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Climate change mitigation dynamics in EU countries: An empirical analysis of environmental and macroeconomic factors

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ABSTRACT

Effective environmental policies and an understanding of macroeconomic impacts on climate change mitigation are vital for achieving the sustainable development goals of the European Union countries. This paper aims to investigate the role of Environmental Policy Stringency (EPS) in climate change mitigation in EU countries from 2000 to 2021. This study employs the panel quantile regression model to investigate the potential role of environmental policy, economic growth, trade openness, foreign direct investments, and CO_2 emissions on climate change mitigation at the 10^{th}, 25^{th}, 50^{th}, and 75^{th}, 90^{th} percentiles. The findings indicate that environmental policy stringency, GDP per capita, and CO_2 emissions have a positive effect on climate change mitigation at higher quantiles, while trade openness has a negative impact at all quantiles. Furthermore, the results provide a bidirectional causality between climate change mitigation and EPS. These findings emphasize the need for policymakers to carefully evaluate and integrate environmental policy stringency with economic, trade, and investment strategies to develop a comprehensive and effective approach to climate change mitigation.

AB ülkelerinde iklim değişikliği azaltım dinamikleri: Çevresel ve makroekonomik faktörlerin ampirik bir analizi

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ÖZ

Etkili çevre politikaları ve iklim değişikliğinin azaltılmasına yönelik makroekonomik etkilerin anlaşılması, Avrupa ülkelerinin sürdürülebilir kalkınma hedeflerine ulaşması için hayati öneme sahiptir. Bu makale, Çevre Politikası Sıkılığının (EPS) 2000-2021 yılları arasında AB ülkelerinde iklim değişikliğinin azaltılmasındaki rolünü araştırmayı amaçlamaktadır. Bu çalışma, çevre politikasının, ekonomik büyümenin, ticaret açıklığının, doğrudan yabancı yatırımların ve karbon emisyonlarının iklim değişikliğinin azaltılması üzerindeki potansiyel rolünü 10., 25., 50. ve 75., 90. kantillerde araştırmak için panel kantil regresyon modelini kullanmaktadır. Bulgular, çevre politikası sıkılığının, kişi başına düşen GSYİH'nın ve karbon emisyonlarının daha yüksek kantillerde iklim değişikliğinin azaltılması üzerinde olumlu bir etkiye sahip olduğunu, ticaret açıklığının ise tüm kantillerde olumsuz bir

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etkiye sahip olduğunu göstermektedir. Dahası, sonuçlar iklim değişikliğinin azaltılması ile EPS arasında çift yönlü bir nedensellik sağlamaktadır. Bu bulgular, iklim değişikliğinin azaltılmasına yönelik kapsamlı ve etkili bir yaklaşım geliştirmek için politika yapıcıların çevre politikasının titizliğini ekonomik, ticari ve yatırım stratejileriyle dikkatle değerlendirmeleri ve bütünleştirmeleri gerektiğini vurgulamaktadır.

1. Introduction

Given their interrelated and detrimental effects on the environment, ecosystems, human health, and socio-economic stability; climate change and dependence on nonrenewable energy resources represent grave and widespread threats to the future of our planet. The burning of nonrenewable energy sources releases large quantities of carbon emissions into the environment, contributing significantly to global warming and climate change, and setting off a chain of repercussions. In recent years, as reported by the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2022), the global average temperature has increased by approximately 1.5 degrees Celsius above pre-industrial levels. In the global effort to combat climate change and transition towards sustainable economies, the European Union (EU) has emerged as a pioneer in implementing rigorous environmental policies. Central to this endeavor is the assessment of policy stringency concerning climate change mitigation within the broader context of fostering a green economy. This article delves into the critical examination of environmental policy stringency and its implications for advancing climate action and green economic growth, drawing upon evidence from EU countries.

The Porter Hypothesis (Porter, 1991, pp. 1-37) has significant implications for addressing climate change by suggesting that stringent environmental regulations can drive innovation in technologies and practices that reduce greenhouse gas emissions. By encouraging firms to develop cleaner, more efficient processes in response to regulatory pressures, the hypothesis implies that well-designed climate policies can stimulate the creation of new, low-carbon technologies. This not only helps firms comply with environmental standards but also positions them as leaders in the emerging green economy. As such, the Porter Hypothesis supports the idea that ambitious climate policies, rather than being a drag on economic growth, can be a catalyst for innovation, leading to more sustainable industrial practices and contributing to global efforts to mitigate climate change. However, the success of this approach hinges on the ability of policies to balance stringency with flexibility, ensuring that firms have the incentives and support needed to innovate effectively.

Against a backdrop of escalating environmental challenges and growing recognition of the imperative for sustainable development, understanding the effectiveness of environmental policies becomes paramount. The aim of this study is to investigate the role of the Environmental Policy Stringency Index (EPSI) on climate change mitigation technologies. This study aims to investigate the role of the EPSI in promoting climate change mitigation technologies. The EPSI is crucial in shaping the development and adoption of these technologies, as it measures the rigor and comprehensiveness of a country's environmental regulations and reflects the level of pressure placed on industries to reduce their environmental impact. A higher EPSI indicates more stringent policies, which can incentivize firms to innovate and invest in cleaner technologies to comply with stricter standards (Tiwari, Mohammed, Mentel, Majewski, and Shahzadi, 2023, p. 23; Wang Yen-Ku, Li, An, Abdul-Samad , 2022, p. 3). This pressure accelerate the development of climate change mitigation technologies, such as renewable energy systems, energy-efficient processes, and carbon capture and storage solutions. By driving technological advancements and promoting the adoption of sustainable practices, a stringent EPSI can significantly contribute to global efforts to reduce greenhouse gas emissions (CO_2) and combat climate change. However, the effectiveness of EPSI in fostering these technologies depends on the balance between regulatory stringency and the provision of supportive mechanisms, such as research funding, subsidies, and clear policy signals that encourage long-term investment in green innovation. The significance of adaptation and mitigation policies related to climate change is underscored by their potential to profoundly affect various dimensions of human well-being, including economic, environmental, technological, and socio-political realms.

