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Modeling the linkage between climate-tech, energy transition, and CO_2 emissions: Do environmental regulations matter?

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ABSTRACT

The transition from conventional energy to clean energy is the ultimate strategy to reduce global CO_2 emissions. In this regard, climate technologies (climate-tech) can pave the way toward achieving the capabilities required to promote alternative energy and energy saving. In addition, environmental regulations can support technological upgrading, energy transition, and emissions reduction to promote sustainable development. With this in view, this study investigates the impact of climate technologies (climate-tech) and energy transitions on CO_2 emissions in the European Union (EU) member countries. Further, we examine the role of environmental regulation in the relationship between climate-tech, energy transition, and CO_2 emissions. The empirical analysis is conducted based on international panel data for 26 EU countries ranging from 1994 to 2019, and the Common Correlated Effects Mean Group (CCE-MG) method is employed to estimate the coefficients of the variables. The outcomes of the analysis indicate that both climate-tech and energy transitions mitigate environmental degradation by reducing carbon emissions. Additionally, environmental regulations are found to be an effective monitoring and controlling tool that can significantly reduce CO_2 emissions. Moreover, economic growth and urbanization as control variables contribute to increasing CO_2 emissions, thus negatively affecting environmental sustainability. The causal analysis demonstrates that decision-making trends related to climate-tech, energy transition, and environmental regulations influence CO_2 emissions. Conversely, strategies for coping with CO_2 emissions and climate change will affect energy transitions and environmental regulations. In light of these analytical findings, this paper proposes that EU countries should vigorously develop climate-related green technologies and actively promote the energy transition process along with the implementation of environmental regulations for sustainable development.

1. Introduction

Climate change is one of the crucial issues hindering the sustainable development of human society and is being widely discussed by all sectors of society (Akimoto et al., 2021; Khan et al., 2022a). The rapidly expanding economic landscape and increasing industrialization have accelerated the widespread use of fossil fuel energy sources and led to significant emissions of air pollutants (Jiang et al., 2022; Verbič et al., 2022). To combat the phenomena, the Sustainable Development Goals (SDGs) emphasize the need to take action on climate change on an urgent basis.

Many studies indicate that climate and environmental technologies are effective and environmentally friendly means of mitigating climate issues (Ding et al., 2021; Obobisa et al., 2022). Climate technologies (climate-tech), also described as green technologies, refer to technological innovation that improves environmental quality, reduces emissions, enhances energy efficiency, as well as promotes green development (Ahmad and Wu, 2022). Theoretically, effective climate-related technologies can reduce equipment losses, excessive costs, and fuel waste in the production process and improve production efficiency. In addition, it can promote the well-being of humans (or society) (Can et al., 2022, 2021). Climate-tech mitigates atmospheric pollution by decreasing

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emissions generated from production and promotes sustainability of production patterns and consumption (Xin et al., 2021; Xu et al., 2022). However, in practice, climate technology development is a highly costly and complex process that requires substantial human and financial resources. In the short term, inadequate climate technologies may consume more resources and may even require additional funding to reduce the costs and challenges of climate technology development. Therefore, technological innovations measured by patents may be deemed a barrier to dealing with climate problems, thus limiting development (Raiser et al., 2017). However, in the long term, complete and advanced climate technologies will lower the portion of fossil energy and escalate the process of the green energy transition, which in turn can improve environmental quality (Danish and Ulucak, 2021).

The energy transition refers to the process of shifting from the use of non-renewable energy sources, such as fossil fuels, to the use of renewable energy sources, such as wind, solar, and hydropower. This process helps to promote sustainable development and address environmental challenges (Saidi and Omri, 2020). The energy transition is a global energy policy implemented by all countries after realizing the threat of CO_2 emissions (Can and Ahmed, 2023; Khan et al., 2022b). Since 1990, the EU has been cutting the share of coal in the primary energy structure and replacing fossil fuels with the widespread utilization of low-carbon fuels (such as natural gas and atomic) and renewable sources. In July 2021, the EU proposed the "Fit for 55" package ("commitment to reduce greenhouse gas emissions by at least 55 % by the end of 2030 compared to 1990"), of which the bill to add a portion of renewable energy is the crucial component. However, the current global energy prices are volatile, and energy supply problems are plentiful. In order to urgently decrease the dependence on imported energy, the European Commission published the "REPower EU" energy plan on its website in May this year, which intends to broaden portions of renewable energy in energy structure from 40 % to 45 % by 2030 (EU, 2022). There are many challenges in the usage of renewable energy. For instance, renewable energy technologies require large initial investments and have long R&D cycles, which imply very high costs (Marques and Fuinhas, 2012; Ocal and Aslan, 2013). However, expanding the quota of green energy and accelerating the energy transition process are undoubtedly important means to attain environmental sustainability. Many studies have shown that renewable energy plays a crucial part in lowering CO_2 emissions (Balsalobre-Lorente et al., 2018; Dogan and Seker, 2016; Ocal and Aslan, 2013).

In addition, environmental regulations as an essential environmental preservation strategy have been a hot issue for research. The government has strengthened environmental pollution control by imposing environment-related taxes and increasing the cost of pollution emissions. However, overly strict environmental regulations may have different environmental effects, and there are different views of scholars in this context. Some research findings support the "green paradox" that strict environmental regulations are not effective in reducing emissions, but rather energy producers will accelerate energy extraction to avoid more losses, leading to the opposite outcome of environmental policies (Hao et al., 2018; Wang and Zhang, 2022; Can et al., 2021). However, another part of the research argues that energy reserves are finite and cannot be sustained indefinitely and that excessive extraction costs will reduce emissions when environmental regulations intervene (Hashmi and Alam, 2019; Kathuria, 2007; Yirong, 2022). Some academics also suggest regional heterogeneity in the effect of environmental regulations on emissions, which may also vary depending on the strength of environmental regulations (Kathuria, 2007; Wenbo and Yan, 2018).

This study concentrates on the countries within the European Union (EU) due to following reasons. The European Union (EU) recently accounted for 8 % of the total CO_2 emissions in the world. However, the cumulative emissions of the EU since the start of industrialization are among the highest globally. Consequently, the EU makes a substantial contribution to the accumulation of greenhouse gases in the atmosphere (Lau et al., 2012). But in tandem, the EU is also a staunch defender and implementer of the Paris Agreement and is one of the first regions which offers a carbon–neutral plan. According to the EU's climate policy, the EU will cut down its emissions by 55 % by 2030 compared with 1990, and realize carbon neutrality, i.e. net zero emissions, by 2050. Therefore, an in-depth analysis of the factors influencing CO_2 emissions in EU countries is crucial to accelerate the EU's goal of carbon neutrality.

However, available studies lack a joint analysis of the impacts of climate-tech, energy transition, and environmental regulations on CO_2 emissions under the context of the EU. Therefore, the objective of this study is to analyze the effect of climate-tech, energy transformation, and environmental regulations on CO_2 emissions by including economic growth and urbanization in the nexus and propose policy insights that would be useful for the reduction of carbon emissions. This study answers the following questions: (i) Are climate technologies significantly effective in mitigating emissions? (ii) Does accelerating the energy transformation process help mitigate environmental degradation? (iii) What is the impact of environmental regulations on climate change? In light of this, this paper investigates the above issues using annual panel data for 26 EU countries from 1994 to 2019 and contributes to the existing literature in the following ways: (1) In terms of research framework design, this study includes climate technology, energy transition, environmental regulation, and carbon emissions in the same framework for the first time, which helps to study the emission reduction effects of climate technology and energy transition while considering the role of environmental regulation in the emission reduction process. (2) At the level of empirical analysis, this study uses the CCE-MG method to examine the relationship between the variables of interest and the CuP-FM and CuP-BC methods to test the robustness of the results. This helps to address possible endogeneity and cross-sectional dependence in the empirical analysis process. (3) This study enriches the findings in the EU context and confirms that climate technologies play an important role in CO_2 emission reduction in the EU. At the same time, the advancement of energy transition can reduce CO_2 emissions faster. More importantly, in the EU context, environmental regulations do not have a "green paradox" effect but have a crucial deterrent effect on CO_2 emissions. In addition, economic development and urbanization are considered to be important drivers of emissions. (4) Finally, the Dumitrescu and Hurlin causality test considering cross-sectional dependence confirms that climate technology, energy transition, and environmental regulation all help to explain future changes in carbon emissions in 26 EU countries.

