% of total final energy usage	World development Iindicators
lnFD	Financial development	Domestic credit to the private industry (% of GDP)	World development Iindicators
Control variables			
HC	Human capital index	Years of schooling and returns back to school	Pen world table version 10.01 DATA
lnGDP	Gross domestic product per capita	Constant 2015 US$	World Development Indicators

Table 2 Descriptive statistics

Variables	$lnCO_2$	lnGTI	lnREC	lnFD	HC	lnGDP
Mean	11.272	4.326	2.413	4.422	3.116	10.310
Median	11.090	4.724	2.444	4.492	3.124	10.521
Maximum	13.770	8.536	4.348	5.916	3.734	11.429
Minimum	7.528	−1.109	−0.497	2.555	1.940	7.431
SD	1.395	2.007	1.110	0.519	0.356	0.785
Skewness	−0.554	−0.368	−0.381	−0.386	−0.506	−1.594
Jarque–Bera	34.573	17.401	21.959	29.431	27.807	448.988
Obs	630	630	630	630	630	630
VIF	/	2.08	1.31	1.25	1.41	1.86

Following the cross-sectional reliance and stationarity tests, a cointegration test by Westerlund (2007) was conducted to confirm the presence of a cointegration among the study variables. Based on the empirical outcomes exhibited in Table 5, the absence of cointegration as the null hypothesis is rejected. This would support the claim that the study variables have a cointegration connection.

4.2 CS-ARDL regression results

Based on the homogeneity test, CSD test, stationarity test, and cointegration tests, it can be concluded that second-generation estimators should be used in the study to tackle heterogeneity and CSD issues. Hence, the long run and short run affiliation between green technology innovation, renewed energy usage, financial growth, human capital, GDP, and carbon emissions is estimated by applying the CS-ARDL regression technique. Table 6 presents the long-term outcomes of the CS-ARDL regression, and Fig. 11 shows the visual illustration. The findings reveal that green technology innovation has a negative effect on the emissions of CO_2 with a coefficient of −0.025 which is statistically significant at a 5% level. This estimated coefficient implies that with a 5% upsurge in green technology innovation, CO_2 emissions would decline by 0.025%. To meet Europe's carbon neutrality target, there has been an increasing need in recent years for more funding for green technologies. Also, many EU initiatives and programs support the deployment of clean technologies. Green technology innovation lowers the level of carbon emanations by producing energy-efficient and advanced technologies that reduce energy usage. The result proposes that green technologies have provided the best opportunities to develop greener economies and reduce anthropogenic CO_2 emissions in European countries. In particular, green technology innovation is critical in supporting European countries in reducing their carbon emissions. Thus, increasing green investment and allowing households and firms to continue to access green technologies could help these European economies reduce their share of CO_2 emissions from a global perspective and achieve carbon neutrality goals.[9] This result aligns with the studies of Dong et al. (2022), Khurshid et al. (2023).

As expected, the regression results expose that renewable energy usage has a negative and significant effect on CO_2 emissions at a 1% level. Specifically, a 1% upsurge in the

[9] Mongo, Belaïd, and Ramdani (2021) also accentuated that increasing investment in environmental-related innovation or green technology innovation is a fundamental step towards carbon neutrality in European nations.