Following this, the main goal of this study is to examine the influence of Environmental Policy Stringency (EPS) and its key determinants on climate change mitigation efforts across 27 EU member states and 3 EU candidate countries during the period from 2000 to 2021. To achieve this, panel quantile regression is utilized due to its capacity to capture varying effects across different levels of climate change mitigation. Furthermore, this study makes a fourfold contribution to the literature. First, unlike prior studies, this study pays attention to the role of Environmental Policy Stringency. Secondly, this study goes beyond prior research by incorporating an extensive array of environmental and macroeconomic factors. The contribution of this study to the literature, from a methodological perspective, lies in its use of panel quantile regression to analyze the impact of EPS and macroeconomic factors on climate change mitigation. Unlike traditional methods that often focus solely on average effects, panel quantile regression allows for a more nuanced examination by capturing the heterogeneous impacts across different quantiles of the mitigation distribution. The results of the panel quantile regression reveal that the influence of each variable on climate change mitigation technologies differs across varying levels of mitigation efforts among the analyzed countries. The results of the panel quantile regression reveal that the influence of each variable on climate change mitigation technologies differs across varying levels of mitigation efforts among the analyzed countries. The findings suggest that environmental policy stringency, GDP per capita, and CO_2 emissions exert a more significant positive impact on climate change mitigation at higher quantiles. Therefore, policymakers should prioritize strengthening environmental policies and promoting economic growth while managing CO_2 emissions, as their positive impacts on climate change mitigation are more substantial at higher levels of mitigation efforts. This study continues with a literature review in section 2. Section 3 presents the data description and empirical findings. Finally, Section 4 summarizes the conclusions and policy implications.

2. Literature review

The concept of a green economy, which emphasizes sustainable development and the efficient use of resources, has been increasingly integrated into environmental policy frameworks. Several studies have examined the effectiveness of environmental policies in promoting a green economy. For example, Fischer and Newell (2008)evaluate the optimal portfolio of environmental policies for decreasing CO_2 emissions and climate change and improving green innovation. Similarly, Jacob, Graichen, Repenning and Grunberg (2014, p. 5) analyze the impact of green fiscal policies in the EU and find that they can significantly reduce greenhouse gas emissions and stimulate green investments.

The relationship between environmental policy stringency and economic outcomes has been extensively studied. Porter and van der Linde (1995) proposed the Porter Hypothesis, which posits that stringent environmental regulations can stimulate innovation and improve competitiveness, leading to positive economic outcomes. Albrizio, Kozluk, and Zipperer (2017, p. 21) found that while stringent environmental policies can initially increase costs for firms, they also promote productivity gains in the long term by encouraging technological innovation and efficiency improvements. Other studies have focused on the impact of environmental policies on specific sectors. For example, Ambec, Cohen, Elgie, and Lanoie (2013, p. 23) reviewed the literature on the Porter Hypothesis and found evidence that stringent environmental regulations can lead to improved environmental performance and, in some cases, economic benefits in sectors such as manufacturing and energy. Similarly, Dechezleprêtre and Sato (2017, p. 1) examined the impact of environmental regulations on international trade and found that stringent policies can lead to a comparative advantage in clean technologies.

In the previous literature, a plethora of studies investigated the role of economic, political, and environmental variables on climate change mitigation policies (Abid, Ahmad, Aftab, and Razzaq, 2023, p. 2; Ferreira, Fernandes, and Ferreira, 2020, p. 5; Ganji, Liu, and Fellows, 2024, p. 1). Numerous theoretical and empirical investigations have been conducted to tackle environmental challenges, particularly those centered around climate change and natural resource depletion. Scholars have extensively examined the effects of climate change on environmental policies, exploring causal factors in existing literature. More importantly, various studies (Albulescu, Boatca-Barabas, and Diaconescu 2022, p. 17; Garrett, Grasselli, and Keen 2020, p. 1; Ladenburg, Kim, Zuch, and Soytas 2024, p. 9; Li, Samour, Irfan, and Ali, 2023, p. 11) point out the role of environmental policy stringency and climate change mitigation technologies on environmental sustainability and reducing CO_2 emissions.

Moreover, recent research by the European Environment Agency (EEA) (2021) highlights the role of policy mixes in achieving green economy objectives. The EEA argues that a combination of regulatory, market-based, and informational instruments is necessary to address the multifaceted challenges of environmental sustainability. Their findings suggest that policy stringency alone is not sufficient; the design and implementation of complementary policies are equally important. At the national level, studies have shown that the stringency of environmental policies varies widely across EU member states. According to the OECD (2020), countries such as Denmark, Sweden, and Germany have implemented some of the most stringent environmental regulations, while others, like Poland and Hungary, lag behind. This variation in policy stringency reflects differences in national priorities, economic structures, and political landscapes.

