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Europe's environmental dichotomy: The impact of regulations, climate investments, and renewable energy on carbon mitigation in the EU-22

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A R T I C L E I N F O

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A B S T R A C T

Although "COP28 UAE Leaders' Declaration" reiterated the critical importance of making finance inclusively available, the gap remains wide even across EU region, hindering the region's collective climate goals. Thus, this study takes on varying socio-economic challenges and diverse environmental policies across the EU-22 nations, and investigates the role of Government's Climate Significant Investment (GCSI) in carbon mitigation through clean energy transitions under the 2030 and 2050 climate commitments of Europe Union countries from 2007 to 2021. Using a novel panel fixed effects model, followed by dynamic panel data estimation techniques and structural equation modeling, a latent class modeling approach, the study controls for factors like Foreign Direct Investment (FDI), economic growth and urbanization. The empirical findings indicate that the effectiveness of environmental regulations in reducing carbon emissions is mediated by GCSI, which, in turn, is influenced by renewable energy transitions. This implies that regulatory measures have an indirect effect measurable through GCSI and renewables, and can be considered key performance indicators. Moreover, based on dynamic panel data estimations technique, the most of the statistically significant coefficients are found to be inelastic (<1), echoing a yet to achieve breakeven when it comes to tradeoff between environment and economic sustainability for overall EU-22 panel. Despite some high-income nations achieving significant environmental sustainability goals, uneven performance across the EU-22 highlights persistent challenges. Stricter environmental regulations have the potential to reduce carbon emissions without negatively impacting GDP. However, countries with less GCSI and FDI investment may struggle to meet climate targets, necessitating policy interventions, and government institutions to ensure green growth pathways.

1. Introduction

Despite decades of global efforts, the recent climate change trajectories show little improvement. Whereas, the divide between developed and developing world remains visible when it come to tackling the issue. There is no way global climate targets are achieved without the substantial contribution from developing nations, which require significant financial support to bridge capacity gaps (Songwe et al., 2022). Climate finance has thus emerged as the linchpin of global climate action. The recent UN climate conferences, have exclusively emphasizes the need of availability, accessibility and affordability of finances across developed and developing world. For instance, COP28 stressed the critical need for \$5–7 trillion in annual investments until 2030, while COP29 pledged \$300 billion annually for developing nations by 2035. There are numerous evidence that the developed countries that are high achievers in climate targets are those employed significant financial resources (Darvas and Wolff, 2023). Although policy frameworks and regulatory imperatives form the backbone of climate initiatives, their efficacy is contingent upon their ability to catalyze substantial green investments. As climate change embodies the quintessential public goods problem, the role of government-induced investments becomes paramount in initiating and sustaining the pathways toward decarbonization and resilience (Drahos, 2021). Climate action demands a collective, multi-level response—national, regional, and global. Failure to adopt such an approach risks deepening socio-economic inequities and derailing both environmental and economic well-being, ultimately resulting in a

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"lose-lose" scenario for humanity. Capitalizing on the notion, this paper highlights how regulatory and climate investment disparity across European Union (EU) region affecting regional climate pledges.

EU has made impressive progress in formulating one of the most comprehensive environmental regulatory frameworks, establishing itself as a global leader in the fight against climate change (Knill and Liefferink, 2021). The European Green Deal, approved in 2020, is a comprehensive plan that aims to make Europe climate-neutral by 2050. This framework includes stringent regulations on emissions, resource efficiency, and transition to clean energy (Sikora, 2021). The EU has implemented robust policies, including the world's largest carbon market, the EU Emissions Trading System, as well as the EU Taxonomy, which guides investments towards environmentally sustainable projects (Oberthür and Von Homeyer, 2023). Additionally, the EU Green Digital Coalition has been established to accelerate the use of green technologies for the benefit of the environment, with member states committing to key digital initiatives that will help the technology sector become more sustainable, circular and zero. However, socio-economic impacts lack of climate significant investment at national and sub-national levels, especially in less industrialized EU regions, remain a concern (Krommyda et al., 2024). The transition to a low-carbon economy may challenge regions reliant on carbon-intensive industries, potentially deepening economic disparities (Weitzel et al., 2023). For instance, Fig. 1 highlights disparities in environmental performance across the EU-22 member states, with several Eastern European nations having some of the lowest scores on regulatory measures. This suggests significant challenges in effectively implementing these policies in these regions. To effectively address these challenges, a comprehensive investigation into the key economic, social, and political hurdles impeding progress is required.

The EU's progress in transitioning to a green economy is exemplified by the western region, where rigorous environmental laws have been successfully integrated with economic growth strategies (Chiti, 2022). For instance, Germany's 'Energiewende' policy, launched in 2010, stands out for reducing fossil fuel dependence and boosting job creation in the renewable energy sector (Rechsteiner, 2021). By 2019, renewable sources accounted for 46% of Germany's electricity, a significant increase from 27% in 2014, illustrating the effectiveness of sustained policy efforts (Energiewende and Verkehrswende, 2020). Similarly, Denmark has become a leader in wind energy through substantial investments, with wind power supplying 50% of its electricity in 2020 (Danish Energy Agency, 2021). Despite these successes, the regional differences in accessing various sources of financing, including both formal and informal, have played a significant role in the environmental sustainability and economic growth trajectories of different regions. See for instance Fig. 2, as of 2022, the percentage of renewables in total final energy consumption mix varies between 13 and 66 percent, highlighting a significant gap across EU-22. Thus, the challenges persist in the eastern and southern regions in maintaining the economic sustainability (Sovacool et al., 2020). There is growing demand for equitable distribution of climate finances to reduce the regional disparities amid efforts of achieving 2030 and 2050 climate targets.