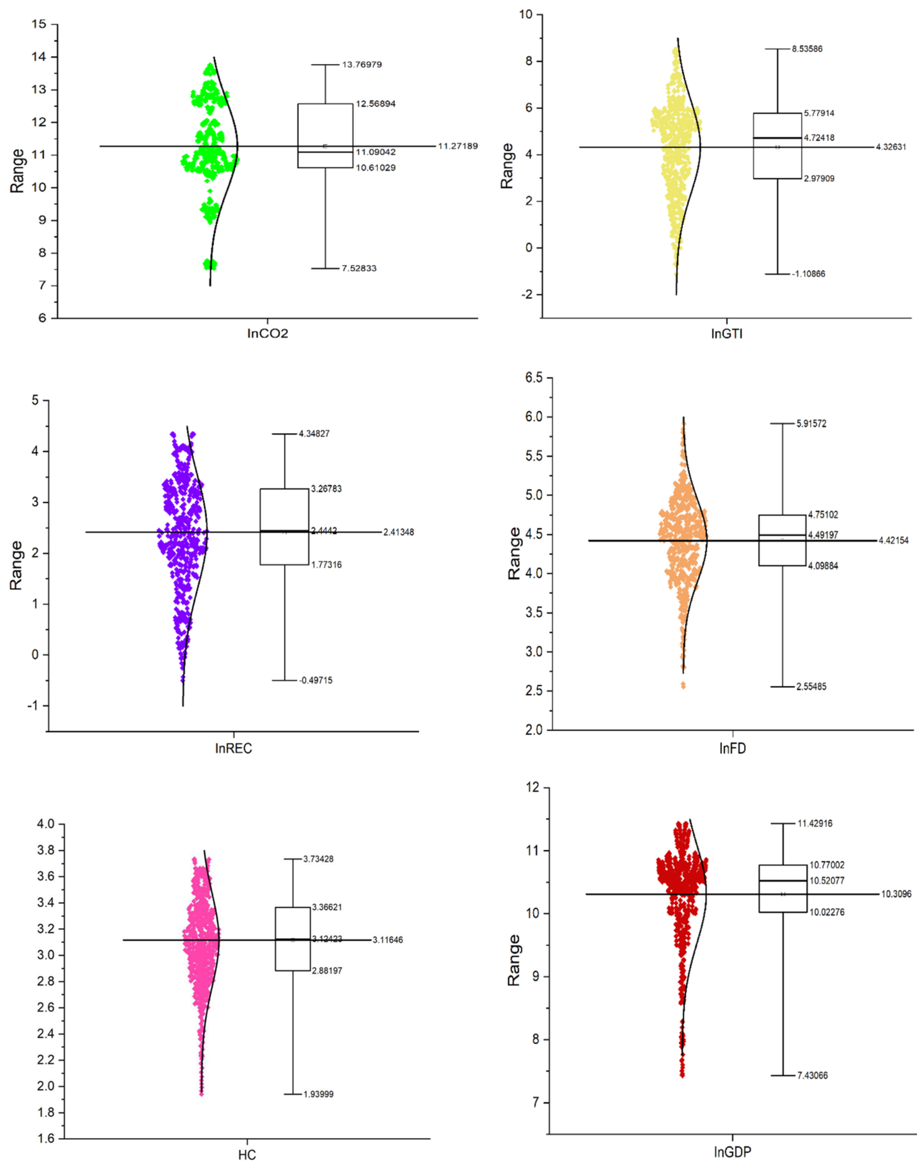

Fig. 4 Boxplot of the selected variables

usage of renewable energies lead to a 0.215% net cut in anthropogenic CO_2 emissions. In the race to avert climate change and secure energy independence, many European countries have been generating more renewable energy, and a growing share of its energy usage is met through renewable energy sources. The European Green Deal also ensures that at least 32% of consumed energy is generated from renewable sources by 2030. Countries across Europe have, therefore, increased investment in green activities, including the deployment of renewable energies, hydrogen generation, and energy efficient products. The corollary