The structure of the paper is as follows: In Section 2, a literature review is presented. Section 3 details the research data and methodology used. The empirical results are discussed in Section 4. Finally, in Section 5, the paper concludes with policy recommendations, limitations, and suggestions for future research.

2. Literature review

2.1. Climate-tech and environmental quality

Technology innovation is widely viewed as the most effective way for countries around the world to accomplish Sustainable Development Goals as they face the Fourth Industrial Revolution (Ahmad et al., 2022). In this background, studies have indicated that technological innovation could be an essential instrument for promoting environmental sustainability (Ahmed et al., 2022a; Cheng et al., 2021b,a; Su et al., 2022), whereas few studies have demonstrated that innovation either contributes to environmental deterioration or has no effect (Chen and Lee, 2020; Danish and Ulucak, 2021).

Interestingly, researchers have mostly relied on patent applications as the proxy of technological innovation, while only a small fraction of environmental studies use climate-tech (green, environmental or eco-environmental innovation), which is quantified by patents related to the field of environment. For example, Du et al. (2019) studied the impact of green technologies on environmental pollution from 1996 to 2012 using panel data comprising 71 economies. In addition, they investigated whether income level influences the impact of the green technologies-emission nexus. Interestingly, the results indicated that green technology developments contribute to cutting emissions in the countries in which the income levels are under the threshold; however, the mitigation effect becomes more prominent in the countries above the threshold. However, the shift of regime happens at a level of wealth that is extraordinarily high. According to a study by Ahmad et al. (2022), the impact of technological innovation on CO_2 emissions varies greatly based on the level of development. Ahmad and Satrovic (2023) argue that environmental innovation has the potential to bring about significant improvements in environmental quality, but its effectiveness depends on various factors, such as the availability of resources and support, the level of public awareness and engagement, and the presence of enabling policies and regulations.

Su and Moaniba (2017) used 70 African countries' data to estimate the influence of green technologies on CO_2 emissions. They discovered that green technologies significantly increase emissions from petroleum and natural gas while responding positively to decreasing the level of emissions from coal and other GHGs. For the N-11 economies, Shao et al. (2021) employed advanced methods to gauge the effect of climate-tech on CO_2 over the period 1980–2018. The findings of the tests reveal that climate-tech has a negative and substantial impact on emissions from a long perspective. However, the relationship between climate-tech and CO_2 is insignificant in the short term. Likewise, the recent work by Sharif et al. (2022) examines the nexus between green technologies and environmental pollution in G7 countries. The results indicate that green technologies significantly but positively contribute to mitigating emissions in these countries. However, in the case of China, Lin and Ma (2022) found that green technologies pose a varied effect on emissions in different kinds of cities and periods. They further added that green technologies failed to lower emissions before 2010 but promoted environmental quality after 2010. Moreover, innovation in environmentally friendly technologies may indirectly cut carbon dioxide emissions via improvements to industrial structures.

In conclusion, climate technologies are crucial in mitigating climate change and reducing CO_2 emissions. However, further research is needed to understand the barriers to the widespread implementation of green innovation and to identify the most effective strategies for promoting environmentally friendly solutions. Synthesizing the above evidence, we hypothesize that climate technologies have the potential to cope with climate change and reduce environmental pollution. Hence, we formulate the following hypothesis:

H1: Climate technologies pose a significant and negative impact on CO_2 emissions.

2.2. Energy transition and environmental quality

A plethora of studies suggest that economic growth is intricately linked to energy usage, which is the main driver of environmental degradation (Jena et al., 2022; Khan et al., 2021; Satrovic and Adedoyin, 2022). Although energy benefits economic growth, burning non-renewable fuels is a major factor that unfavorably impacts the environment (Pata, 2018). To reduce environmental pollution, it is necessary to decrease the use of fossil fuels and increase energy efficiency. As a result, many nations are implementing various measures to achieve this goal. These measures have a relatively limited ability to reduce energy use since growth is directly correlated with fossil fuels (Apergis and Payne, 2014; Pata and Kumar, 2021). Thus, expanding the quota of renewable energy(RE) will be a viable strategy that may limit environmental damage (Pata, 2021). In this context, Bilgili et al. (2016) employed DOLS and FMOLS methods to gauge the impact of RE on CO_2 emissions of 17 Organisation for Economic Cooperation and Development (OECD) economies from 1977 to 2010. The findings unveil that RE use can lower pollution in these countries. This paper recommends that OECD countries develop strategies for providing equitable and convenient access to renewable energy sources, along with policies that improve the supply of renewables, such as advanced renewable energy technology. This will enable them to mitigate the effects of global warming while boosting their GDP.

Koengkan and Fuinhas (2020) employed the panel-ardl approach to gauge the impact of RE on emissions in Latin American & Caribbean (LAC) nations from 1990 to 2014. The findings disclosed that energy transition significantly and negatively affects environmental pollution in the short and long term. Thus, the energy transition can potentially alleviate environmental damage in LAC nations. Likewise, in 22 well-developed countries, Rahman et al. (2022) found that RE positively contributes to enhancing environmental quality by lowering emissions. Yu-Ke et al. (2022) investigated the effect of clean energy use on transportation and industry-based air pollution. Interestingly, the results show that although using RE first improves environmental quality related to transportation, it initially degrades environmental quality related to the industry. In a later stage, using clean energy degrades environmental quality related to transportation while enhancing environmental quality related to industries. This leads to the conclusion that in the selected economies, clean energy usage has a U-shaped association with transport-based emissions but an inverted U-shaped with industry-based emissions.

On the flip side, Jebli and Youssef (2017) studied the linkage between CO_2 emissions and RE in North American economies. Their findings conclude that in the long run, RE (containing combustible and waste) escalates environmental pollution in these countries. Likewise, Raihan and Tuspekova (2022) studied the possibility of achieving environmental sustainability in Malaysia using RE sources. The outcomes depict that RE poses a negative but insignificant impact on CO_2, meaning that increasing the proportion of RE in Malaysia's total energy structure may not contribute to CO_2 emissions reduction.

Regarding energy transition, the following hypotheses can be proposed for this study based on the review of the literature:

H2: There is a negative relationship between energy transition and CO_2 emissions.

2.3. Environmental regulations and environmental quality

Academic circles have three primary schools of thought concerning whether environmental legislation can promote environmental sustainability. The first school of thought holds that environmental regulations (ER) can lower environmental pollution. For instance, Danish et al. (2020) used BRICS countries' data as a study sample and found that ER is a key driver in mitigating emissions, and the existing environmental governance measures are effective in attaining pollution reduction objectives in these nations. In addition, ER supports the establishment of an inverted

U-shaped income-emissions nexus. Likewise, Wenbo and Yan (2018) used the Chinese provincial data to assess the linkage between ER and pollution. The results found that the influence of ER on emissions is variant among different regions. The work of Adams and Acheampong (2019) explained that environmental-related rules reduce emissions levels in the OECD. Similarly, Pei et al. (2019) found that ER can reduce emissions directly, and even improve ecological quality through technical efficiency indirectly. Moreover, using the data from Chinese provinces, Zhao et al. (2020) demonstrated that ER mitigates environmental degradation by decreasing coal consumption in China.