There are several studies on green economy in the context of environmental policies and macroeconomic factors. Ahmed (2020, p. 5) examine the effect of stringent environmental regulations on environmentally friendly technological innovation, CO_2 emissions, and macroeconomic factors in 20 OECD countries. The findings indicate that stringent environmental policies combined with eco-friendly innovation serve as a driving force for sustainable development. Hao, Umar, Khan, and Ali (2021, p. 1) explore how green growth contributes to a sustainable environment, particularly its impact on CO_2 emissions. The findings indicate that green growth, both in linear and non-linear forms, reduces CO_2 emissions. Furthermore, environmental taxes, human capital, and renewable energy use also decrease CO_2 emissions. Moreover, Anser, Usman, Godil, Shabbir, Sharif, Tabash, and Lopez (2021, p. 1) investigate the relationship between globalization, energy use, and economic expansion in selected South Asian countries to support a green economy and environment. The findings reveal that non-renewable energy use and globalization significantly enhance CO_2 emissions, negatively impacting the environment. However, the study also confirms the Environmental Kuznets Curve (EKC) hypothesis with both positive and negative growth levels. Another study by Abid, Ceci, and Ikram (2022, p. 15) examines the dynamic relationship between technological innovation and green growth in Pakistan, considering environmental challenges such as energy consumption and population growth. Their empirical findings conclude that there is a significant correlation between technological innovation and green growth. Recently, Lee, Wang, Hong and Lin (2024, p. 4) investigate the impact of EPS on bank risks, emphasizing the role of the green economy in this relationship. The primary finding is that EPS can increase bank risks. However, EPS also mitigates these risks through the green economy.

A plethora of empirical studies has focused on climate change mitigation, Bosetti, Carraro, and Tavoni (2009, p. 22) investigates the economic repercussions of climate change, noting that while initial effects may appear positive, they ultimately transition to negative impacts over the long term. A study by Tol (2018, pp. 1-19) underscores the alignment between poverty reduction efforts and the reduction of CO_2 emissions, presenting a strategy to mitigate climate change impacts. Similarly, Khan (2020, p. 8) conduct a comprehensive analysis focusing on the estimation of long-term economic costs and benefits associated with climate change mitigation. Their study highlights the significance of technological advancements, particularly in research and development investments and energy efficiency technologies. Another study by Li and Shao (2023, p. 1) explores the macroeconomic effects of climate change mitigation strategies in Zimbabwe and Venezuela. The findings suggest that simultaneous implementation of mitigation strategies has the potential to enhance economic welfare and facilitate successful implementation.

Furthermore, a body of literature extensively examines the dynamic impacts of climate change mitigation on both sustainable development and economic growth through empirical investigations. In preliminary inquiries, Li, Kuo, Mahmud, Nassani, Haffar and Muda (2022, p. 5) delve into the correlation between climate change mitigation and various factors including energy efficiency, cleaner technology, financial development, and economic growth. Their findings suggest that renewable energy and financial development possess the capacity to reduce CO_2 emissions and mitigate climate change effects. Similarly, Magazzino, Mele, Drago, Kuşkaya, Pozzi, and Monarca (2023, p. 7) scrutinize the interplay between economic growth and environmental quality within the framework of climate change mitigation and the EKC curve. They present evidence supporting the existence of an inverted U-shaped relationship between per-capita GDP and per-capita CO_2 emissions.

Additionally, Tao, Ren, Chen, Huang, and Liu (2023, p. 1) analyze the impact of climate change and technological innovation on economic growth, energy consumption, and carbon emissions in Asian and European countries. The findings reveal regional differences, with technological innovation more effectively promoting sustainable growth in Europe than in Asia. Lastly, Ciccarelli and Marotta (2024, p. 6) examine the macroeconomic impacts of climate change, environmental policies, and green innovation in 24 OECD countries from 1990 to 2019. Their findings conclude that countries with low income, high emissions, and little environmental policy face more severe economic disruptions.

Many studies (Albrizio et al., 2017, p. 1; Appiah, Naeem, and Karim 2023, p. 9; Chu, Doğan, Ghosh, and Shahbaz 2023, p. 11; Obydenkova and Salahodjaev, 2017, p. 1; Paroussos, Fragkiadakis, and Fragkos 2020, p. 27; Zhang, Zheng, Feng and Chang 2022, pp. 1-33) have investigated the drivers of environmental policies, climate change policies and sustainable development. Recently, Chang (2023) delves into the efficacy of environmental policies in reducing the ecological footprint, employing the Cross-Sectional Autoregressive Distributed Lags (CS-ARDL) approach. Their empirical findings reveal that environmental policy measures effectively diminish the ecological footprint, primarily through the avenues of renewable energy adoption and innovation.

Despite increasing interest in the green economy, climate change mitigation and environmental policy stringency have not been thoroughly examined in the context of EU countries. However, these elements are crucial for sustainable development, as they tackle environmental, economic, and social issues at both local and global levels. The gaps identified in the existing empirical literature highlight the need for further investigation. Unlike previous studies (Ahmed, 2020, p. 8; Danish, Ulucak, Khan, Baloch, and Li 2020, p. 5; Wolde-Rufael and Mulat-weldemeskel, 2023, p. 23), this research focuses specifically on the impact of climate change mitigation and environmental policy stringency on the sustainable development process.

3. Data description and empirical findings

This study utilizes annual data from 2000 to 2020 for 27 EU and 3 EU candidate countries which are shown in Table 1 below. These countries and periods are chosen based on the data availability.