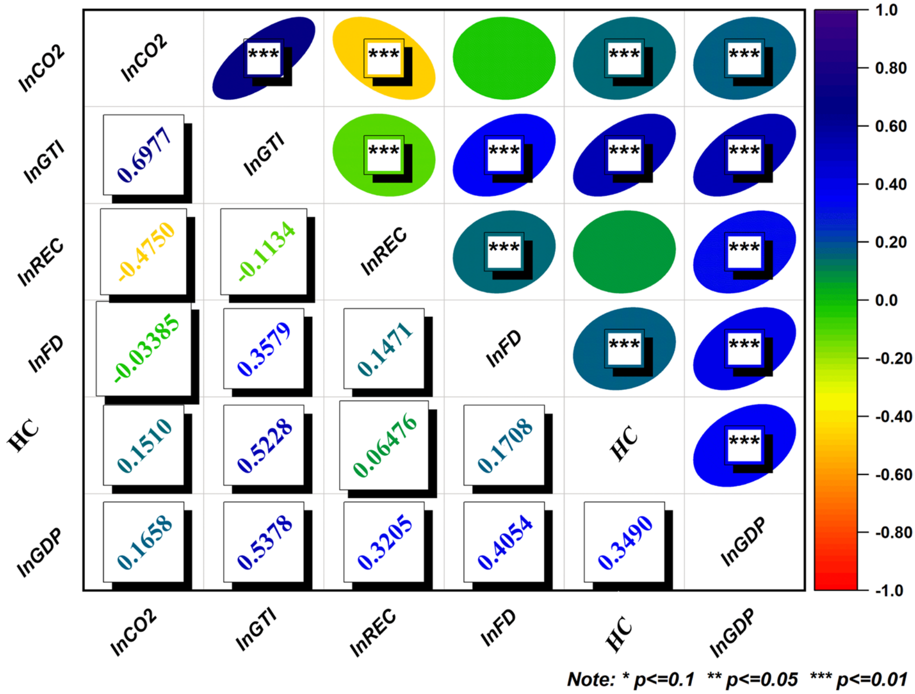

Fig. 5 Correlation matrix

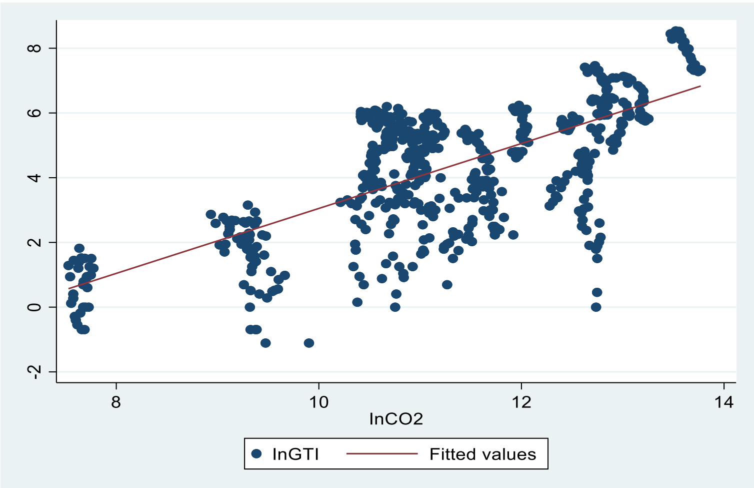

Fig. 6 CO_2 emissions with green technology innovation

of this outcome shows that European economies have benefitted in terms of CO_2 reduction from the deployment of renewable energies that have taken place. This supports the literature (Adedoyin et al., 2021a, 2021b; Balsalobre-Lorente et al., 2021) in the EU, Chen et al.

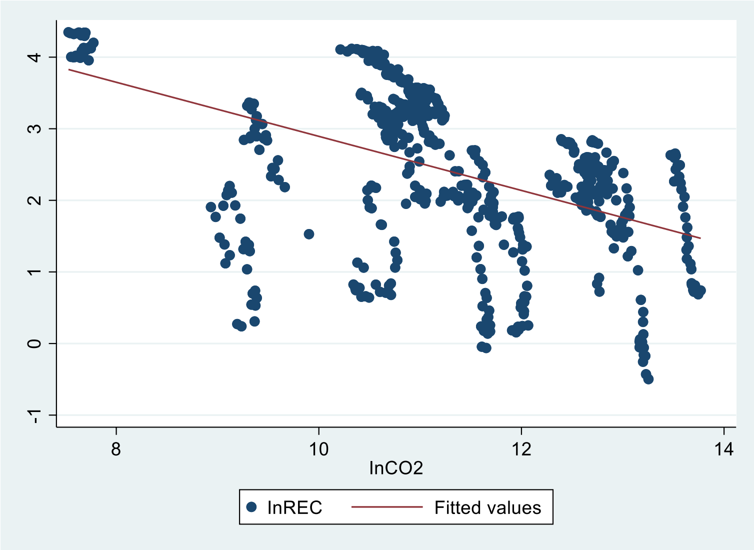

Fig. 7 CO_2 emissions with renewable energy consumption

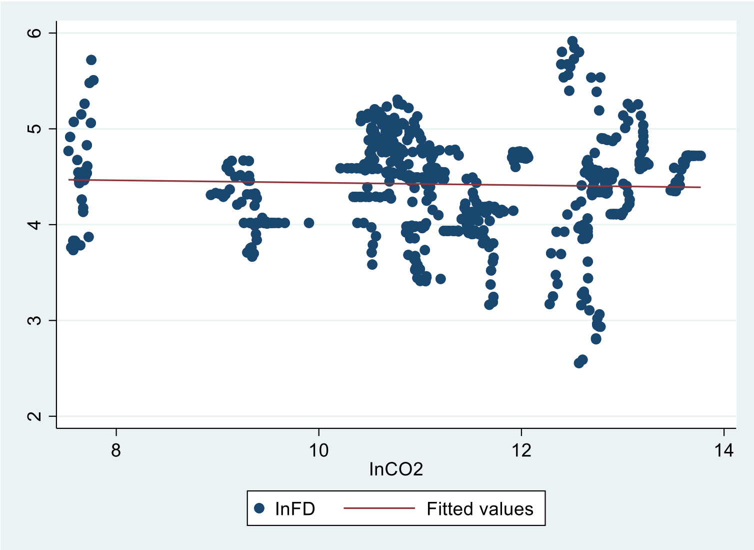

Fig. 8 CO_2 emissions with financial development

(2023) in top emitter economies and Obobisa (2022), who argued that increased usage of renewable energy is a significant mechanism for realizing net-zero emissions target in the European economies.