Climate finance has been instrumental in supporting the EU's green transition, facilitated through initiatives like the 'Cohesion Fund' and the 'Just Transition Mechanism'. These mechanisms, according to the European Commission (2020), play a crucial role in developing sustainable infrastructure, advancing clean technologies, and enhancing climate resilience across the regions, more competitive and resilient economies. The European Environment Agency (2019) has documented improved environmental and economic outcomes in the countries benefiting from substantial climate finance. Such claims are endorsed in the empirical investigations conducted by De Haas and Popov (2023) and Monasterolo and Raberto (2019). The research also concludes the positive link between stringent environmental regulations and increased green investment flows, thereby fostering sustainable finance markets. However, challenges remain in ensuring equitable distribution of these funds, with concerns raised about inadequate support for vulnerable regions, as noted (Pauw et al. (2020), which calls for greater inclusivity in climate finance distribution strategies. Similarly, the taxonomy, central to EU Green Deal, aims to help the EU achieve its 2030 and 2050 climate targets, comprises of a sustainable finance platform, a permanent expert group under the taxonomy regulation, advises the European Commission. However, how effective the group has been diverting the finances to the countries, underperforming on the 2030 and 2050 targets is yet to be investigated through various lenses. In technologically and economically developed region across Europe has invested in future with Government's Climate Significant Investments (GCSI). These investment initiatives are national and subnational levels and benefitted in mitigating carbon footprints significantly. Fig. 3 demonstrate the GCSI across EU-22 in 2022. It is pertinent to notice that most of the countries with stringent regulatory framework has shown significant investments followed by a better performance on transitioning towards a clean energy and vice versa.

Besides, another component that has played a significant role in attracting and diversifying green growth investments in emerging economies is Foreign Direct Investment (FDI). However, it is recently debated that the low rate of FDI in EU require a policy intervention in middle and high-middle income economies in Europe (Lee-Makiyama,

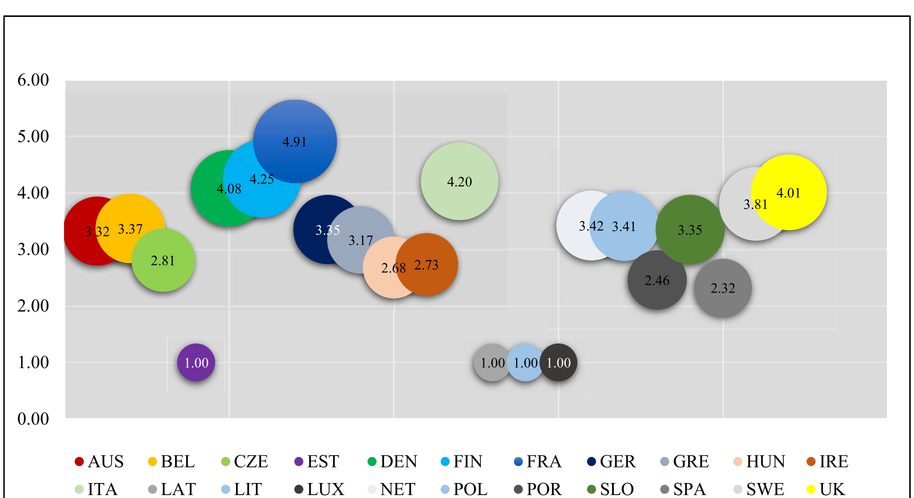

Fig. 1. Environmental policy stringeny index of EU-22.
Source: OECD

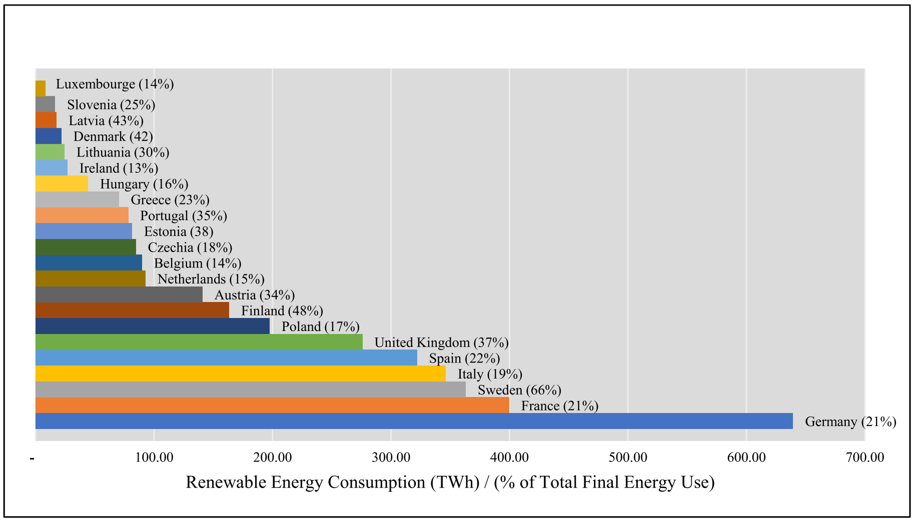

Fig. 2. Renewable energy consumption (2022).
Source: World Bank & European Environmental Program (EEP)

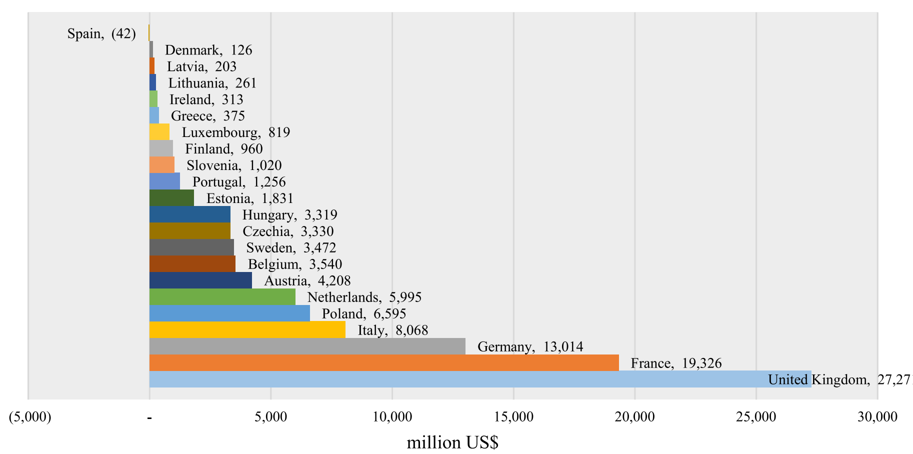

Fig. 3. Government's climate significant investment (GCSI), 2022
Source: OECD

2021). Fig. 4 demonstrate net FDI for EU-22 as of 2022. Although stringent environmental regulations within the EU have not only reshaped its FDI landscape but also aligned FDI policies with environmental objectives to promote sustainable development. Despite these efforts, concerns persist that excessively stringent FDI regulations could deter beneficial investments, particularly in sectors reliant on