The second school of thought holds that ER can add carbon emissions. For instance, Sinn (2008) suggested the notion of the "green paradox" effect and believes that climate change mitigation policies would increase the extraction of fossil fuels and greenhouse gas emissions. Research conducted by Werf and Maria (2012) endorses the findings of Sinn (2008) that flawed climate policies lead to an upsurge in short-run emissions. However, the net present value of the future environment due to climate change will decline over time as a result of environmental regulations. Zhang et al. (2021b) found a reversed U-shaped curve between ER and CO_2. It has been shown that environmental legislation mainly impacts carbon dioxide emissions via changes in industry structure and technological advancements. Wang and Zhang (2022) argue that environmental regulations have the potential to successfully reduce CO_2 emissions by necessitating structural improvements in industry and technological advancement. Nevertheless, within the restrictions of environmental regulations, FDI demonstrates a pollution–haven impact. The third opinion is that the influence of ER on CO_2 emissions is ambiguous. For instance, Zhao et al. (2015) discovered that market-based regulations and government subsidies significantly influence the environmental pollution level, but command and control regulations have no significant effect on CO_2 emissions in China. Wu et al. (2020) found that ER restrained the rise of emissions in the central and eastern regions, while ER failed to limit emissions in the western area of China. These arguments motivated us to develop the following hypothesis:

H3: Environmental regulations impede CO_2 emissions.

2.4. Knowledge gap

Summing up, the above review of the literature uncovered diverse and inconclusive results regarding the impacts of climate-tech and CO_2 emissions. Previous research on climate-tech and CO_2 emissions has overlooked the possibility of slope heterogeneity and cross-sectional dependence within panel data, which could result in biased and misleading estimates. Aside from this, the link between energy transition, environmental regulations, and environmental deterioration is scant. To address this, it is crucial to examine the determinants of CO_2 emissions using appropriate estimation methods for improved policymaking. Thus, this work proposes the idea which integrates climate-tech, energy transition, and environmental regulations into the same environmental policy framework. The research conclusion will help improve the climate-related policies for EU countries and help achieve carbon neutrality. This paper fills the gap in the previous literature as follows:

(1) Methodologically, previous studies on climate technologies and CO_2 emissions have ignored the possibility of slope heterogeneity and cross-sectional dependence in panel data, which may lead to biased and misleading estimates. To address this issue, it is crucial to use appropriate estimation methods to study the determinants of CO_2 emissions to improve decision-making. Therefore, this paper adopts a more novel CCE-MG estimation strategy to address panel data concerns and provide more robust research results.

(2) In terms of research objects, most of the current studies focus on the carbon emission reduction effects of environmental regulations in China, BRICS countries, and OECD, and only a few papers focus on the effects of environmental regulations on carbon emissions in the EU region. Neves et al. (2020) suggest that there is still a lack of research on the carbon reduction effects of environmental regulations in the EU region.

(3) Besides, there is still a research gap regarding the role played by environmental regulations in climate technologies, energy transition, and environmental degradation, especially in the context of EU studies. Therefore, this work presents the idea of integrating climate technologies, energy transition, and environmental regulations into the same environmental policy framework. The findings will contribute to improving climate-related policies in EU countries and help to achieve carbon neutrality.

3. Material and methods

3.1. Theoretical foundation and model construction

The work intends to quantify the effect of climate-tech, energy transition, and environmental regulations in accomplishing carbon neutrality targets in EU countries. To achieve this objective, this paper uses the STIRPAT framework of Dietz and Rosa (1997), which is expressed below:

$$I_{it} = \alpha P_{it}^{\lambda_1} A_{it}^{\lambda_2} T_{it}^{\lambda_3} \mu_{it} \tag{1}$$

where I denote the environmental impact, while P, A, and T indicate the population, affluence, and technology for country i and time t. The symbol λ_1, λ_2, and $, \lambda_3$ represent the elasticates of population, affluence, and technology, while α and μ denote the constant and error term, respectively. The explained variable is per capita CO_2 emissions measured in metric tons of oil equivalent. As a foremost greenhouse gas, CO_2 has been frequently utilized in the literature to gauge the state of the environment (Acheampong et al., 2022; Zafar et al., 2021). Among the explanatory variable, climate-tech entails patents in environment-related technologies, which is the proxy for the technology (T) level in EU economies. "Endogenous growth theory" and "ecological modernization theory" both support the premise that advancement in environmentally friendly technologies may assist nations in achieving sustainable development while safeguarding environmental quality (Ahmad et al., 2020). Since the increase in climate-tech can improve resource usage efficiency and alleviate environmental deterioration, it can be projected to decrease CO_2 emission levels.

The energy transition is another explanatory variable measured by the percentage shares of RE in total primary energy consumption. It is widely believed that different type of energy resource determines the degree of CO_2 emissions (Shahbaz et al., 2013). In this regard, renewable energy use is theorized to curtail environmental pollution in these countries. Besides, countries develop and implement ER to improve energy efficiency, stimulate green production, and reduce the negative effects of development (Ahmed et al., 2022b). ER cannot only reduce emissions directly but also encourage the extensive utilization of RE, which may also boost environmental quality (Wang and Zhang, 2022; Zhang et al., 2021b). Finally, following the previous studies (Ahmad et al., 2021; Balsalobre-Lorente et al., 2021), we employed urbanization to determine the environmental impacts of population (P). Considering that the urban population has a significant effect on the emissions levels and that EU countries have already attained a high degree of urbanization, CO_2 emissions will soar. In line with the study's objective and theoretical underpinning, we expand the basic STIRPAT model by adding a new variable. The modified model can be specified as:

$$LCO2_{it} = \alpha_0 + \lambda_1 LCT_{it} + \lambda_2 LET_{it} + \lambda_3 LER_{it} + \lambda_4 LGDP_{it} + \lambda_5 LURB_{it} + \mu_{it} \tag{2}$$

where in equation (2), CO_2 refers to the carbon dioxide emissions, CT, ET, ER, GDP, and URB denotes the climate-tech, energy transition, environmental regulations, economic growth, and urbanization, respectively. The symbol L means the natural log transformation of underlying variables.

3.2. Data

This study covers the annual data set from 1994 to 2019 for 26 EU nations ("Austria, Belgium, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Luxembourg, Netherlands, Poland, Portugal, Slovak Republic, Spain, Sweden, Bulgaria, Croatia, Cyprus, Estonia, Latvia, Lithuania, Romania, Slovenia"). The duration of the study and the countries considered was solely dependent on the data availability. The starting year of 1994 is based on data from environmental regulations, whereas the data on climate-tech is only available until 2019. The data on CO_2 emissions, energy transition, GDP, and Urbanization is acquired from the WDI (2021). The data on climate-tech and environmental regulations is attained from the (OECD, 2022a, 2022b). Table 1 explains the variables applied in this work.

3.3. Econometric methodology

The empirical estimate technique comprises seven steps explained in subsequent sections and graphically shown in Fig. 1.

3.3.1. CSD and slope homogeneity test

The initial procedure of this empirical analysis is investigating underlying panel data issues such as cross-sectional dependence (CSD) and slope homogeneity. Economies often interact with other countries in this globalized world, which may create a ripple effect that can influence the estimators' consistency. The assessment of these issues in the data is indispensable to prevent the estimate of biased results. Hence, the Pesaran (2004) test will be used to inspect the existence of CSD in EU countries. The CSD can be modeled as:

$$CSD = \sqrt{\frac{2T}{N(N-1)}}\left(\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\rho_{ij}\right) \tag{3}$$

where in equation (3), N and T denote the sample size and duration, while ρ_{ij} is the residual

coefficient. In addition to the Pesaran CD test, this study also utilized the Pesaran scaled LM test and the Breusch-Pagan LM test to ensure the accuracy of the results.