Moreover, the 21 European nations' CO_2 emissions are positively impacted by financial development. Thus, advancement in the financial sectors in the European nations

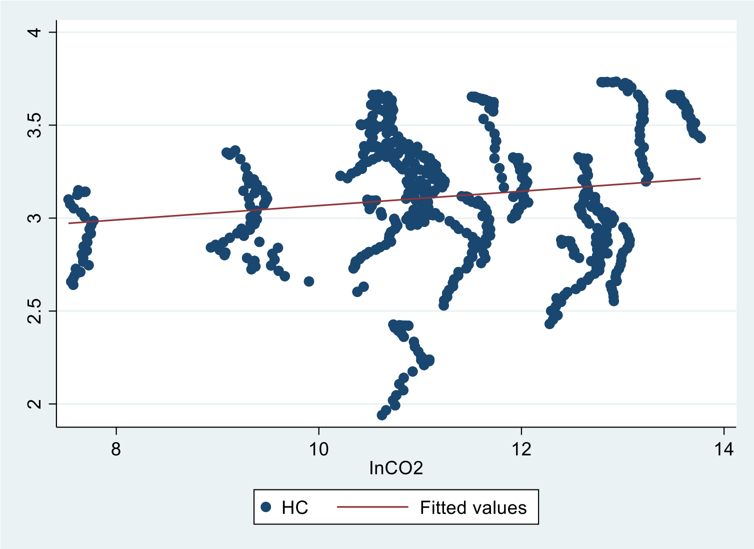

Fig. 9 CO_2 emissions with human capital

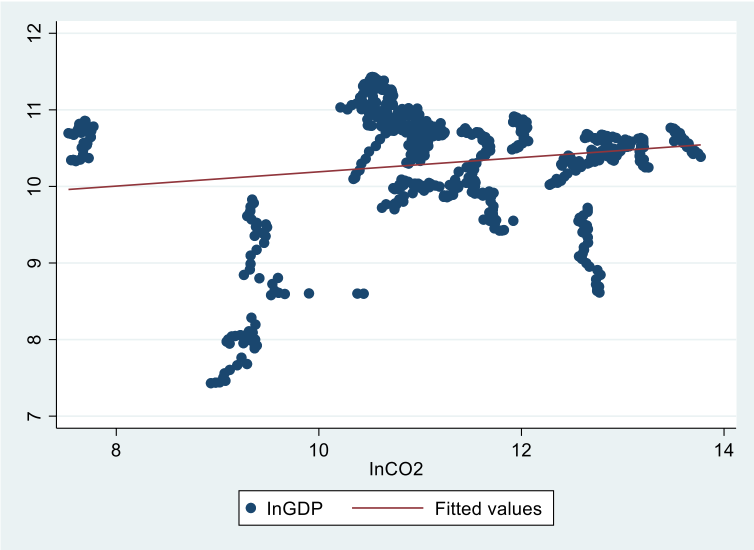

Fig. 10 CO_2 emissions with GDP per capita

leads to a statistically significant increase in carbon discharges. Specifically, the results suggest that a 1% expansion in financial sectors will increase CO_2 concentration in the atmosphere by 0.079%, which contrasts with the research of (Musa et al., 2021; Obobisa, 2022) but corroborates the studies of (Bayar et al., 2020; Musah et al., 2023) for several

Table 3 Slope heterogeneity and CSD tests

Variables	CSD test	Correlation
$lnCO_2$	25.236*** (0.000)	0.48
lnGTI	63.603*** (0.000)	0.80
lnREC	54.189*** (0.000)	0.79
lnFD	18.571*** (0.000)	0.54
HC	77.42 ***(0.000)	0.98
lnGDP	67.064 ***(0.000)	0.85
Slope heterogeneity estimations		
	Tilde	Tilde adjusted
	26.981*** (0.000)	30.815*** (0.000)

***, **, and * illustrates statistical significance at 1%, 5%, and 10% respectively

Table 4 Stationarity evidence by CIPS

Variables	Level intercept	Trend	First difference intercept	Trend
$lnCO_2$	−2.115	−2.454	−4.686***	−4.960***
lnGTI	−4.034***	−3.933 ***	_	_
lnREC	−2.044	−2.687**	_	_
lnFD	−1.220	−1.743	−3.829***	−3.990***
HC	−1.080	−1.015	−2.310**	−3.177***
lnGDP	−0.956	−1.205	−2.471***	−2.308***

***, **, and * illustrates statistical significance at 1%, 5%, and 10% respectively

Table 5 Evidence of cointegration

Statistics	Values	Z-values	Robust P-value
G_t	−3.570	3.569	0.004***
G_a	−13.621	1.985	0.003***
P_t	−15.464	3.425	0.006***
P_a	−11.926	1.045	0.026**

***, **, and * illustrates statistical significance at 1%, 5%, and 10% respectively

Table 6 Long run estimation

Variables	Coefficient	t-statistics	P-Value
Dependent variable: CO_2 emissions			
lnGTI	−0.025**	0.009	0.005
lnREC	−0.215***	0.053	0.000
lnFD	0.079***	0.025	0.002
HC	−1.086**	0.465	0.020
lnGDP	0.316***	0.073	0.000