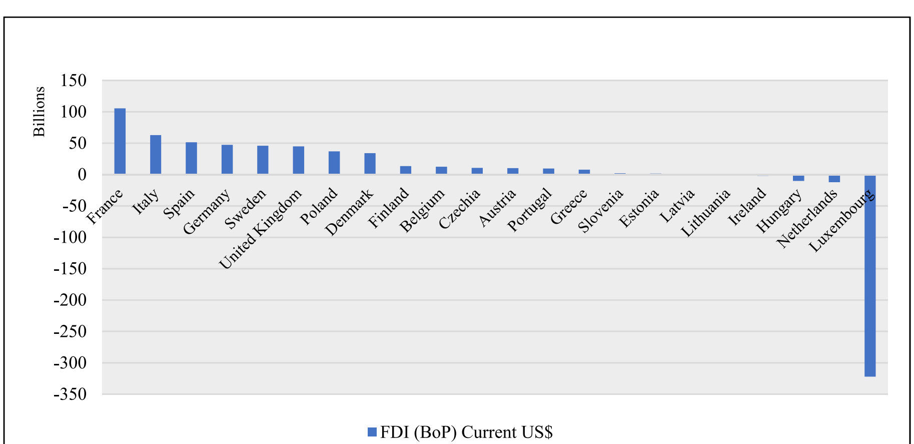

Fig. 4. FDI, 2022 (BoP_Current US$).
Source: OECD

foreign expertise and capital (De Beule et al., 2022). Ambec et al. (2013) highlight mixed evidence, indicating that while green regulations attract environmentally conscious investors, they may deter traditional industries. This sentiment is endorsed by Pauw et al. (2020), the study stresses the ongoing challenge of balancing rigorous environmental standards with attracting necessary investments. Aghion et al. (2016) further suggest that while stringent environmental regulations can drive innovation in green technologies, they may impose short-term economic costs. Future research requires to focus on refining these regulations to optimize both environmental and economic benefits while fostering innovation and growth. Additionally, the EU Green Digital Coalition has been established to accelerate the use of green technologies for the benefit of the environment, with member states committing to key digital initiatives that will help the technology sector become more sustainable, circular and zero. However, the effectiveness of such policies in regard to climate finances including of FDI needs to be investigated in an EU panel setting.

Nevertheless, the transition to a green economy presents significant economic implications and challenges (Mealy and Teytelboym, 2022). This shift may disrupt traditional industries, leading to short-term economic adjustments and job losses, particularly in sectors like coal mining and fossil fuel production. Urbanization efforts must adapt by integrating sustainable infrastructure and energy-efficient buildings to accommodate population growth without compromising environmental goals. However, studies such as those by Sovacool et al. (2020) caution that while green transitions can stimulate new economic sectors, they may also exacerbate socio-economic disparities if not managed carefully. The EU addresses these challenges through integrated policies and funding mechanisms, yet disparities in economic capabilities among member states complicate unified implementation and outcomes. Happaerts (2012) emphasize the need for policies that bridge economic divides and ensure a just transition for all regions. Additionally, empirical evidence from Costantini and Mazzanti (2012) underscores the sectoral and regional variability in the economic impacts of environmental regulations, calling for tailored policy approaches to maximize benefits across diverse contexts. Different countries within the EU have experienced varied degrees of success. Germany and Denmark are often cited as success stories due to their significant investments in renewable energy and stringent regulatory frameworks. However, other countries, particularly those with economies heavily reliant on fossil fuels, face more significant challenges in transitioning to green energy. The effectiveness of climate finance distribution is also debated, with some studies indicating that funds are not adequately reaching the most vulnerable regions.

Environmental efficiency improves through the implementation of policies aimed at reducing greenhouse gas emissions. The US and EU have enhanced environmental standards to help mitigate emissions. Economic performance is directly related with the environmental sustainability. Low-cost production and efficient technologies boost economic efficiency whereas, reliance on traditional energy sources, such as fossil fuel causes environmental inefficiency and other ecological damages. Promoting environmental sustainability is crucial for pollution control. Environmental sustainability shows the institutional efficacy by minimizing environmental challenges, reducing emissions, and advancing energy transition and clean practices (Muhammad and Long, 2021). Sustainable ways can significantly reduce carbon emissions, therefore, improving environmental performance (Barra and Ruggiero, 2022). To achieve environmental benefits, regulations can play an important role in reducing urban pollutant emissions (Yang et al., 2021), minimizing carbon emissions, and promoting energy efficiency (Cheng et al., 2023). For better impacts of policy standards on carbon emission, firms need to improve the resource efficiency and technological innovation, reducing investment uncertainty, alleviating environmental protection pressure, and change the traditional competitive environment. Regulations can also improvise financing constraints and increase financing efficiency.

This study holds significant relevance for boosting environmental sustainability, as climate change has rigorously affected the environment and energy production. The lack of regulations related to use of biogas, fossil fuels, and unsustainable investments is a major concern. Economic and social injustices, have further worsened the issue of the climate change. There is a need of transparent regulations and policy formulation to discourse these challenges (Bertolino et al., 2023). The EU must focus on carbon mitigation by reducing emissions, and improving economic systems (Peiró-Palomino et al., 2022). Besides the relevance, the purpose of this study is to encourage economic development while highlighting the significance of achieving environmental efficiency by transitioning energy towards sustainability. Climate change and environmental pollution are caused by extreme use of fossil fuels, which have negatively impacted the world economy, including the EU. The urgency of introducing the environmental policies would significantly help to address climate change and foster economic growth and sustainable development. Examining regulations, the government's climate-significant investments and renewable energy transition would further explore deeper insights into how it benefits both the environment and the economy by reducing greenhouse gases. Moreover, this study aims to investigate how to manage ecological pressure and complexity of the economic system affected by climate change by investigating regulations roles, government's climate-significant investments, and renewable energy.