Despite several economic, social, and political factors, countries may differ in the level of innovation, geography, and decision-making. The assessment of whether the slope is homogenous or heterogenous in the data is also imperative to prevent the estimate

Table 1
Variable's description.

Variable	Symbol	Measurement	Source
Environmental quality	CO_2	CO_2 emissions (metric tons per capita)	WDI (2021)
Climate-tech	CT	Patents on environment technologies (% of overall technologies)	OECD (2022a)
Energy transition	ET	Renewable energy consumption (% of total final energy consumption)	WDI (2021)
Environmental regulations	ER	Environmental tax (% of GDP)	OECD (2022b)
Economic Growth	GDP	Per capita (constant 2010$)	WDI (2021)
Urbanization	URB	Urban population (% of total population)	WDI (2021)

Note: WDI - World Development Indicators, OECD - Organisation for Economic Co-operation and Development.

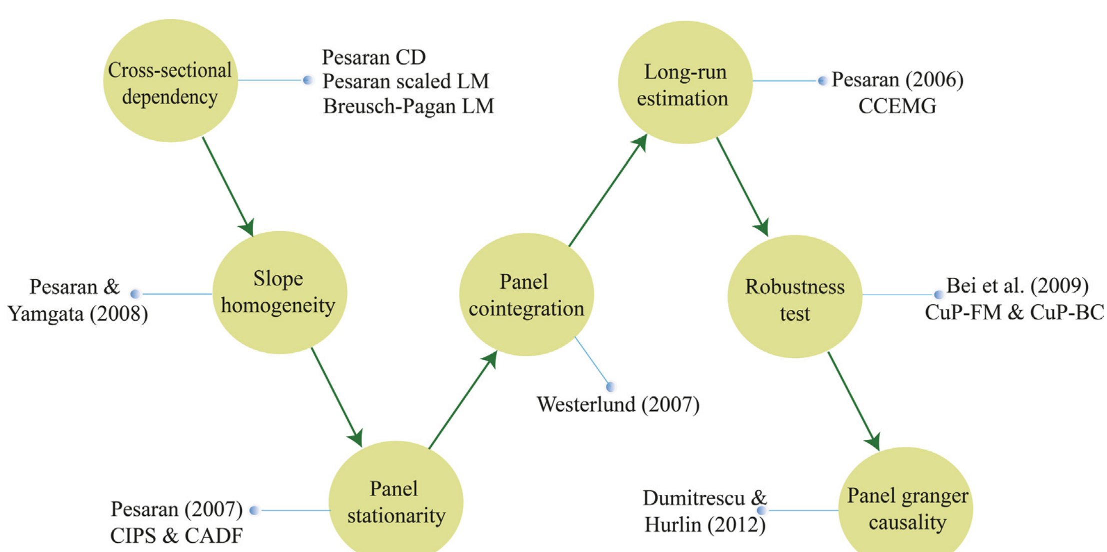

Fig. 1. Estimation method flow diagram.

of biased outcomes. Therefore, Pesaran and Yamagata (2008) test is utilized to ascertain the slope characteristics of the data. The test equation is written as:

$$\widetilde{\Delta}_{SH} = (N)^{\frac{1}{2}}(2K)^{-\frac{1}{2}}\left(\frac{1}{N}\widetilde{S} - k\right) \tag{4}$$

$$\widetilde{\Delta}_{ASH} = (N)^{\frac{1}{2}}\left(2k\left(\frac{T-k-1}{T+1}\right)^{-\frac{1}{2}}\left(\frac{1}{N}\widetilde{S} - k\right)\right) \tag{5}$$

The values of $\widetilde{\Delta}_{SH}$and $\widetilde{\Delta}_{ASH}$give the tilde and adjusted tilde, respectively.

3.3.2. Unit root analysis

The panel stationarity analysis is the next recommend subsequent step after the CSD and slope heterogeneity. If there are CSD issues in the data, the traditional unit root methods may produce inaccurate outcomes (Dogan and Seker, 2016). Therefore, the CADF and CIPS tests are conducted, which are fairly well-known for tackling CSD (Pesaran, 2007). The CADF test can be specified in equation (6) as:

$$\Delta CA_{i,t} = \varphi_i + \varphi_i Z_{i,t-1} + \varphi_i \overline{CA}_{t-1} + \sum_{l=0}^{p} \varphi_{il} \Delta\overline{CA_{t-1}} + \sum_{l=0}^{p} \varphi_{il} \Delta CA_{i,t-1} + \mu_{it} \tag{6}$$

where $\overline{CA}_{t-1}$ and $\Delta\overline{CA_{t-1}}$ are the averages of cross-sections. The CIPS is an average of CDF that is given in equation (7):

$$\widehat{CIPS} = \frac{1}{N}\sum_{i=1}^{n} CDF_i \tag{7}$$

3.3.3. Cointegration test

The panel cointegration test of Westerlund (2007) is taken to ascertain the equilibrium association between studied variables since it is appropriate for panel datasets with CSD. This test is regarded as one of the most reliable panel cointegration methods due to its efficient predictability. This test provides 4 test statistics under the alternative hypothesis of a cointegrating relationship against the null hypothesis of no cointegrating association in the data. The test equation can be written as:

$$\Delta Z_{it} = \delta_i' d_t + \alpha_i\left(Z_{i,t-1} + \lambda_i' X_{i,t-1}\right) + \sum_{j=1}^{p_i} \alpha_{ij}\Delta Z_{i,t-1} + \sum_{j=-q_i}^{p_i} \gamma_{ij}\Delta X_{i,t-1} + \mu_{it} \tag{8}$$

3.3.4. Long-run analysis

For estimating the long-term elasticities, this paper uses the CCE-MG approach by Pesaran (2006). This method is more flexible compared to first-generation estimation methods (such as DOLS, FMOLS, ARDL, etc.) and induces robust results under the situation of CSD and slope heterogeneity. Moreover, this technique is robust to the existence of both weak (e.g. local spillover effects) and strong (e.g. global shocks) undetected factors (Cheng and Yao, 2021; Pesaran and Tosetti, 2011). The test equation for the CCE-MG estimator can be taken as:

$$z_{it} = \beta_i x_{it} + \eta_i \bar{z}_{it} + \theta_i \bar{x}_{it} + \alpha_i + \gamma_i f_t + u_{it} \tag{9}$$

where in equation (9), $\bar{z}_{it}$, and $\bar{x}_{it}$ signifies the cross-sectional averages of explained and explanatory variables. β_i denotes the unit slope, while f_t, and u_{it} indicates the unobservable common factors and the random error term. Similar to the MG technique, each panel regression is assessed using OLS, and the MG estimators are derived by averaging each panel unit:

$$CCEMG = \frac{1}{N}\sum_{i=1}^{N}\hat{\beta}_i \tag{10}$$

3.3.5. Robustness test

To verify the findings of CCEMG results, this paper uses the CuP-BC and CuP-FM methods by Bai et al. (2009). These methods also provide tempting benefits, such as addressing endogeneity, CSD, serial correlation, and heteroscedasticity. The test equation can be modeled as:

$$\widehat{\beta}cup, \widehat{F}cup = \text{armin}\frac{1}{nT^2}\sum_{i=1}^{n}(y_i - x_i\beta)' M_F(y_i - x_i\beta) \tag{11}$$

3.3.6. Causality test

Finally, the Granger causality test developed by Dumitrescu and Hurlin (2012) is employed for examining the directional flow and causal associations between the variables. To conclude a casualty, the alternative hypothesis, that there is a causal link between variables, is assumed to be true, contrary to the null hypothesis of the absence of causal links between variables. The test equation can be written as:

$$y_{i,t} = \beta_i + \sum_{k=1}^{N}\lambda_i^{(k)} y_{i,t-k} + \sum_{k=1}^{N}\alpha_i^{(j)} x_{i,t-k} + e_{i,t} \tag{12}$$

Where $\beta_i$is the intercept term and k is the lag order $(1 \sim K)$. λ_i and x_i are the autoregressive coefficients.