Table 1

Selected Countries

Albania	Austria	Belgium	Bosnia and Herzegovina	Bulgaria
Croatia	Cyprus	Czechia	Denmark	Estonia
Finland	France	Germany	Greece	Hungary
Ireland	Italy	Latvia	Lithuania	Luxembourg
Malta	Netherlands	Poland	Portugal	Romania
Slovakia	Slovenia	Spain	Sweden	Türkiye

Figure 1 presents a time-series depiction of the overall levels of climate change mitigation across EU countries from 2000 to 2020. The mitigation efforts encompass six distinct sub-categories, including energy generation, transmission and distribution, water treatment and waste management, information and communication technologies (*ICT*), transportation, and building production or goods processing.

Climate change mitigation technologies (*CMM*) are based on patent applications from OECD statistics. The OECD uses the Cooperative Patent Classification (CPC) system and the International Patent Classification (IPC) system to categorize patents that fall under climate change mitigation technologies. The patent classifications cover a wide range of technologies, including renewable energy technologies, energy efficiency improvements, carbon capture and storage, electric and hybrid vehicles, smart grids and energy storage technologies, and water and waste management technologies aimed at reducing emissions. EPSI is also taken from OECD statistics based on environmental and climate change mitigation policies with 13 policy instruments[*] CO_2 emissions is taken from the World Development

[*] These policy instruments are CO_2 Trading Schemes tax, Renewable Energy Trading Scheme, CO_2 Taxes, Nitrogen Oxides (NOx) Tax, Sulphur Oxides (SOx) Tax, Fuel Tax (Diesel), Emission Limit Value (ELV) NOx, ELV for SOx, ELV for Particulate

Indicator (WDI). Economic growth is measured in GDP per capita (constant 2015 US$) which is taken from the WDI, while foreign direct investments (*FDI*) is measured net (BoP, current US$) which are also from the WDI. Trade openness (*TO*) is based on trade as a percentage of GDP from the WDI. Table 2 presents the codes, definition, and sources of the variable considered.

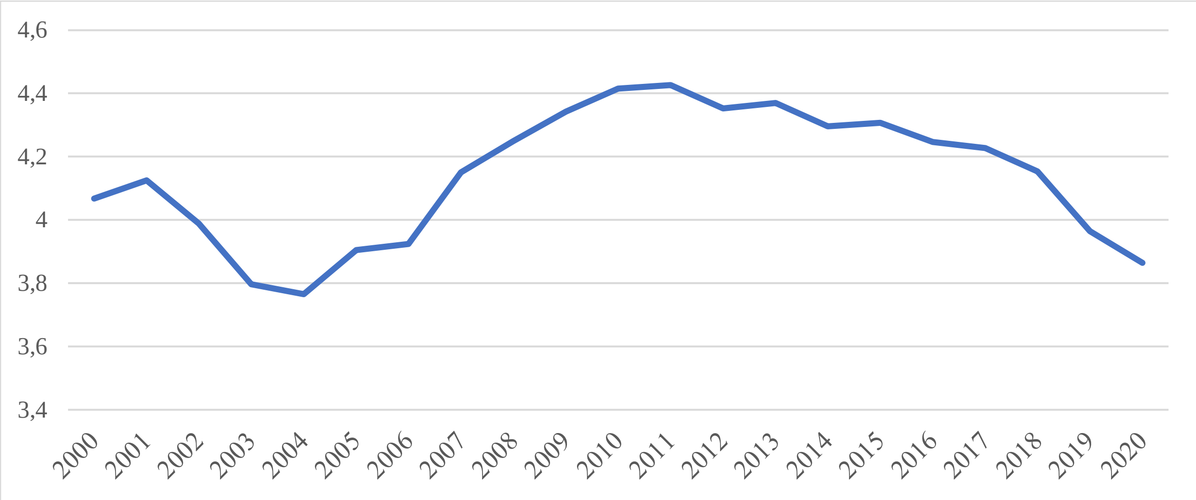

Figure 1. Climate change mitigation, 2000-2020

Table 2

Data information

Indicators	Information	Source
CMM	Climate change mitigation technologies	OECD.STAT
EPSI	Environmental Policy Stringency Index	OECD.STAT
GDP	GDP per capita (current US$)	WDI
TO	Trade openness- Trade as a percentage of GDP	WDI
CO	CO_2 emissions (metric tons per capita)	WDI
FDI	FDI net (BoP, current US$)	WDI

Within the framework of Sustainable Development Goals (SDGs), these studies investigate various dimensions including the influences of climate change, shifting precipitation patterns, and extreme weather events on ecosystems, biodiversity, and natural resources. Moreover, they delve into the ramifications of climate change on human health, livelihoods, and socio-economic systems, with the objective of identifying strategies to mitigate and adapt to these challenges, thereby fostering long-term environmental sustainability. In previous studies, Catalano, Forni, and Pezzolla (2020) employ an overlapping generations (OLG) model to represent public policies that mitigate the adverse effects of climate change on the rate of capital depreciation. Sun and Weng (2024) analyze the dynamic effects of climate change with a model of demographic, economic, and technological variables. In this context, this study present an empirical model designed to examine the mediating role of the environmental policy stringency index in conjunction with causal factors aimed at mitigating climate change. The model encompasses several explanatory variables such as economic growth, CO_2 emissions, Foreign Direct Investment (FDI), and the trade openness within EU countries. The articulated model is as follows:

Matter (PM), Sulphur content limit for diesel, Public research and development expenditure (R&D), Renewable energy support for Solar and Wind.