The significance of this study is to highlight the efforts towards environmental efficiency to mitigate pollution (Arkinson and Tsionas, 2021) while controlling harmful inputs. This undertakes the technology to reduce the undesirable outputs. Institutional quality can impact environmental efficiency through executing innovative systems. It can reduce innovation costs, increase resource efficiency, and promote new investment opportunities and develop strategies to reduce carbon emissions. Furthermore, this study can explore ways to minimize ecological pressures and the complexity of economic systems. The previous studies investigated the role of institutional quality on total factor energy efficiency, environmental efficiency, and bio-economy performance by political system, regulatory practices, and anti-corruption steps (Barra and Falcone, 2023, 2024). Institutional factors such as political institutional quality have a significant effect on environmental performance (Barra and Falcone, 2024). This study would answer the impact of environmental regulations, government climate-significant investments, and renewable energy on carbon mitigation in the EU-22. Factors like control of corruption, government effectiveness, political stability, and regularity quality are influential in achieving environmental sustainability. The past studies have examined the effect of environmental efficiency on middle-income countries and their efforts to alleviate carbon emissions. This study would be highly related to EU countries and would focus on how to mitigate carbon emissions and what regulations would need to be implemented. This indicates the significance of promoting regulatory reforms, government climate-significant investments, and renewable energy transitions that would ultimately enhance environmental performance. Renewable energy sources can play a significant role in long-term sustainable development. Along with renewable energy, technological innovation can drive business growth and improve environmental sustainability.

Looking ahead, the EU faces ongoing challenges in maintaining clean energy adoption while ensuring economic security amid escalating global climate change impacts. Enhancing adaptive capacities to address extreme weather events, resource scarcity, and migration pressures will be crucial. Investing in advanced technologies, diversifying energy sources, and strengthening grid resilience are essential strategies. Studies by Haas and Sander (2020) highlight the importance of robust adaptation strategies to mitigate climate risks. Furthermore, ensuring a just transition for all member states requires continuous policy innovation and socio-economic support. Future research must focus on optimizing the balance between stringent regulations and investment attraction, ensuring equitable climate finance distribution, and developing adaptive policies that accommodate the diverse economic landscapes within the EU. There is a noticeable literature gap regarding the long-term socio-economic impacts of stringent environmental regulations on different member states. More research is needed to understand the localized effects of the green transition, particularly in economically diverse regions of the EU. Studies like those by Costantini and Mazzanti (2012) and Aghion et al. (2016) suggest that a deeper empirical investigation into sector-specific and regional impacts could provide valuable insights for policymakers.

The rest of the paper is structured as follows. Section 2 provides the Review of literature. Section 3 details the research design. Section 4 offers and deliberates results and discussion. Section 5 explains the conclusion and policy implication. Section 6 closes with future research direction.

2. Literature review

2.1. Theoretical background

Theoretically, environmental policy stringency can impact carbon emissions and enhance eco-friendly environment quality through increasing renewable energy and government climate significant investments. Albeit, environmental protection enterprises are beneficial for the whole society, their project investment is high and their income generation is low, thus, most of the financial institutions avoid investing in them. In this study, we have selected the environmental Kuznets Curve EKC model with respect to carbon emissions, environmental regulations and renewable energy source.

Changing carbon emissions and global warming has impeded the development. Carbon and other greenhouse gases emissions block the achievement of environmental quality. They harm the environment in the absence of environmental stringency policy. As per the common command and control regulation theory, for fighting against the carbon emissions, stringent guidelines through the enforcement of fines, penalties and other strict measures can regulate the behaviors of firms in different nations to comply with the environmental safety (Berck, 2018). This theory regulates that when countries improve their business operations and productions, they contribute to sustain the environment from the hazards of carbon emissions. Stringent policies oblige them to abide by the adoption of eco-friendly technology and renewable resources. They promote the green development that help to achieve not only the safe environment but also the sustainable economies. To strengthen the same strand, the ecological modernization theory postulates that countries should be incentivized to become the environmentally responsible economies by implementing market mechanisms, lawful procedures and cultural disciplines (Christoff, 1996). It is commendable to transform the economies through eco-friendly regulation by which low-carbon economies can be achieved by the funding of government climate significant investments and renewable energy and the mindset green industrial production.

2.2. Environmental policy stringency and carbon emissions

Stringency is defined as an implicit and explicit cost of ecologically harmful behavior. For instance, tax on items for which non-renewable energy is used for the production which can promote utilization of green goods. These strict ecological laws can determine the influence the industries to protect the environment from deleterious causes of climate change (OECD, 2016). Past study shows that strict policies may help reduce fossil fuel dependency for mitigating environmental pollution (Shahbaz et al., 2021). It can further build the connection between environment and green technologies. Nations ambitions to achieve higher economic growth through the shift from agriculture to industry caused environmental risks (Ji et al., 2021). Global warming become an alarming issue due to emission of deleterious gases (Naqvi et al., 2023). To promote the low-carbon economies, environmental initiatives have been suggested to be taken in order to alleviate the impact of such an emission bringing pollution and climate change (Ni et al., 2022). Environmental policies were incorporated into the pacts and accords. Paris climate accord, COP26 and Kyoto Protocol have been paying serious attention to the consumption of energy resources to maintain the climate (Bai et al., 2022). Consideration of environmental policy stringency, economies inclined towards the green industrialization. Initially, carbon dioxide was the prominent hazard to the climate change, recent times have been witnessing disastrous floods in the Asian regions, the tsunami in Indonesia, and unceasing fires in Russia (Pata et al., 2022). Overall, the environment has been affected by increasing temperature and emissions (Shahzad et al., 2023). Environmental policy stringency related to countries producing coal, petroleum and gas.

To mitigate the environmental concerns, environmental policy stringency related to trade in coal, oil and gas commodities leading to carbon emissions, studies pacify the solution into regional and international collaboration by avoiding the trade imbalances by reducing the carbon leakage. The results of implementation may increase environmental harmony and decrease the negative trade externalities. Observing the seriousness of the climate, the nations are committing to put a limit tag of 1.5C as temperatures are rising. To attain the net zero emissions by 2050, environmental policy stringency is the exact need of the time. These policies offer to utilize renewable energy sources that encourage the carbon neutrality in the future. It would bring the sustainable growth, less dependence on fossil fuel energy that would minimize the greenhouse gases emission and improve the health and job market (Stern et al., 2020). Past studies lack to provide the evidences that environmental policy stringency index on renewable energy (Bashir et al., 2022) in the perspective of European nations. Therefore, we propose the following hypothesis.