4. Results and discussion

Table 2 outlines the descriptive statistics of underlying variables in EU countries which are also visually shown in Fig. 2. The mean value of CO_2 emission in EU countries is 7.841, which is quite high compared to the world average (4.197 metric tons per capita) from 1994 to 2019. In some years, the emissions reached up to 26.829 (metric tons per capita), indicating that the EU member country (Luxembourg) badly deteriorated the environmental quality. The spatial distribution of emissions for individual countries can be seen in Fig. 3. The climate-tech values range between 0.840 and 26.829, with an average of 10.980. The climate-tech for individual countries can be seen in Fig. 4, indicating that 13 EU member countries have lower patents on environmental innovation than the world average in 2019, while Denmark is leading in innovation among these countries. The mean value of energy transition is 16.008, and Fig. 5 illustrates the trend in these countries over 1994–2019. It is evident that these nations have made high progress in the energy transition. Fig. 6 represents the trends in environmental taxes in EU countries from 1994 to 2019. Environmental taxes range between 0.015 and 5.360 with an average value of 2.693.

To trace the multicollinearity in the dataset, this study employed VIF. The results given in Table 3 depict that the VIF values of the regressors are under 5, and we can continue with further analysis.

In the next step, it is important to ascertain whether the EU countries' data is cross-sectionally dependent or independent. For this, we utilized three different CSD tests, including the Pesaran CD test, Pesaran scaled LM test, and the Breusch-Pagan LM test to guarantee reliable results. The findings demonstrated in Table 4 depict that the variables are strongly interdependent in these countries. Thus, owing to the convergence and regional agreements, environmental and economic changes in one country may quickly propagate to others.

Table 2
Descriptive statistics.

	CO_2	CT	ET	ER	GDP	URB
Mean	7.841	10.980	16.008	2.693	30486.990	70.605
Median	7.341	10.525	12.755	2.577	25891.740	68.760
Minimum	2.927	0.840	0.723	0.015	3784.078	50.449
Maximum	26.829	31.580	52.880	5.360	111968.400	98.041
Std. Dev.	3.611	4.933	11.496	0.715	21058.870	11.901
Skewness	1.869	0.916	0.850	0.752	1.350	0.278
Kurtosis	8.498	4.414	2.962	4.530	5.527	2.358
Jarque-Bera	1245.071	150.874	81.420	129.640	385.305	20.314
Probability	0.000	0.000	0.000	0.000	0.000	0.000
Observations	676	676	676	676	676	676

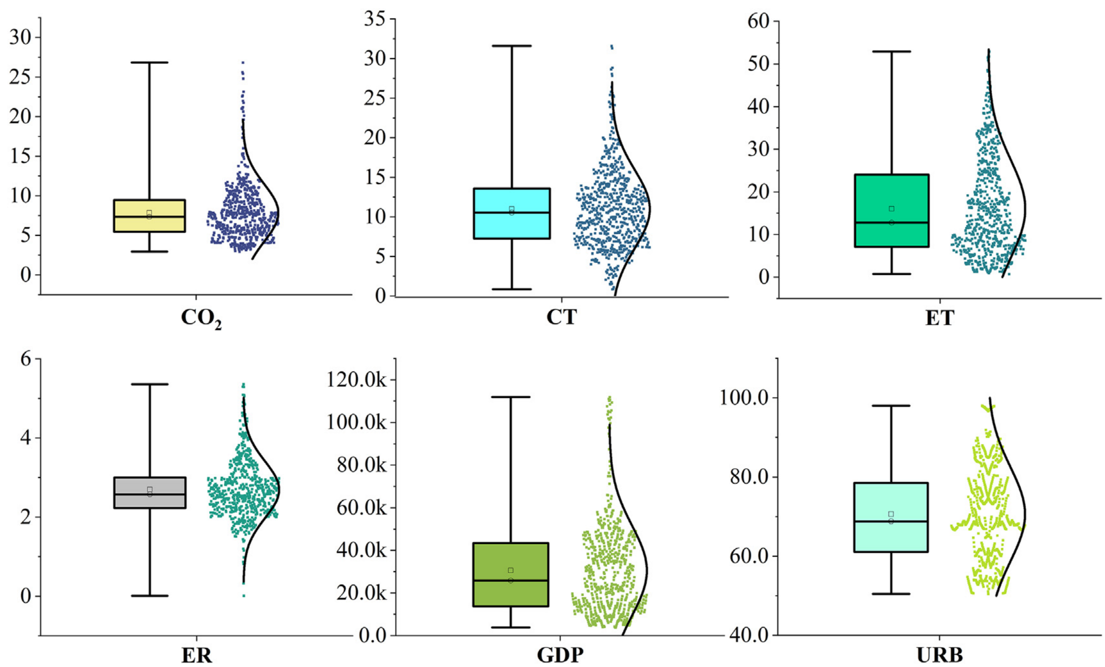

Fig. 2. Box chart of study variables with scatterplot and distribution.

Table 5 presents the slope homogeneity test results, indicating the heterogenous slope parameters in EU countries. The findings demonstrate that despite several regional agreements and cooperation, the EU countries have diverse innovation rates, energy transitions, and environmental regulations. These initial investigation results necessitate selecting appropriate methods for further evaluation that counteract the CSD and slope heterogeneity.

The findings from the stationarity test are provided in Table 6. The CADF test results show that CO_2, ER, GDP, and URB have unit root problems. On the other hand, at the level, CT, and ET do not possess unit root problems. The findings from the CIPS test suggest that CT, ET, and GDP have unit roots at I(0). Therefore, after considering the first difference, the underlying variables reach a stationary state.

The subsequent proposed step is to ascertain the long run cointegrating relationship between variables. And the results of the Westerlund (2007) test are displayed in Table 7. The outcomes from the group test statistics (G_t *and* G_a), and panel statistics (P_t, *and* P_a) indicate that the regressors and explained variables are cointegrated with a 5 % significance level.

The long-term estimation results from the CCEMG method are displayed in Table 8, indicating that the coefficient of climate-tech (CT) is negatively related to CO_2 emissions. Statistically, a 0.064 % decrease in CO_2 emissions can be obtained by increasing the climate-tech by 1 %. Hence, these outcomes indicate that decarbonization in EU countries can be attained by fostering innovation in technologies that are explicitly focused on reducing GHG emissions. The negative emissions effect of CT is consistent with our theoretical expectation (Hypothesis H1) as the progress in CT can lead to reduced resource consumption in the production process and curtail the emissions. This outcome complies with Sharif et al. (2022) and Ahmed et al. (2022) for G-7 countries, Chen et al. (2022) for China, and Ahmad et al. (2020) for 22 emerging economies. This finding is important because climate-tech advancements are essential for developing energy and pollution mitigation targets (Hasanov et al., 2021). The EU is more determined than other regions to lower its emission by 2030, but it is losing momentum in the next wave of climate-tech. EU businesses possess more than 38 % of climate-tech patents than the corporation in the US and more than twice the number of Chinese enterprises and more mature technology deployed per person. However, overall, the EU's chances of being the world leader in climate-tech are diminishing. The US is in the lead for the majority of ground-breaking inventions, while China is in the lead for clean technology production in all fields, with more than 50 percent market shares (McKinsey & Company, 2022). Thus, EU countries need to increase and pool their resources to increase as well as support to increase in the share of climate mitigation technologies.