***, **, and * illustrates statistical significance at 1%, 5%, and 10% respectively

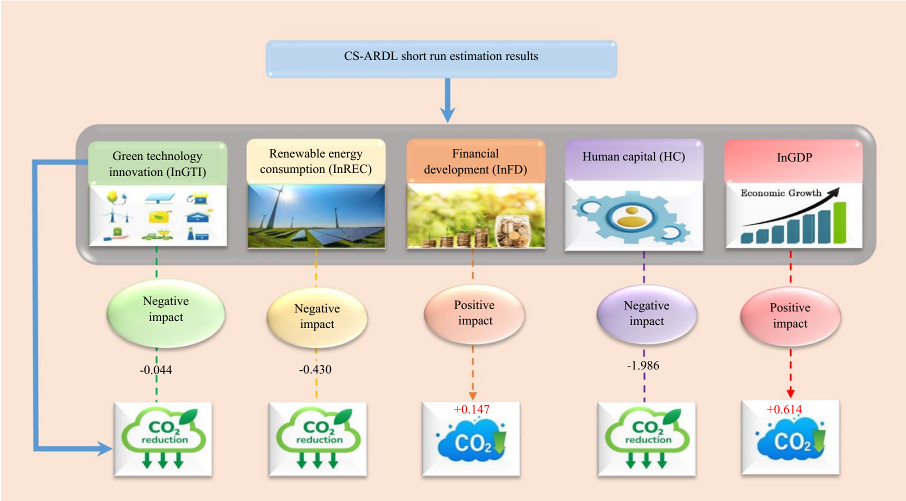

Fig. 11 Visual display of long-run results

reasons. Financial development makes it easier for households and firms to get loans to buy energy-intensive goods or equipment, such as vehicles, air conditioners, and cooking appliances, which inexorably generate more carbon (Anwar et al., 2022). Moreover, easy access to finance enhances households' and businesses' consumption and production activities, resulting in increased emissions. Some European countries have expanded their financial sectors in recent years. These regions have witnessed an increase in banks, credit unions, and some financial institutions, and energy-intensive firms are more likely to receive financial support since they are more profitable. As previously stated, this could have resulted in increased environmental damage.

The findings expose further a negative and significant connection between human capital and CO_2 emissions. A 5% advance in human capital leads to a 1.086% net diminution in CO_2 emissions in the long term.[10] This may be because many European countries are promoting environmental awareness through ecological education, which motivates residents to change their behaviour and consume sustainable products. Also, it is evident in several European economies' sustainable development initiatives, such as green technologies development projects, smart city projects, and educating residents about the conservation of energy, clean energies, and electric vehicles (EVs), which have increased environmentally friendly activities and abated CO_2 emissions. These findings contradict Ganda (2019b) results but approve Saqib et al. (2023) results in European countries, and Wang et al. (2020) study in N-11 as well as Zia et al. (2021) highlight that human development help in promoting technological innovation and minimizing carbon emisions through education.

GDP, measured as economic growth, has been exposed to impact CO_2 emissions positively and significantly. Thus, a 1% surge in economic growth activities such as the manufacture of products and services, consumption, and transportation heightens CO_2 concentration in the atmosphere by 0.316% in the long term. GDP is well recognized for measuring the health of the economy and includes a variety of factors such as production,

[10] The result indicates that human capital may offer mitigation potential in European countries.

Table 7 Short-run estimation

Variables	Coefficient	t-statistics	P-Value
Dependent variable: CO_2 emissions			
lnGTI	−0.044**	0.016	0.005
lnREC	−0.430***	0.105	0.000
lnFD	0.147***	0.049	0.003
HC	−1.986**	0.913	0.030
lnGDP	0.614***	0.128	0.000
ECM (−1)	−1.893***	0.070	0.000