H1. Based on compliance cost theory, environmental policy stringency has a significantly negative impact on carbon emissions reduction.

2.3. Renewable energy on environmental policy stringency and carbon emissions

Transformation from the fossil fuel to the renewables is crucial for gaining the global environmental sustainability (Sims, 2004). It also affected the traditional fuel chains globally. For decarbonizing power system contingent upon fuel requires to adhere to sustainable development goals and objectives of the Paris Agreement (Kapica et al., 2021). Wind, solar, and hydropower are the main sources of renewable energy sources. However, how much to increase their share in the power grid is still the issue for the scientists (Denholm et al., 2018). Studies show that 100% renewable energy systems can be achieved in numerous location if not initially as universally. Several studies assess the impacts of the renewable energy on several regions due to pessimistic carbon emissions as greenhouse gas emissions have been rising. Earlier studies analyze the effects of the renewable energy technologies and the cost supply relationships around the world. The fossil fuels like coal and oil fulfil the 66% of the total energy demand that both affects the quality of the environment and sustainable growth. The acceptance of the renewable energy has got much appreciation after the UNFCC's conference of parties (COP21) for coping with the temperature levels. The European Union has been willing to adopt the climate and renewable energy policies for achieving the carbon neutrality by 2050. To achieve such ambitious goal, dangers of fossil fuel energy are looming. This requires calculated moves to transition to the renewable energy sources as the countries face financial and technological limitations.

Achieving the large scale funding is the tough task to achieve too (Behera et al., 2024). Studies explore that deployment of renewable energy is associated with high investment costs for which environmental policies are important to be implemented. On the other hand, financial sector produces several advantages for renewable energy industries dependent on the external financing (Habiba and Xinbang, 2023).

Studies figure out that funding can be funneled from investment projects and enhanced liquidity of assets at level and efficiency effects. G7 countries analyzed such effect on renewable energy and the results show that interaction impact of ecological regulations and financial development on the renewable energy that has powerful impact on transitioning to the environmental sustainability. However, although past studies shed light on relationships renewable energy, the mediation relationship of renewable energy between environmental policy stringency and climate change has been less attended (Omri and Jabeur, 2024). Henceforth, we propose the following hypothesis:

H2. As per resource dependence theory, renewable energy has a negative mediation impact on carbon emissions and help environmental policy stringency to mitigate carbon emissions.

2.4. Government climate significant investments on renewable energy and carbon emissions

Besides, the funding at level and efficiency effects, government climate significant investments (GCSI) is the new concept that has been missing in the European nations' context. The European countries are the third major carbon emissions regions by 9% at global level in 2019 (Osička et al., 2020). The EU nations have been devising policies and strategies to curb the carbon emissions. The previous studies looked into the carbon emissions in association with the Paris Agreement and EU climate law. The issues of carbon emissions found in the institutionalization of the climate change; however, implementing such concept was an alien until the government climate significant investments. Government climate significant investments remained a challenge due to lack of awareness for providing the finances to the projects supporting mitigating the carbon emissions (Van Beurden et al., 2023). The past study reflects that 52% of European need awareness regarding GCSI, 40% of them require skills in investment planning and 35% stressed on climate neutrality. As a matter of fact, GCSI expedites economic development with the efficient use of allotting funds. External financing is an expedient to facilitate the quality of development and protection of the environment (Long et al., 2021). Increasing carbon emissions due to human activities, urbanization and urban transportation evoke the significance of the climate change for curtailing the carbon emissions. The past study shows role of emission trading scheme and carbon border adjustment mechanism in driving industrial decarbonization and GCSI; however, GCSI has not been linked as a mediating variable between renewable energy and carbon emissions (Hiçyılmaz and Karakaya, 2023). The European Union has been confronting to achieve the carbon neutrality yet, it has been looking for the carbon dioxide removal technologies where robust integration of such technologies are not found. Comprehensiveness of environmental policies in link with the feasibility and potential outcomes has been not analyzed (Tamme and Beck, 2021).

Government climate significant investments can play a crucial role in achieving the low carbon industries to reduce deleterious effects on the environment (Bai et al., 2022). It configures the structures of the industries for minimizing the urban carbon emissions. It can bring extra social capital into the environment. It affects significantly green technological innovation within industries (Yang et al., 2022). Technology related to carbon emissions can have a crucial impact on electric power sector and less on overall reduction of emission. Scholars also pacify that climate related financial assistance to mitigate the carbon emissions issues that is curbed verily as the allocation of resources (Xu et al., 2023). However, GCSI has been paid less attention though it can have positive impacts on reducing environmental pollution and biotechnologies can facilitate the climate resilient seeds to produce food and income adapted to carbon emissions effects (Lee et al., 2022). Therefore, we propose the following hypothesis:

H3. Based on the resources and legitimacy theory, renewable energy has negative mediation impact and help government climate significant investment to mitigate carbon emissions

2.5. Literature gap

The European countries as the champions of the sustainable development goals have been facing great pressure to achieve the carbon neutrality goals by 2050. Overall very few studies provide the mitigation strategies. The past study assessed the energy drought due to climate change that affects the European renewable energy generation from wind, solar, and hybrid wind-solar. There has been small studies on environmental policy stringency on carbon emissions in the context of European countries. The previous studies only looked into the effect of technology innovation, green finance, fiscal decentralization, and political risks in promoting the renewable energy. Such studies cover political determinants of renewable energy considering the federal and local government (Behera et al., 2024) that did not produce the desired results and the risks of the climate change still prevail severely. However, many previous studies have focused on using renewable energy sources for electricity generation to fight against the carbon emissions where other projects related to the economy and the households were not brought into consideration at the large scale like transportation and industries. Other challenges like carbon emissions are sky rocketing where the European nations commissions mandated to reduce greenhouse gases emissions by 55% and gain the carbon neutrality by 2050 (Pastore et al., 2022). The earlier studies analyzed the impact of policies on national energy and climate plans (Balode et al., 2021) and missed to see the stringency of the policies for suggested results.