Furthermore, the energy transition (ET) effect on CO_2 emissions is negative as ET positively contributes to curtailing emissions in

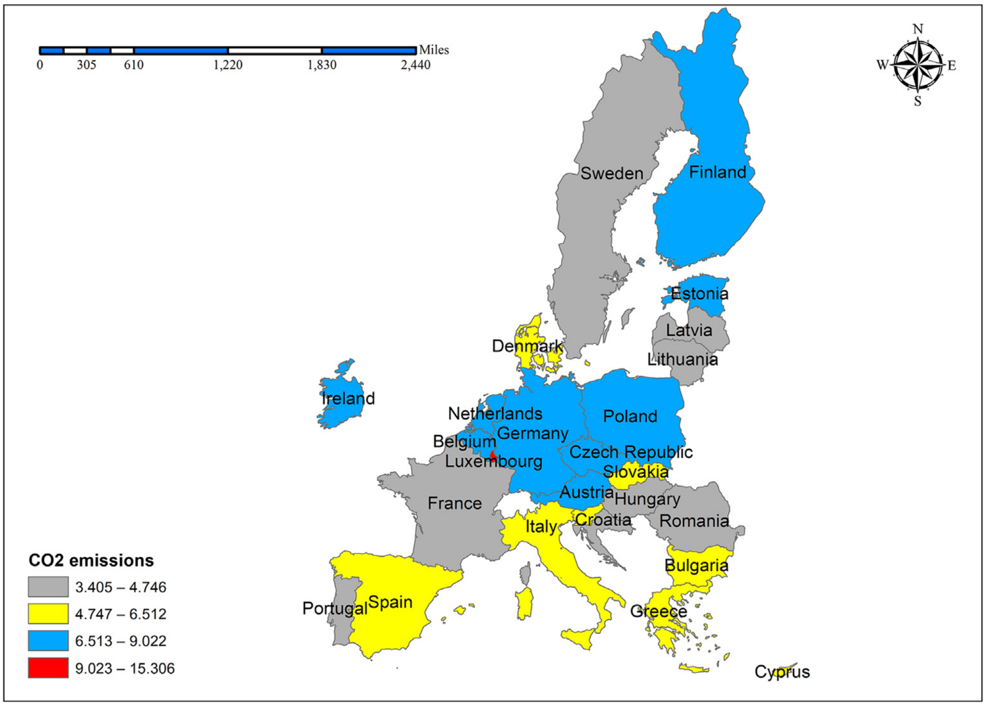

Fig. 3. Spatial distribution of CO_2 emissions in EU countries for the year 2019.Data Source: WDI (2021).

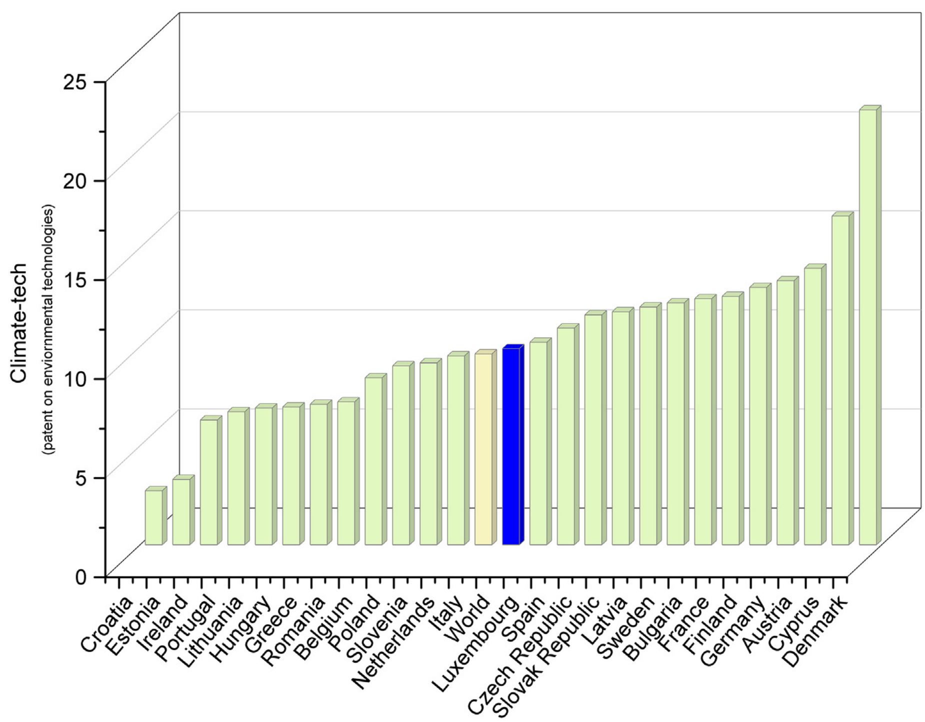

Fig. 4. Climate-tech trend in EU member countries compared to the world average in 2019. Data source: OECD (2021a).

EU countries. Numerically, a 1 % increase in RE can reduce CO_2 emissions by −0.276 %. Our findings are consistent with the anecdotal evidence and also support hypothesis 2 (H2). The EU countries successfully reached their objective for 2020, with RE share in the total energy mix growing from 9.6 % in 2004 to 22.1 % in 2020. Also, in 2020, both petroleum and natural gas consumption declined by 12.6 % and 2.4 %, respectively, in the EU (Eurostat, 2022). The percentage of energy from renewable sources continues to increase in the EU. Renewable energy sources have already overtaken solid fossil fuels in 2018 and 2019, and this trend continued in 2020. The value of solid fossil fuels dropped by 18.4 % in 2020, attaining its lowest point since 1990. These statistics indicate that EU countries are putting great effort into the energy transition to achieve the goal of the European Green Deal of becoming the first climate-neutral continent worldwide by 2050. In summary, increased renewable energy usage provides several societal

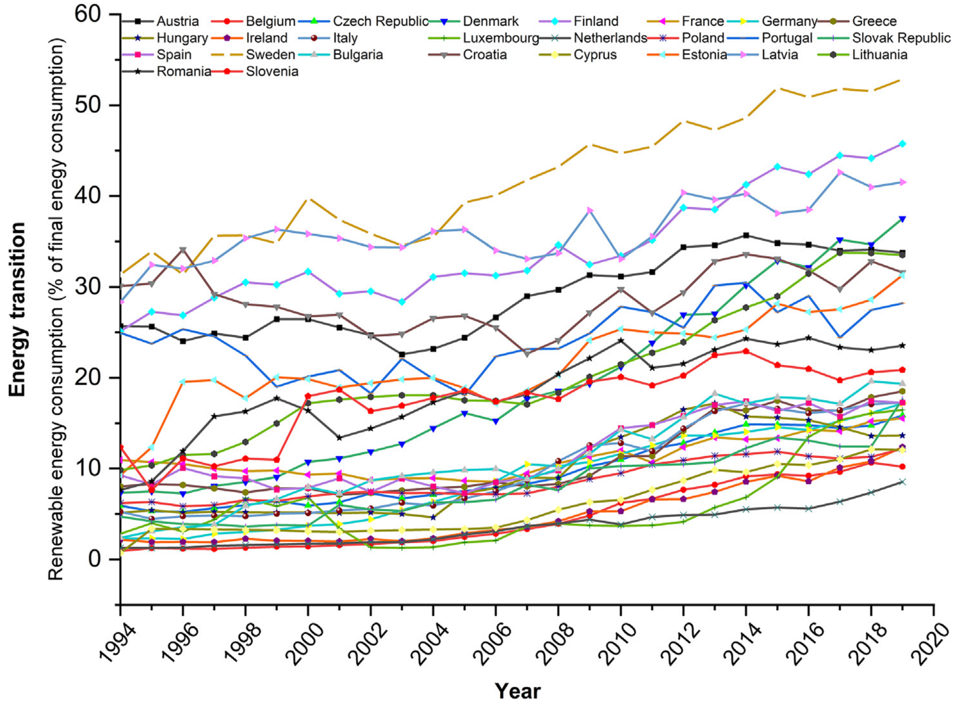

Fig. 5. Trends of energy transition in EU member countries during 1994–2019. Data Source: WDI (2021).