***, **, and * illustrates statistical significance at 1%, 5%, and 10% respectively

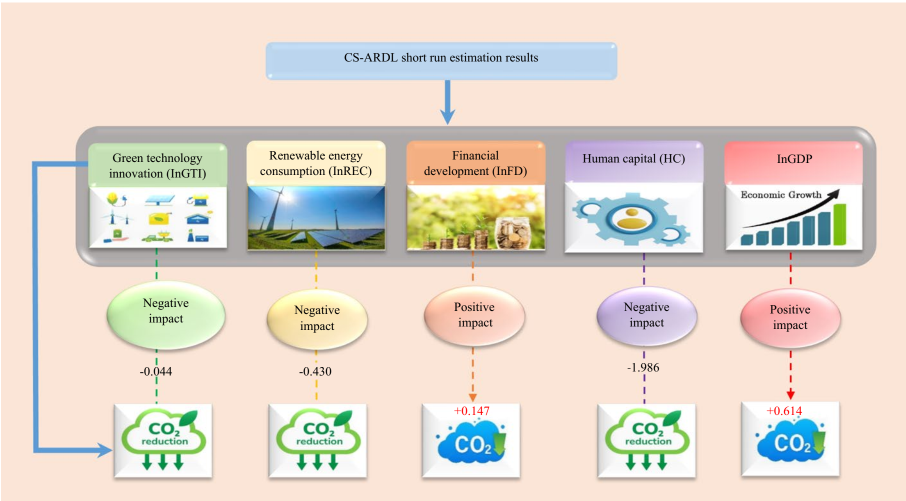

Fig. 12 Visual display of short-run results

transportation, government spending, and energy consumption, among others. Therefore, an increase in national revenue might also raise income at the company and residential levels. This increases the utilization and development of nonrenewable energy, raising the level of CO_2 emissions. This empirical finding supports earlier studies (Mohsin et al., 2022; Radmehr et al., 2021) in European countries.

Moreover, Table 7 exhibits the results of the short run CS-ARDL analysis, and Fig. 12 presents the visual illustration. The results show that green technology innovation negatively correlated with CO_2 emissions, with a coefficient of −0.044 at a 5% significance level. Meanwhile, the short-run coefficient of −0.430 indicates that renewed energy utilization dampens CO_2 emissions significantly. These findings indicate that investment in environmental-related technologies such as carbon capture technology, solar, wind, circularity, electrification, the integration of hydrogen, and energy efficiency will help European countries transition towards a sustainable and climate-compatible economy. Nevertheless, financial growth heightens carbon emissions in the short term. Also, the control variables, such as human capital, curb CO_2 emissions, whereas economic growth (GDP) positively

Table 8 Robustness test results

Variables	AMG		CCEMG	
	Coefficient	*P* Value	Coefficient	*P* Value
lnGTI	−0.026**	0.011	−0.049*	0.083
lnREC	−0.238***	0.000	−0.287***	0.000
lnFD	0.015*	0.074	0.027**	0.043
HC	−0.347**	0.045	−1.724***	0.004
lnGDP	0.683***	0.000	0.538***	0.000
Wald-Test	77.20***	0.000	54.83***	0.000
RMSE	0.031		0.022	

***, **, and * illustrates statistical significance at 1%, 5%, and 10% respectively

Table 9 Causality evidence

Null hypothesis	W-Stat	Zbar-Stat	Prob
lnGTI - $lnCO_2$	4.190***	3.803	0.000
$lnCO_2$ - lnGTI	3.453**	2.401	0.016
lnREC - $lnCO_2$	6.298***	7.811	0.000
$lnCO_2$ - lnREC	9.110***	13.158	0.000
lnFD - $lnCO_2$	7.034***	9.210	0.000
$lnCO_2$ - lnFD	4.512***	4.414	0.000
HC - $lnCO_2$	3.707***	2.883	0.004
$lnCO_2$ - HC	7.358***	9.825	0.000
lnGDP - $lnCO_2$	5.765***	6.798	0.000
$lnCO_2$ - lnGDP	1.920	−0.514	0.607

***, **, and * illustrates statistical significance at 1%, 5%, and 10% respectively

and significantly impacts carbon emanations. Additionally, the ECM coefficient is negative and statistically significant, as predicted, indicating the system's stability and ability to revert to equilibrium.

4.3 Robustness test results

Table 8 displays the results of the robustness for AMG and CCEMG, which confirm that green technology innovation, utilization of renewable energy, and human capital connect negatively and significantly with CO_2 emissions. Thus, clean energy technologies and human development are the key enablers for the transition to carbon neutrality in Europe. However, financial growth and GDP have a positive influence on CO_2 emissions. The long-run estimates produced by the AMG and CCEMG techniques strikingly confirm the CS-ARDL long run outcomes.