$$LCCM_{it} = \beta_{it} + \alpha_{2i}EPSI_{it} + \alpha_{3i}LGDP_{it} + \alpha_{4i}LFDI_{it} + \alpha_{5i}LTO_{it} + \alpha_{6i}LCO_{it} + \varepsilon_{it} \quad (1)$$

where LCCM represents climate change mitigation technologies, EPSI denotes environmental policy stringency index, LCO shows CO_2 emissions, LGDP denotes GDP per capita, and LFDI represents foreign direct investment and lastly, LTO denotes trade openness. All variables are taken at their natural logarithm level, except for EPSI which is the index value. The employ of panel quantile regression as the methodology for this study is driven by its ability to capture heterogeneous effects across different levels of climate change mitigation, providing insights that go beyond the average effects typically estimated by ordinary least squares (OLS) regression. This method is particularly robust to outliers, ensuring that the results remain reliable even in the presence of extreme values, which are common in cross-country analyses. Additionally, panel quantile regression offers distributional insights, revealing how environmental policies, economic growth, trade openness, foreign direct investment (FDI), and CO_2 emissions impact climate change mitigation differently across the distribution. This study develops an empirical model where Q represents quantile regression, by incorporating the quantile method in the following:

$$Q_{\tau}(LCCM_{it}) = \beta_{\tau} + \alpha_{2\tau}EPSI_{it} + \alpha_{3\tau}LGDP_{it} + \alpha_{4\tau}LFDI_{it} + \alpha_{5\tau}LTO_{it} + \alpha_{6\tau}LCO_{it} + \varepsilon_{it} \quad (2)$$

Table 3 summarizes the descriptive statistics for all variables. The results indicate that *GDP* per capita has the highest mean value among the variables.

Table 3

Descriptive statistics

Variable	Obs.	Mean	Std. dev.	Min.	Max.
LCCM	630	4.139	2.134	0	8.933
EPSI	630	10.30	0.672	0.166	4.888
LGDP	630	4.416	0.550	8.698	11.62
LCO	630	2.509	0.989	0.4664	4.418
LTO	630	0.899	0.351	2.973	5.946
LFDI	630	2.291	0.079	1.840	2.473

Table 4 shows the correlation estimates, indicating positive correlations among most variables. However, *LFDI* is an exception, displaying negative correlations.

Table 4

Correlation Matrix

Variable	LCCM	EPSI	LGDP	LTO	LFDI	LCO
LCCM	1.0000					
EPSI	0.1954*	1.0000				
LGDP	0.1426*	0.2283	1.0000			
LTO	0.6931*	-0.0205	0.0565*	1.0000		
LFDI	-0.1212*	0.1612*	0.2882	0.2359*	1.0000	
LCO	0.0507	-0.1046	0.0512*	0.0259	0.0896	1.0000

Note: *denote significance levels at 5%.

Prior to model estimation, preliminary panel data analyses are carried out to check for cross-sectional dependency (*CD*) and unit root tests of the variables. Table 5 displays the results of the *CD* tests performed using methods by Pesaran (2021), Friedman (1937), and Frees (1995). The results indicate the presence of cross-sectional dependency based on the statistical significance of the test statistics for each variable.

Table 5

Cross-sectional dependence test

Model*	Pesaran Test	Friedman Test	Frees Test
Test statis.	14.912	123.842	4.970
Prob-value	0.000	0.000	0.000

Note: * shows the model of *LCCM=f (EPSI, LGDP, LTO, LFDI, LCO)*.

Given the presence of cross-sectional dependence (*CSD*), we apply second-generation unit root tests to strengthen the validity and reliability of the results. This entails employing various panel unit root tests to evaluate the stationarity of the variables, such as Pesaran's (2007) *CSD*-adjusted Im-Pesaran-Shin (*CIPS*) test and Pesaran's Augmented Dickey-Fuller (*CADF*) test. The results in Table 6 consistently indicate the presence of a unit root under both constant and trend conditions for all tests, with the exception of *LCCM*, *LGDP*, *LTO*, and *LCO*, which are stationary at their levels. Consequently, the data indicates that all series exhibit stationarity in their first differences. Therefore the outcomes of unit root tests of the variables show a mixed integration.

Table 6

Panel unit root tests

Series	Model	CIPS^a	CIPS^b	CADF ^{a}	CADF ^{b}
LCCM	Constant	-1.873	-3.862***	-1.462	-2.157*
	Constant&Trend	-2.226	-4.299***	-2.074	-2.436**
EPSI	Constant	-2.653***	-4.686***	-2.467***	-2.918***
	Constant&Trend	-3.079***	-4.596***	-2.766***	-2.800***
LGDP	Constant	-1.788	-2.873***	-1.650	-1.815*
	Constant&Trend	-1.997	-3.037***	-1.952	-2.052**
LTO	Constant	-1.873	-4.224***	-1.443	-2.730***
	Constant&Trend	-2.041	-4.218***	-2.132*	-2.887***
LFDI	Constant	-3.483***	-5.525***	-2.012*	-2.865***
	Constant&Trend	-3.949***	-5.540***	-2.326	-2.938***
LCO	Constant	-3.541***	-5.511***	-1.503	-2.538***
	Constant&Trend	-4.059***	-5.647***	-2.538	-2.767***

Note: a refers to unit root test model at level and b refers to unit root test model at first difference.

Table 7 presents the results of the Kao, Westerlund, and Pedroni cointegration tests, which are employed to assess the existence of a long-term relationship among the variables under study. These tests collectively suggest the potential for a long-run association between the predictors and the dependent variable, LCMM. The cointegration tests yield significant results, indicating that a long-run equilibrium relationship exists between the predictors and LCMM. Therefore, we reject the null hypothesis of no long-term relationship, confirming that the variables are indeed cointegrated over the period analyzed. This finding underscores the stability and persistence of the relationship between the predictors and climate change mitigation efforts in the long term.