To the same line of literature, government climate significant investments has not received attention from scholars yet, its relation to global environmental policies have attracted less to work on it. Previous studies investigate the several factors affecting the economies in milieu of investment, foreign trade, institutional quality, government consumption, human capital and inflation but they miss to see the combined impact of environmental policy stringency and government climate significant investments on CO2 carbon emissions mitigation. The past study find the significant impact of environmental policy stringency on trade diversification by reducing the carbon footprints (Dai and Du, 2023). Another study investigates that carbon emissions is influenced by such policies and the globalization whereas, the impact of renewable energy and industrialization have less investigated. Moreover, the past study also show that positive shock in environmental policy stringency impede trade that has undertaken the non-renewable energy consumption (Zhu et al., 2024). They augment the prices on commodities that increase pollution that can be reduced by the implementation of research and development on renewable energy sources. As a matter of fact, fossil fuels, governmental expenditures and taxation revenues can impede environmental progress and energy transition (Bashir et al., 2024). Also, GCSI can be boosted by introducing the stringent environmental policies through trade openness. But GCSI has not been covered in this link of environmental policy stringency and carbon emissions (Balsalobre-Lorente et al., 2023). Therefore, this study can provide the comprehensive relationship of environmental policy stringency and government climate significant investment on carbon emissions reduction through renewable energy as mediating associations.

3. Research design

3.1. Econometric model

Taking into account of pragmatic model designed by (Vermunt and Magidson, 2002) the study has utilized the D-GMM model for panel-unit root test with 352 observations. The empirical investigation is too in coherence with the unique developing tactics grounded on dynamic models. In our view, the factors affecting carbon emissions in the context of strict environmental policy, renewable energy and government climate significant investments analyzed through different models and the reckonable structure; therefore, allowing for highly convenient model with factor coefficients across sets with diverse performance.

For testing whether the evolution of these variables considered for D-GMM model influencing the carbon emissions considering time and the nations, the quantitative model is utilized by putting in use the logarithm of Eq. (1) and adding the time dimension. Dietz and Rosa (1994) has designed the following equation model for stochastic form with quantitative variables:

$$CE_i = \alpha EPS_i^{\beta_0} GCSI_i^{\beta_1} RE_i^{\beta_2} FDI_i^{\beta_3} UP_i^{\beta_4} GDP_i^{\beta_5} e_i \tag{1}$$

Where CE_i, EPS_i, $GCSI_i$, RE_i, FDI_i, UP_i, and GDP_i shows Carbon Emissions, environmental policy stringency, government climate significant investments, renewable energy, foreign direct investment, urban population, and GDP in Europe *i; α and β's* are parameters for evaluation, and e_i denotes the random error.

In order to assess the growth factors measured in the model bearings the availability of carbon emissions over period and across Europe. Therefore, we employed the pragmatic model by using natural logarithms of Eq. (1) and incorporating the time effect into the following equation:

$$\begin{aligned} lnCE_{it} &= \delta_i + \beta_0 lnEPS_{it} + \beta_1 lnGCSI_{it} + \beta_2 lnRE_{it} + \beta_3 lnFDI_{it} + \beta_4 lnUP_{it} \\ &\quad + \beta_5 lnGDP_{it} + \phi_t + \varepsilon_{it} \end{aligned} \tag{2}$$

Where CE, EPS, GCSI, RE, FDI, UP, and GDP are defined in above equation (1). The sub-index *i,* denotes Europe countries and *t* denotes time in an altered year. δ_i and ϕ_t show Europe and period fixed effects separately, and ε_{it} shows the error term. Natural logarithm is used for model derivation; the coefficients of the independent factors can be understood as elasticities. The time effects and ϕ_t well-thought-out proxy of all factors which can be mutual across Europe and varied over span of time.

In the context of above eq. (1), where CE, EPS, GCSI, RE, FDI, UP, and GDP are determined. The sub-index i, represents Europe, and t mentions diverse time period. δ_i and ϕ_t represent Europe and time fixed effects, in that order, while ε_{it} denotes the error term. The model is formulated using natural logarithms, allowing the coefficients of the independent factors to be understood as elasticities. The time effects and ϕ_t well-thought-out as a substitution of all factors which can be mutual across nations and change by the span time. Finally, we have adopted dynamic specification model that incorporates the past impact of carbon emissions on the present points. The amplified model is suggested by the following equation (3):

$$\begin{aligned} lCE_{it} &= \delta_i + \phi_t + \lambda lCE_{i,t-1} + \gamma_0 lEPS_{it} + \gamma_1 lGCSI_{it} + \gamma_2 lRE_{it} + \gamma_3 lFDI_{it} \\ &\quad + \gamma_4 lUP_{it} + \gamma_5 lGDP_{it} + \varepsilon_{it} \end{aligned} \tag{3}$$

The variables in eq. (3) are defined in eqs. (1) and (2), where i denotes the natural logarithms. eq. (3) captures the overall sample of all European utilizing panel data procedures suitable for dynamic models, including fixed effect instrumental, D-GMM method, and two-stage least square estimation. The model's specification might be unsuccessful to fit the data owing to misspecification, such as omitted covariates or possible correlation among the countries. To address these challenges, we employ a flexible estimation technique. Moreover, we explain for the likelihood that several parameters of the model may vary across unnoticed subsections.

To simplify the approach, we used the latent class (LC) model (Vermunt and Magidson, 2002), also recognized for finite mixture model. Due to the flexibility, the LC is being gradually exploited as a convenient, semi parameter method when the distributional shapes of the model are unknown (Alfò et al., 2008). This addition in the application assesses group structure in the data (Wedel and DeSarbo, 1995). The following equation that assumes carbon emissions, CE*it*, can be bunched into K groups.[1] We introduced a latent variable Z[2] which encapsulates k discrete standards like z1, …zk, with spreading P (Z = zk), $\prod_k, 0 \le \prod_k \le 1$, k = 1, …K, and $\sum_k \Pi_k = 1$. The likelihood compactness role is driven by the following equation:

$$f(CE_{it}) = \sum\nolimits_k \Pi_k f_k \left(lCE_{it} \middle| \beta_k, \alpha_k^2 \right) \tag{4}$$

Where $f_k(.)$ represents the conditional distribution of I_{it} within k-th latent class, and $\prod_k$ shows the former likelihood of module k. In this study, f(.) is a univariate Gaussian density, with a component specific vector denoted by $\theta_k = (\beta_k X, \alpha_k^2)$ to comprehensive the parameter vector equal to $\psi = (\Pi_1 \ldots, \Pi_K, \theta_1, \ldots, \theta_K)$. equation (4) explains the mixture typical linear regression model (DeSarbo and Cron, 1988).