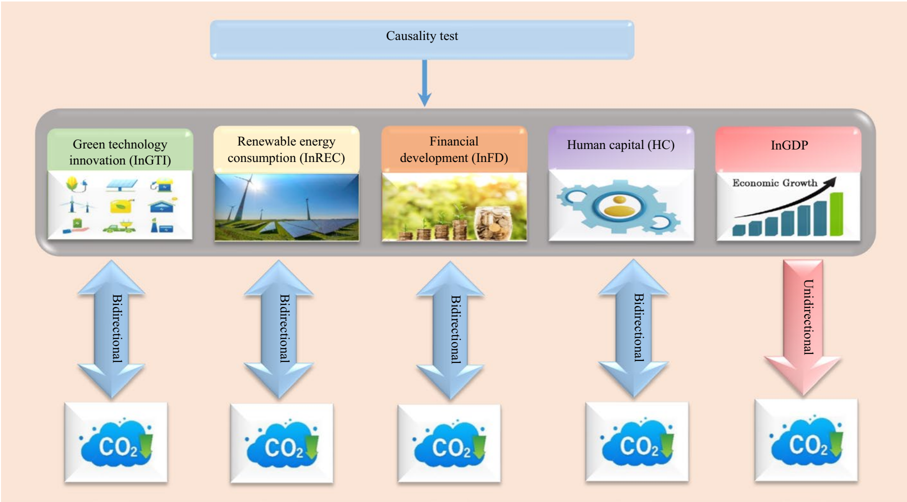

Fig. 13 Visual display of causality results

Table 10 Variance decomposition of CO_2 emissions results

Period	S.E	lnCO_2	lnGTI	lnREC	lnFD	HC	lnGDP
1	0.088	100.000	0.000	0.000	0.000	0.000	0.000
5	0.236	96.268	0.007	0.020	0.005	0.743	2.956
10	0.346	94.525	0.055	0.011	0.007	1.921	3.481
15	0.411	94.046	0.153	0.009	0.027	2.669	3.096
20	0.454	93.890	0.289	0.017	0.073	3.074	2.658
25	0.484	93.752	0.446	0.033	0.136	3.296	2.336
30	0.509	93.550	0.610	0.058	0.205	3.433	2.144

4.4 Causality test

Table 9 and Fig. 13 display the outcomes of the causality test, demonstrating which of the study variables are causative mediators for others. All the variables except GDP demonstrate evidence of bidirectional causality. For instance, there is a causal feedback connection between green technology innovation and CO_2 emissions, which approves the results of (Habiba et al., 2022; Qin et al., 2021), who also discovered this affiliation between green technology innovation and CO_2 emissions. Additionally, a feedback causal connection is discovered between CO_2 emissions and the utilization of renewable energy, which corroborates Dogan and Seker (2016) findings in EU nations. Similar to the findings of Obobisa (2022) in European nations, a two-way causal link between financial development and CO_2 emissions is documented. Moreover, human capital exhibits feedback causation with CO_2 emissions, as evident in the research of Shujah ur et al. (2019) in central and eastern European nations. Contrarily, a one-way linkage is observed from GDP to CO_2 emissions, which justifies the verdicts of Mohsin et al. (2022) in European and Asia countries.