Table 7

Panel cointegration tests

Statistic	Value	*p*-value
Dickey-Fuller t (Kao test)	-2.803	0.0025***
Augmented Dickey-Fuller t (Kao test)	-2.083	0.0040***
Modified Dickey-Fuller t (Kao test)	-1.762	0.0390**
Variance ratio (Westerlund test)	1.244	0.0403**
Phillips-Perron t (Pedroni test)	-7.442	0.0002***

Note: ** and *** indicate at 5% and 1% sig. level, respectively.

Table 8 presents the results of fixed effects (*FE*) and quantile regression analyses at the 10th, 25th, 50th, 75th, and 90th quantiles for the variables. As seen in fixed effect results *EPSI* has a positive and highly significant effect, suggesting that stricter environmental policies are beneficial for climate change mitigation. *LGDP* has also a positive but not significant effect, indicating a negligible effect of GDP per capita on climate change mitigation in the FE model. However, *LTO* shows a negative and not significant effect, implying that trade openness has a limited impact on climate change mitigation. Also, *LFDI* shows positive but not significant effect, suggesting that *FDI* does not have a substantial impact on climate change mitigation in the FE model. Lastly, *LCO* has positive and not significant effect, indicating that CO_2 emissions have a limited impact on climate change mitigation in the FE model.

Considering the quantiles findings presents that *EPSI* has positivity and significance across all quantiles. The impact is highest at the 90th quantile, suggesting that stricter environmental policies have a more substantial effect on climate change mitigation in countries with higher mitigation efforts. Also, *LGDP* shows a positive significance at the 10th, 25th, 50th, and 75th quantiles but not at the 90th quantile. The effect is strongest at the 25th quantile, indicating that GDP per capita plays a significant role in lower to middle quantiles of climate change mitigation efforts

Table 8

Panel quantile regression results

Variable	FE	Quantile Regression				
		10th	25th	50th	75th	90th
C	0.0471***	1.489**	10.961***	14.29***	14.807***	8.108***
	(0.24)	(0.62)	(4.42)	(7.23)	(3.98)	(2.70)
EPSI	0.164***	0.330***	0.250***	0.336***	0.237**	.643***
	(3.89)	(3.91)	(2.88)	(4.84)	(1.82)	(6.10)
LGDP	0.0238	0.718***	0.758***	0.404***	0.369**	0.235
	(0.12)	(5.65)	(5.79)	(3.88)	(1.88)	(1.48)
LTO	-0.1094	-2.242***	-2.539***	-2.866***	-2.885**	-2.800***
	(-0.54)	(-14.92)	(-16.38)	(-23.20)	(-12.41)	(-14.9)
LFDI	0.3074	1.003	-2.278**	-1.181	-1.243	1.603
	(0.59)	(0.92)	(-2.02)	(-1.31)	(-0.73)	(1.18)
LCO	3.254	0.245	0.163	0.165	1.496***	3.055***
	(1.54)	(1.06)	(0.68)	(7.23)	(4.18)	(0.288)
Pseudo R^2	0.6731	0.6922	0.7092	0.7341	0.7503	0.7961
Observations	630	630	630	630	630	630

Note: *, ** and *** indicate at 10%, 5% and 1% level, respectively. The z statistics-values are represented in parentheses.

In contrast, *LTO* is negative and significant across all quantiles. The effect is consistently negative, with the strongest impact at the 50th quantile, suggesting that trade openness negatively affects climate change mitigation efforts. On the other hand, *LFDI* shows negative and significant at the 25th quantile but not significant at other quantiles. This indicates that *FDI* has a negative impact on climate change mitigation efforts at the lower middle quantile.

Lastly, *LCO* is positive and significant at the 75th and 90th quantiles. The impact is highest at the 90th quantile, suggesting that higher CO_2 emissions are associated with increased climate change mitigation efforts at the higher quantiles. Moreover, the pseudo-R^2 values range from 0.6731 to 0.7961, indicating a good fit for the models.

Figure 2 also illustrates panel quantile regression models with specific variations of coefficients across quantiles. Concerning the findings taken from the quantile regression model, the coefficient of *EPSI* on *CMM* generally increases across higher quantiles, particularly peaking in the upper quantiles. This suggests that stricter environmental policies have a more significant positive impact on climate change mitigation technologies in countries with higher levels of mitigation. Later, the relationship between *LGDP* and *CMM* shows some variability but remains generally positive across most quantiles.

Countries with higher GDP per capita tend to invest more in climate change mitigation technologies, though the effect is somewhat less stable.

The coefficient for *LTO* is consistently negative across quantiles, indicating that greater trade openness is associated with lower levels of climate change mitigation technologies. The impact diminishes slightly at higher quantiles but remains negative throughout. On the other hand, the relationship between *LFDI* and *CMM* is more complex, showing significant fluctuations across quantiles. While the coefficient is negative at lower quantiles, it becomes positive at higher quantiles, indicating that *LFDI* may initially have a negative impact on climate change mitigation technologies but turns positive in countries with higher mitigation efforts. Lastly, the coefficient for *LCO* is relatively flat and positive at lower quantiles, with a sharp increase at higher quantiles. This suggests that higher CO_2 emissions are positively associated with investments in climate change mitigation technologies, especially in countries with higher levels of mitigation.