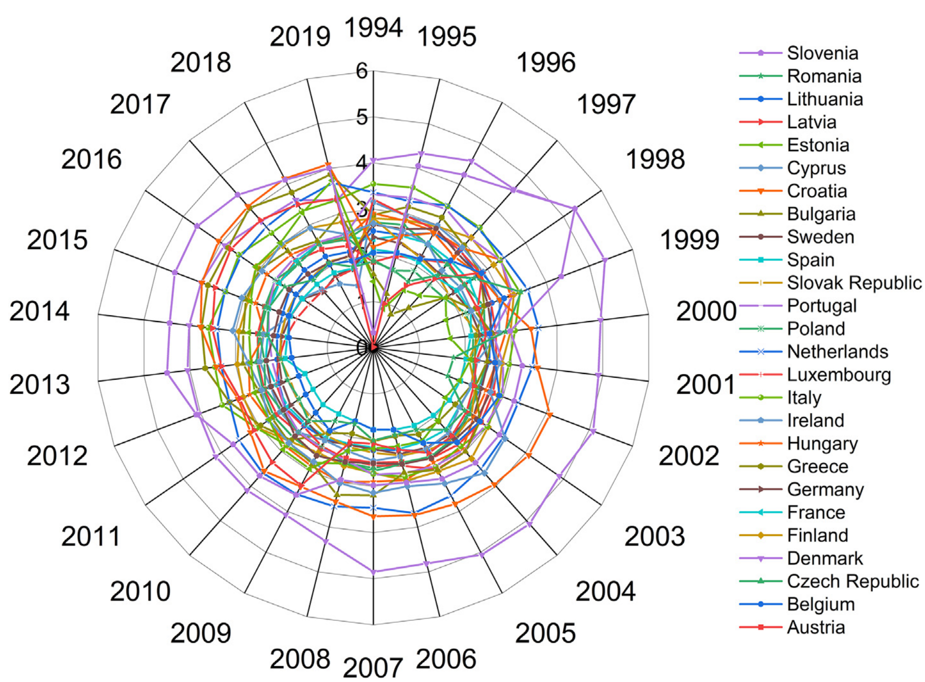

Fig. 6. Trends in environmental taxes (% of GDP). Data source. OECD (2021b).

Table 3
Variance inflation factor.

	VIF	1/VIF
LGDP	1.524	0.656
LURB	1.517	0.659
LET	1.094	0.914
LET	1.084	0.922
LER	1.072	0.933
Mean VIF	1.258	–

advantages, including climate change mitigation, reduced air pollution emissions, improved energy security, and lessened reliance on fossil fuel markets. This outcome corroborates with Bilgili et al. (2016) for 17 OECD countries, Koengkan and Fuinhas (2020) for LAC nations, and Rahman et al. (2022) for 22 developed nations. Overall, our result supports Hypothesis 3 (H3) and underpins that energy transition mitigates environmental degradation.

In terms of control variables, the coefficient of economic growth (GDP) carries a positive value, indicating that economic growth is environmentally unsustainable in EU countries. The expansion of

Table 4
CD test results.

Variable	Peasran CD	Pesaran scaled LM	Breusch-Pagan LM
LCO_2	42.934*	123.302*	3468.601*
	[0.000]	[0.000]	[0.000]
LCT	24.613*	50.245*	1606.000*
	[0.000]	[0.000]	[0.000]
LET	72.654*	204.404*	5536.287*
	[0.000]	[0.000]	[0.000]
LER	3.504*	49.809*	1594.874*
	[0.000]	[0.000]	[0.000]
LGDP	79.551*	246.908*	6619.939*
	[0.000]	[0.000]	[0.000]
LURB	18.358*	223.470*	6022.399*
	[0.000]	[0.000]	[0.000]

Note. Asterisks * show 1 % level of significance.

Table 5
Slope heterogeneity.

Test	Value	P-value
$\widetilde{\Delta}$	23.590*	0.000
$\widetilde{\Delta}_{adjusted}$	27.596*	0.000

Note. Asterisks * show 1 % level of significance.

Table 6
Unit root test results.

	CADF		CIPS	
	Level	First-difference	Level	First-difference
LCO_2	−1.866	−4.596*	−1.566	−3.437*
LCT	−3.452*	−5.799*	−2.673*	−4.534*
LET	−2.651*	−4.950*	−2.356*	−3.473*
LER	−2.101	−4.655*	−1.732	−3.282*
LGDP	−1.601	−3.020*	−2.293*	−2.963*
LURB	−1.505	−4.085*	−1.446	−3.610*

Note: Asterisks * show 1% level of significance.

Table 7
Panel Cointegration results.

Statistic	Value	Z-statistic	P-value	Robust P-value
G_t	−2.770*	−2.866	0.002	0.000
G_a	−8.515**	2.131	0.983	0.025
P_t	−13.031**	−2.812	0.003	0.015
P_a	−8.102**	−0.045	0.482	0.025

Note: Asterisk *, and ** show 1% and 5% level of significance, respectively. Bootstrap replications at 300 for robust P-values.

the economy is inextricably tied to increases in production, consumption, and the use of resources, all of which have negative impacts on the natural environment. Thus, increasing economic activities leads to increased energy use that deteriorates the environment. The improvement of the environment mainly relies on the adjustment of economic structure, the improvement of resource efficiency, the change of input composition, and the progress of production technology (Zhang et al., 2021a). Many studies have found a positive connection between GDP and emissions (Charfeddine, 2017; Zaman and el Moemen, 2017).

The findings further unfold the escalating effect of urbanization on CO_2 emissions in EU nations. The average urbanization in EU countries is more than 72 %; therefore, the positive correlation between urbanization and emissions is reasonable. Higher energy consumption-related environmental challenges in EU nations can be correlated with urban population density (Amin et al., 2020). Urbanization can increase CO_2 emissions in European countries due to several factors including transportation, energy use, land use, and waste management. As cities grow, the number of vehicles on the road increases leading to higher emissions from gasoline and diesel fuel, while the demand for energy to power homes, businesses, and infrastructure also rise resulting in increased emissions from the burning of fossil fuels. Urbanization often involves paving over green spaces, reducing their ability to absorb carbon dioxide, and requires large amounts of concrete and steel which are energy-intensive materials to produce. The increase in waste generation in urban areas also requires more energy to transport and process, leading to higher emissions. To mitigate these impacts, cities can implement policies to promote sustainable transportation, energy-efficient building practices, and adopt renewable energy sources along with more sustainable waste management practices. Cities are responsible for seventy-five percent of the world's carbon dioxide emissions, with transportation and buildings being two of the major sources (Wang et al., 2022). Our results corroborate with the Chinese case of Liu and Bae (2018) and Sadorsky (2014) for emerging countries.

Table 8
Long-run Results (CCEMG).

Variable	Coefficient	Std. Error	Z.value	P.value
LCT	−0.064**	0.032	−2.000	0.045
LET	−0.276*	0.088	−3.15	0.002
LER	−0.152**	0.071	−2.15	0.031
LGDP	0.575*	0.119	4.83	0.000
LURB	1.843***	1.006	1.83	0.067
Constant	−7.618***	4.320	−1.76	0.078

Note. Asterisks show 1% (*), 5% (**) and 10% (***) level of significance.