Using this model, parameter approximation is justified by Expectation-Maximization (EM) algorithms (Dempster et al., 1977) within maximum likelihood perspective. Consequently, researchers introduced the following logarithm purpose that cannot be maximized directly.

$$\log L = \sum\nolimits_i \sum\nolimits_t \log \sum\nolimits_k \Pi_k f_k \left(lCE_{it} \middle| \beta_k, \alpha_k^2 \right) \tag{5}$$

The EM algorithm make the most of Eq. (5) with detail to ψ through a repetitive technique, which initially evaluates the posterior class likelihoods for each remark.

$$w_{ik} = \pi_k \Pi_t f_k \left(lCE_{it} \middle| \beta_k, \alpha_k^2 \right) \Big/ \left[\sum\nolimits_k \pi_k \Pi_t f_k \left(lCE_{it} \middle| \beta_k, \alpha_k^2 \right) \right] \tag{6}$$

It subsequently originates likelihoods as

$$\Pi_k = \Sigma_i w_{ik} / N \tag{7}$$

By optimizing the log likelihood for every factor individually, using the posterior likelihoods as weights

$$\text{Max} \sum\nolimits_i \sum\nolimits_t w_{ik} \log f_k \left(lCE_{it} \middle| \beta_k, \alpha_k^2 \right), w.r.t. \beta_k, \alpha_k^2 \tag{8}$$

These show the weighted amount through ordinary linear regression

[1] The selection of the number of latent classes (K) was based on a combination of statistical fit criteria and interpretive considerations. Specifically, we employed the Bayesian Information Criterion (BIC) and Akaike Information Criterion (AIC) to evaluate the fit of models with different values of K. The optimal value of K was selected as the one minimizing both BIC and AIC while ensuring interpretability of the resulting groups. Sensitivity analyses were conducted to assess the robustness of findings across varying values of K. These analyses indicated that while the choice of K influenced the granularity of subgroup classifications, the overall patterns of relationships remained consistent, providing confidence in the robustness of the chosen specification. For explanation on the implication of difference in the K values, see Appendix B.

[2] The latent variable Z represents unobserved heterogeneity within the dataset, allowing for the identification of distinct subpopulations. Through the latent class modeling framework, Z assigns each observation a probabilistic membership to one of K latent classes, enabling the estimation of class-specific parameters. This approach accounts for heterogeneity that is not directly observable but influences the relationships among variables. In this study, Z moderates the relationship between key independent variable(s) and dependent variable(s), providing insights into how structural differences within subgroups impact the overall findings.

model. Steps are performed recurrently until the log likelihood show variations by a randomly small value. To determine the optimal value for K, we obtained the model with suitable maximized log likelihood. If we achieve the logarithms for an assigned K, we can further continue assumes K=K+1 and ensue to estimate parameter for the number of components of this value. After we have used the reprimanded likelihood standards (like AIC or BIC) for comparison the likelihood ratio.

The above approach permits the classification of European countries based on posterior probabilities estimates w_{ik}, which explains possibly useful by-product of adopted technique.

As per the simple maximum posterior rule, the i-th Europe can be categorized in k-th constituent like $w_{ik} = \max(w_{i1}, \ldots w_{iK})$. It is very important to note that each factor is considered by homogenous values projected for latent effects. The dormant factors show the impacts of omitted covariates linked to the foundations.

$$\ln CE_{it} = \alpha_0 + \mu_i + \alpha_1 EPS_{it} + \sum C_{it} + \sum Year_{it} + \varepsilon_{it} \tag{9}$$

$$M_{1it} = \beta_0 + \mu_i + \beta_1 EPS_{it} + \sum C_{it} + \sum Year_{it} + \varepsilon_{it} \tag{10}$$

$$\ln CE_{it} = \alpha_0 + \mu_i + \alpha_1 GCSI_{it} + \sum C_{it} + \sum Year_{it} + \varepsilon_{it} \tag{11}$$

$$M_{2it} = \beta_0 + \mu_i + \beta_1 GCSI_{it} + \sum C_{it} + \sum Year_{it} + \varepsilon_{it} \tag{12}$$

$$\ln CE_{it} = \gamma_0 + \mu_i + \gamma_1 EPS_{it} + \gamma_2 GCSI_{it} + \gamma_3 M_{1it} + \gamma_4 M_{2it} + \sum C_{it} + \sum Year_{it} + \varepsilon_{it} \tag{13}$$

To explore the mechanism mediation model, specifically probing the mediating role of the GCSI and RE. $\alpha_0, \beta_0, and \gamma_0$ are intercept terms, μ_i is unobserved and ε_{it} is random disturbance term. Whereas $\alpha_1, \beta 1, and \gamma_1 - \gamma_4$ are coefficients represented by vectors. $\sum C_{it}$ represents the country effect, $\sum Year_{it}$ represent time effect. The present study formulates a mediation model and outlines the ensuing testing procedures following the guidelines of Baron and Kenny (1986) and Wu et al. (2020). First we have run eq. (9) and eq. (11) to evaluate the impact of environment policy stringency and government climate significant investments on carbon emissions. If the coefficient of α_1 is significant, it indicates EPS and GCSI have significant impact on carbon emission reductions, the next step proceeded, otherwise the analysis would be stopped. The next eq. (10) and eq. (12) are carried out to assess β_1 coefficient between EPS, GCSI and mediator. If the coefficients are significant, it indicates that EPS and GCSI have prominent impact on carbon emissions reduction. Finally eq. (13) is used to perform the regression model. The significance results of $\gamma_1, \gamma_2, \gamma_3, \gamma_4$ indicate partial mediation impacts and while significance only mediation values points to full mediation. Through mediation analysis, we have identified the direct, indirect, and total effects. This sequential approach ensures a systematic exploration of mediating effects, thereby enhancing the depth of our analytical insights.