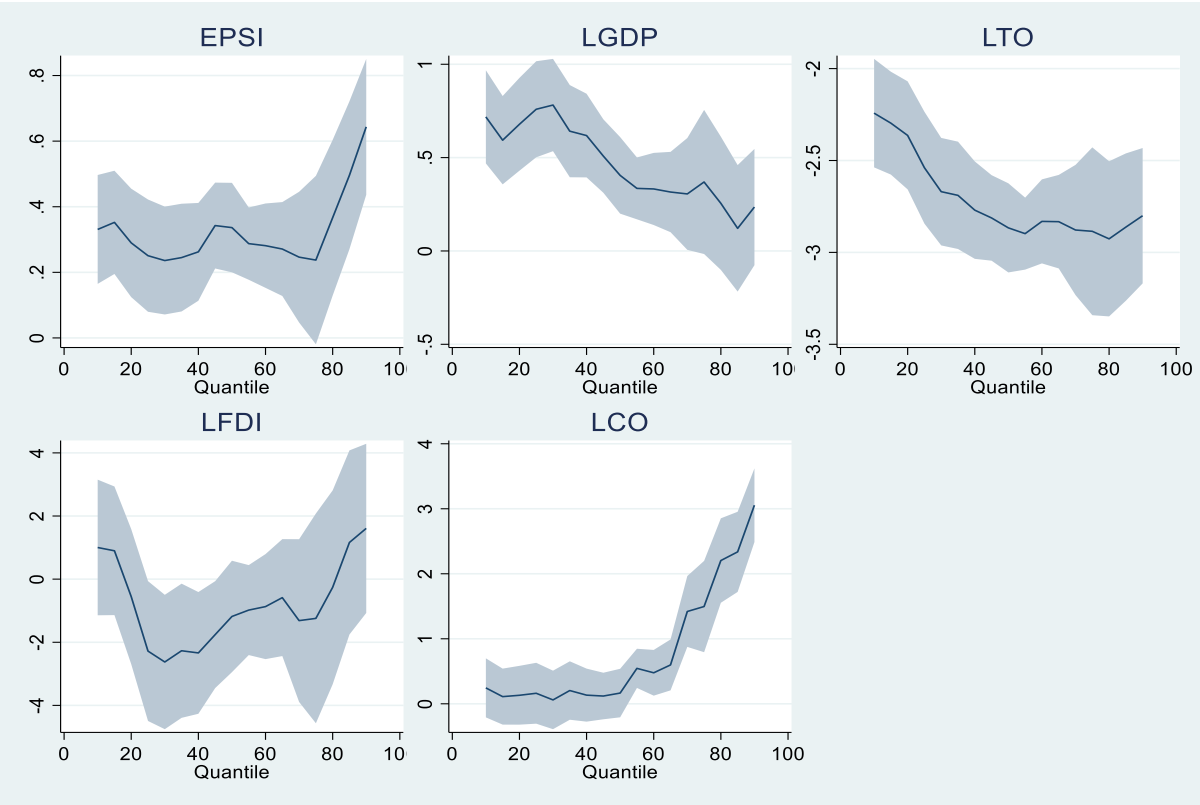

Figure 2. Change in panel quantile regressions coefficients of climate change mitigation

Following this, this study employs the Dumitrescu and Hurlin (2012) Granger non-causality test to investigate the causality of all pairs of variables, and the results are presented in Table 9. The causality test results show a bidirectional causality between all pairs of variables.

Table 9

Panel causality test results

Null Hypothesis	W-Stat	Zbar-Stat	Probability
LCCM → LEPSI	1.9985	4.3525	0.0000
LEPSI → LCCM	4.9611	7.8400	0.0000
LCCM → LGDP	1.8574	3.7374	0.0002
LGDP → LCCM	2.6848	7.3437	0.0000
LCCM → LTO	5.8766	9.8556	0.0000
LTO → LCCM	3.1637	3.8829	0.0001
LCCM → LFDI	3.5123	4.6503	0.0000
LFDI → LCCM	3.1142	3.4037	0.0005

LCCM → LCO	2.5124	6.5925	0.0014
LCO → LCCM	2.1526	5.0241	0.0000

4. Conclusion and policy implications

The primary objective of this paper is to explore the impact of Environmental Policy Stringency (EPS) and its underlying determinants on climate change mitigation efforts across EU countries over the period from 2000 to 2021. This research employs a panel quantile regression model to analyze how various factors, such as environmental policy, economic growth, trade openness, foreign direct investment (FDI), and CO_2 emissions, influence climate change mitigation at different points in the distribution (specifically the 10th, 25th, 50th, 75th, and 90th quantiles). By examining these quantiles, the study aims to capture the heterogeneous effects of these variables across EU countries, providing a more nuanced understanding of how stringent environmental policies and other economic factors contribute to climate change mitigation across the region.

The panel quantiles regression findings show that the impact of each variable on climate change mitigation technologies varies across different levels of mitigation efforts within the countries analyzed. The findings indicate that environmental policy stringency, GDP per capita, and CO_2 emissions have a more pronounced positive effect on climate change mitigation at higher quantiles. This result aligns with previous studies that emphasize the importance of stringent environmental regulations in promoting cleaner technologies and reducing emissions. For instance, Albrizio et al. (2017) found that stringent environmental policies are positively correlated with green innovation, particularly in countries with higher levels of economic development, where firms are more capable of adapting to regulatory pressures . Similarly, the positive relationship between GDP per capita and climate change mitigation observed in this study echoes findings by Stern (2015), who argues that economic growth can facilitate investment in green technologies, thereby enhancing a country's ability to reduce emissions. On the other hand trade openness generally shows a negative impact. The effect of *LFDI* is mixed, turning positive in higher quantiles. Moreover, we conclude that there is a long-term cointegration between climate change mitigation, *EPS*, *LGDP*, *LTO*, *LFDI*, and *LCO* analyzed in this study. According to Dumitrescu & Hurlin (2012) causality test, there is a bidirectional relationship between *EPS*, *LGDP*, *LTO*, *LFDI*, and *LCO*, and climate change mitigation at all significance levels.