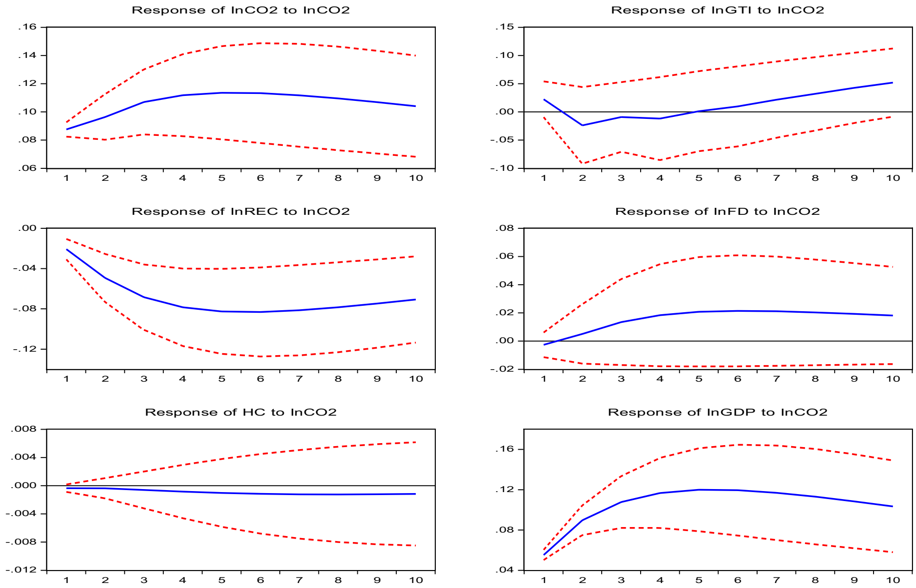

Fig. 14 Results of impulse response analysis

4.5 Results of variance decomposition and impulse response functions

Table 10 displays the results from the analysis of variance decomposition for the 30-year forecast horizon. Green technology innovation (0.610%) is observed to continue exerting predicted effects on CO_2 emissions with increasing amplitude, implying that green technology innovations will contribute considerably to Europe's future attempts to reduce CO_2 emissions. Regarding renewable energy usage, the findings show that its capacity to explicate the drop in CO_2 emissions would be greater in the ten-period projection than in the initial first five-year period. Within the next 30 years, the actual effect of financial development on CO_2 emissions will swiftly rise to 0.205% (a substantially higher percentage than predicted for the first five years). According to these results, future CO_2 emissions reductions in the European continent will be predominantly driven by human capital, which will be more relevant than the other factors considered. It is also evident that over time, the effect of GDP on CO_2 emissions will progressively wane. Figure 14 indicates that the variation in CO_2 itself upsurges over the first seven years and then somewhat decreases between the eighth and tenth periods. This implies an upsurge in its determinants, including green technological innovation, renewable energy use, financial developmentinclusion, GDP, and human capital. The variation of green technology innovation on CO_2 emissions is observed to increase highly. This supports the assertion of Khan et al. (2020) that the deployment of green technology innovations leads to an upsurge in energy utilization and promotes the use of efficient and new products, which results in a rebound influence on carbon emissions. When compared to the utilization of renewable energy, GDP, and human capital, the variation in CO_2 emissions from financial development is very low. This indicates that within ten years, the growth of the financial sectors will have a major influence on dampening CO_2 emissions in European economies.

5 Conclusion and policy implications

Becoming the world's first carbon–neutral continent by the year 2050 is the goal behind the European Green Deal. Clean energy technologies and sustainable finance have been proposed as effective factors that can make energy-intensive Europe a carbon–neutral continent. This study evaluates the effect of green technological innovation, the usage of renewable energy, financial development, and other control factors, such as GDP and human capital, on CO_2 emissions utilizing second-generation regression approaches. The regression analysis outcomes indicate that green technology innovation, renewable energy utilization, and human capital adversely correlate with CO_2 emissions , which suggests that environment-related technology innovations, renewable energy sources, and human capital improve environmental quality. The results also indicate that financial development and GDP are associated positively with CO_2 emissions. Thus, environmental degradation will increase as the financial sectors and GDP of European countries increase. Results of the test for causality also demonstrate a one-way causal link from GDP to CO_2 emissions and a bidirectional causality between green technology innovation, financial growth, renewable energy usage, human capital, and CO_2 emissionsemanations. Furthermore, the analysis of variance decomposition and impulse-response indicates that innovation in green technology innovation, renewable energy usage, and human capital will be the main factors reducing CO_2 emissions, while financial developmentgrowth and economic growth will show higher variations of CO_2 emissionanations in the next decade.

Based on the results, the ensuing policies and recommendations are offered. Theoretically, the study's results indicate that human capital, renewable energy sources, and innovative green technologies may aid European nations in their climate shift to a sustainable and climate-neutral continent. The analysis's practical conclusions point to the benefits of encouraging companies to participate in green initiatives in this field. In this sense, regional governments should provide firms with greater financial support. Import taxes should be reduced, especially for goods that encourage green investment. It would also be advantageous to provide tax incentives to firms or businesses that engage in green projects. In order to encourage businesses to invest in clean energy resources and dampen their dependency on nonrenewable energies, the government may choose to offer tax breaks. The financial commitment of European governments to invest more money in green technology projects and infrastructure for renewable energy is also necessary. Addressing supply–demand gaps for critical minerals like lithium and nickel is crucial for the clean energy technology sector. Resilient supply chains are critical for expediting the shift to a low-carbon energy region.

The study also recommends that financial sectors identify potential low-carbon emission projects and activities to undertake. Finance departments must simulate the risks associated with clean energy contracts or compare the profit and loss implications of investments in energy efficiency, employee inclusion programs, and the conversion of vehicles to electric ones. Teams in charge of Treasury operations must also be knowledgeable of Green Bonds and how assessing climate risk may affect insurance policies or credit facilities. Financial sector authorities ought to be convinced that endorsing environmentally sustainable practices pays more dividends in the long term than subsidizing energy-intensive initiatives.

This current study analyzes how financial growth, GDP, human capital, green technology innovation, and the utilization of renewable energy affect CO_2 emissionsemanations in European economies. To realize carbon neutrality, stronger economic tools such as carbon price and digitalization will be needed. Hydrogen, electrification, and, in some circumstances, carbon capture, CO_2 collection, use, and storage (CCUS) may also result in the significant emissions reductions required in energy-intensive businesses to keep the rise in global warming below 1.5 °C. However, unless EVs, batteries, and hydrogen are produced using clean energy, the process of production can adversely affect the environment. Thus, the production effect of technology should be the main focus of future study.

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Author's contribution DZ and ESO provided conceptualization. DJZ, ESO and ECA did data curation, formal analysis, investigation, methodology, and writing—review, and editing. DZ provided funding acquisition. DZ and ESO were involved in software and validation and project administration. ESO supervised the study. DZ and ESO did roles/writing—original draft.

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