To validate the results obtained through the CCEMG method, we employed the CuP-FM and CuP-BC methods. The outcomes in Table 9 depict that an increase in climate technologies and renewable energy transition alleviate CO_2 emissions, while economic growth and urbanization escalate emissions in EU nations. Thus, our findings are robust regardless of the methods used.

The causality outcomes of this panel data are presented in Table 10, indicating that one-way causality runs from CT to CO_2. In this context, one-way panel Granger causality from CT to CO_2 emissions means that the adoption and use of climate technologies reduce CO_2 emissions over time. Moreover, the results of bidirectional causality between energy transition and CO_2 emissions show that the adoption of new energy technologies and policies, leading to an energy transition towards low-carbon energy sources, has an effect on CO_2 emissions, and conversely, changes in CO_2 emissions can also influence the pace and direction of the energy transition. For instance, increased CO_2 emissions may drive governments and consumers to adopt more aggressive energy transition policies and technologies, which would in turn result in lower CO_2 emissions. Conversely, the implementation of energy transition policies

Table 9
Robustness check.

	CuP-FM		CuP-BC	
Variable	Coefficient	*T*-stat.	Coefficient	*T*-stat.
LCT	−0.015*	−3.396	−0.019*	−6.522
LET	−0.061*	−11.158	−0.004*	−3.951
LER	−0.023*	−10.553	−0.043*	−7.531
LGDP	0.039*	4.301	0.047*	3.046
LURB	0.094*	5.678	0.101*	7.233

Note. Asterisk * show 1% level of significance.

Table 10
Dumitrescu-Hurlin causality tests.

Null hypothesis	W-statistics	$\bar{Z}$-statistics	P-value	Causality direction
LCT $\nleftrightarrow$ LCO_2	3.175*	6.298	0.000	LCT → LCO_2
LCO_2 $\nleftrightarrow$ LCT	2.783	1.112	0.266	
LET $\nleftrightarrow$ LCO_2	6.708	9.066	0.000	LET ↔ LCO_2
LCO_2 $\nleftrightarrow$ LET	3.431*	7.074	0.000	
LER $\nleftrightarrow$ LCO_2	2.417*	3.997	0.000	LER ↔ LCO_2
LCO_2 $\nleftrightarrow$ LER	2.670*	4.766	0.000	
LGDP $\nleftrightarrow$ LCO_2	4.139*	p.224	0.000	LGDP → LCO_2
LCO_2 $\nleftrightarrow$ LGDP	2.841	1.228	0.219	
LURB $\nleftrightarrow$ LCO_2	6.816*	9.285	0.000	LURB → LCO_2
LCO_2 $\nleftrightarrow$ LURB	2.855	1.257	0.208	

Note. Asterisks show 1% (*), 5% (**) and 10% (***) level of significance.

and technologies may lead to lower CO_2 emissions, which could further incentivize further progress towards a low-carbon energy system. In the context of environmental regulations and CO_2 emissions, bidirectional causality would mean that both environmental regulations and CO_2 emissions have a mutual effect on each other. Furthermore, the findings unfold that unidirectional causality runs from GDP and URB to emissions. Thus, policies related to GDP and URB can Granger cause CO_2 but not the other way around.

5. Conclusion and policy implications

This paper investigates the effect of a set of determinants on CO_2 emissions against the context of EU members, including climate technology (CT), energy transition (ET), environmental regulations (ER), economic growth (GDP), and urbanization (URB). Overall, these factors are all crucial for EU countries to influence the climate change process and achieve environmental sustainability. The study is based on panel data for 26-EU nations from 1994 to 2019 and the procedures of the empirical analysis are carried out through the CCE-MG estimation strategy that takes into account cross-sectional correlation.

Prior to the analysis, we identified possible problems with the panel data, such as cross-sectional dependence, slope heterogeneity, and unit roots, and applied relevant tests. The final empirical results demonstrate that climate technologies and energy transition are effective in mitigating climate change in EU countries. Meanwhile, environmental regulations defined by environmental taxes are effective in curbing CO_2 emissions in EU countries. In contrast, rising economic growth levels and growing urbanization are revealed to be major factors that increase CO_2 emissions in EU countries. To verify the stability of the results, this paper conducted a robustness review of the empirical results using CuP-FM and CuP-BC. Finally, the causality tests confirm a unidirectional causal association from CT, GDP, and URB to CO_2 emissions, and a two-way causal link between ET and ER and CO_2 emissions. Hence, policymakers should be aware that the policies related to CT, ET, ER, GDP, and URB will cause changes in CO_2 emissions. Conversely, any policy fluctuation related to CO_2 emissions will cause changes in ET and ER.

In light of the above results, the following policy implications have been drawn. The results highlight that climate technologies significantly mitigate environmental degradation. The study suggests encouraging the use of climate technologies for environmental sustainability. In this context, governments can implement various policies such as financial incentives for companies that invest in and implement these technologies and tax credits for companies that use or develop them. In addition, governments should increase funding for research and development for innovations and awareness campaigns to educate people. These policies will encourage the adoption of climate technologies and help reduce dependence on fossil fuels, thereby promoting environmental sustainability. Renewable energy consumption significantly and positively impacts environmental quality. The European Union (EU) countries can increase their transition to renewable energy through a combination of policies and measures. Despite various commitments to reduce greenhouse gas emissions and move towards a more sustainable energy mix, many EU countries continue to invest in fossil fuels, particularly in the extraction and production of oil and gas. To address this, stronger and more comprehensive environmental regulations may be necessary to discourage investment in fossil fuels and promote investment in renewable energy sources instead. This could help to reduce the negative impacts of fossil fuels on the environment and support the transition towards a low-carbon, sustainable energy future.

In addition, In order to meet the "REPower EU" target for renewable energy consumption, policymakers in the EU economies may develop a series of incentives to encourage plants and businesses to expand the market for clean, sustainable energy use. Small and medium-sized enterprises (SMEs) face more barriers to renewable energy utilization, so governments could introduce "energy subsidies" for SMEs to prevent them from incurring additional financial liabilities for research and development of clean technologies, which could affect production. The findings indicate that environmental regulation poses a mitigating effect on environmental degradation. Thus, comprehensive and effective policy regulations that reach every corner of the industry are crucial in ensuring the success of the EU's transition towards a low-carbon, sustainable energy mix. This includes measures to enforce environmental taxes and prevent emissions evasion, as well as measures to promote investment in renewable energy and clean technology. By aligning and integrating climate technology, energy transformation, and environmental regulations, the EU can increase the pace and effectiveness of its efforts to achieve its goal of carbon neutrality.

Although several determinants of CO_2 emissions are examined, this study still has some limitations. For example, the theoretical model of the paper is linear and lacks the non-linear impacts of climate technology, energy transition, and environmental regulations on CO_2 emissions. Also, some other factors may influence the impacts of climate technology, energy transition, and environmental regulations on CO_2 emissions. Therefore, in the subsequent studies, the mechanisms and pathways of impacting CO_2 emissions in the EU can be studied from multiple perspectives. Other than this, future studies can add the interaction terms of climate technologies and urbanization to the models for exploring the possible moderating effects.

CRediT authorship contribution statement

Mahmood Ahmad: Conceptualization, Methodology, Software, Data curation, Formal analysis, Funding acquisition, Visualization, Writing - original draft. **Zahoor Ahmed:** Writing – review & editing, Supervision. **Muhammad Riaz:** Writing – original draft, Formal analysis. **Xiyue Yang:** Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

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

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