The fundamental finding of this study shows that trade openness negatively affects climate change mitigation efforts, which can be explained through several theoretical backgrounds. The Pollution Haven Hypothesis (Copeland and Taylor, 2004) suggests that companies may relocate to countries with lax environmental regulations, leading to carbon leakage and higher global emissions. Race to the Bottom Theory (Daly, 1993) argues that countries might lower environmental standards to remain competitive, undermining climate policies. Comparative Advantage theory (Krugman et al., 2015) implies that countries specializing in carbon-intensive industries for export may increase global emissions. The Jevons Paradox (or rebound effect) (Alcott, 2005) highlights that increased trade efficiency can paradoxically lead to higher overall emissions. Additionally, the Environmental Kuznets Curve (EKC) (Grossman and Krueger, 1995, pp. 353-377) suggests that trade-integrated global value chains can hinder environmental progress by shifting emissions to developing countries. These theories collectively explain how trade openness, despite its economic benefits, can complicate and often undermine efforts to mitigate climate change. A similar result is reported in a study by Shapiro (2020), which explores how differing environmental standards affect international trade. The research found that countries with stricter environmental regulations often face pressure to reduce these standards to remain competitive in global markets, which can dilute the effectiveness of climate policies and hinder global mitigation efforts.

Moreover, this study expands upon previous research by considering a wider range of factors relevant to the green economy. By encompassing a broader timeframe and incorporating multiple European economies, our findings provide additional robust evidence beyond prior studies. To effectively address climate change mitigation within the framework of a green economy, EU countries should prioritize policy coherence, cross-sectoral collaboration, and investment in renewable energy and energy efficiency measures. Strengthening coordination among environmental policies at the EU level is essential to ensure a unified approach towards sustainability goals while fostering collaboration between stakeholders can facilitate innovation and knowledge exchange. Increasing investments in renewable energy sources and promoting energy efficiency across various sectors will help reduce greenhouse gas emissions and decrease reliance on fossil fuels. Enforcement mechanisms and monitoring systems should be strengthened to ensuring compliance with environmental regulations and track progress toward climate change mitigation targets.

Based on the empirical results of this study, several policy recommendations are proposed to aid governments and policymakers in promoting environmental sustainability within nations and achieving the eco-friendly goals of sustainable development. First, EU countries should strengthen and enforce stringent environmental policies, tailoring them to address specific needs at different levels of mitigation efforts. Incorporating green growth strategies into economic planning is essential, incentivizing sustainable industries and decoupling economic growth from carbon emissions through energy efficiency and low-carbon technologies. Second, sustainable trade policies should be advocated, ensuring trade agreements include environmental standards and that domestic climate efforts are not undermined. Foreign direct investments in green sectors should be encouraged with incentives while ensuring FDI does not lead to environmental degradation. Third, increasing investment in research, development, and deployment of green technologies is essential to accelerate the transition towards a sustainable economy, particularly in areas such as renewable energy and energy efficiency. Fourth, fostering international cooperation and knowledge sharing can enhance collective efforts in climate change mitigation, while promoting sustainable consumption and production patterns is vital to reduce environmental impact. Fifth, strengthening monitoring and evaluation mechanisms is crucial for tracking progress and ensuring accountability, while integrating climate action into economic policies can align environmental sustainability objectives with broader economic goals. By implementing these recommendations, EU countries can fortify their environmental policy framework and advance towards a more sustainable and resilient green economy. These recommendations aim to leverage the positive impacts of EPS, economic growth, and other factors while addressing the challenges posed by trade openness and FDI, thereby enhancing climate change mitigation efforts across the EU.

While this study offers valuable insights into the impact of Environmental Policy Stringency (EPS) and macroeconomic factors on climate change mitigation, several limitations must be acknowledged. Firstly, the reliance on patent data to measure climate change mitigation technologies may not fully capture all relevant innovations, as not all technologies are patented or covered by patent databases. Moreover, the study's focus on EU countries and candidate countries may limit the generalizability of the findings to other regions with different economic and policy contexts. The impact of trade openness on climate change mitigation, for example, may differ in non-EU countries with distinct trade and environmental policy frameworks.

Future research could address these limitations by incorporating alternative measures of climate change mitigation, such as direct assessments of technological adoption or implementation rates. Expanding the analysis to include a broader range of countries, including developing nations and non-EU economies, would provide a more comprehensive understanding of how environmental policies and macroeconomic factors influence climate change mitigation globally. Additionally, longitudinal studies that track the long-term effects of policy changes on innovation and mitigation outcomes could offer deeper insights into the dynamic interactions between environmental policies, economic growth, and technological advancements.

Author statement

Research and publication ethics statement

This study has been prepared in accordance with the ethical principles of scientific research and publication.

Approval of ethics board

Ethics committee approval is not required for this study.

Author contribution

All authors have contributed the study equally.

Conflict of interest

There is no conflict of interest arising from the study for the authors or third parties.

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