Explaining the dynamic model, we can offer the noteworthy link structure between factual and seeming link (Aitkin and Alfò, 1998). In the previous studies, both present and future observations can be impacted by the past values that reason a considerable vary over period of time. Then the cases arise when the observations are measured from a different population (as mentioned in LC models). Finally, the static LC model can lead to misleading findings due to unobserved values but consistent heterogeneous can be understood due to strong successive dependency. Furthermore, Fig. 5 depicts the research conceptual framework of the study.

3.2. Research methods and data sources

The data for carbon emissions, renewable energy, foreign direct investment, urbanization, population and GDP are retrieved from World Bank Development Indicator (WDI), while the data for environmental policy stringency index, and government climate significant investment are obtained from the OECD website. The dataset covers European countries over the period of 2007–2022. Table 1 provides the detailed description of the variables. The multiple methods are used to ensure the accuracy, consistency and robustness of the results. For instance, the panel cointegration is used to check the long-run relationship, followed by the dynamic panel data estimation technique along with baseline

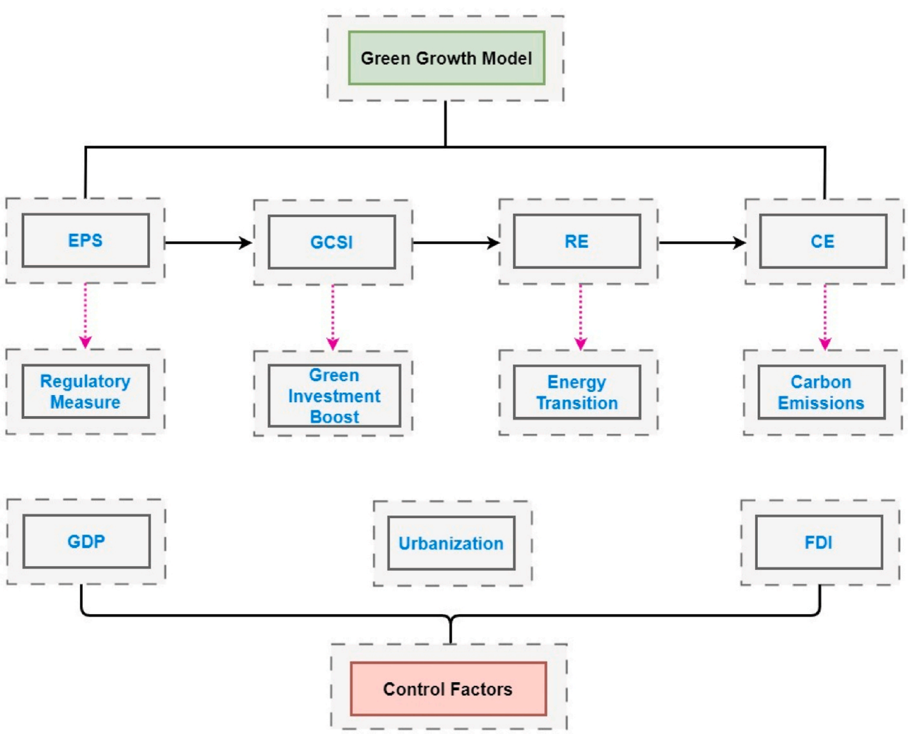

Fig. 5. Research conceptual framework.

Table 1
Description of the variables.

Parameters	Symbol	Measurement Unit	Source
Environmental Policy Stringency	EPS	Environmental Policy Stringency Index	OECD (2024)
Carbon Emissions	CE	CO2 emissions (metric tons per capita)	WDI (2024)
Climate Significant Investment	GCSI	Government's climate significant investment (US dollars PPP, million)	OECD (2024)
Renewable Energy	RE	Renewable Energy Consumption (TWh)	WDI (2024)
Foreign Direct Investment	FDI	Foreign direct investment, net inflows (BOP, current US$)	WDI (2024)
Urbanization	UP	Urban population	WDI (2024)
GDP	GDP	GDP (constant US$ 2015)	WDI (2024)

regression methods for direction and magnitude of the independent variables on the dependent variable. In the end, the mediation analysis is conducted for clear cut policy implications.

4. Results and discussion

The summary of descriptive statistics results is shown in Table 2. Through mean value, it can be seen from 2007 to 2022, the Carbon Emissions of explained variable, environmental policy stringency of explanatory variable, renewable energy and government climate significant investment of mediation variables show the upward trend. This shows the increased level of Carbon Emissions and environmental policy stringency in European countries during the period of 2007–2022. From the Kurtosis perspective, the data is normally distributed. From the skewness values, the Carbon Emissions is positive skewed and EPS, GCSI, RE, FDI, UP and GDP are negatively skewed that reflects these variables are asymmetric in nature. The study employs the multi models of panel techniques for co-integration and regression analysis to validate the high values of Kurtosis.

Before estimating the regression models, we test the stationarity of the data. If the data is not stationarity, the results would be reflecting spurious relationships. Three different panel based unit root tests are applied: Levin-Lin-Chu ADF (Levin et al., 2002), PP Fisher (Maddala and Wu, 1999); and Pedroni (1999) tests. All tests are examined for unit root, and results are reported in Table 3 and showing the null hypothesis is rejected. Furthermore, we have also used the Bartlett kernel test and variables are stationarity at 1% of significance level. Therefore, all tests' results are stationarity at the levels only few variables are stationary at first level and now we proceed with econometrics analysis.

Table 4 presents the pairwise correlation result for the variables included in the present study. The results reveal that Environmental Policy Stringency (EPS) is negatively correlated with carbon emissions (CE) at the 5% significance level. Similarly, both CE and EPS also indicate a correlation with all control variables. The correlation values between the independent and dependent variables and the control variables are below 0.80, indicating no multicollinearity issues in the

Table 3
Panel-unit root test.

Method	LLC	PPF	Pesaran-Shin	Bartlett kernel test
Variables				
$ln\ EPS_{it}$	−3.422***	5.629***	–	−6.192***
$\Delta ln\ EPS_{it}$	−10.751***	19.922***	–	
$lnCE_{it}$	−0.435	−1.101	2.376	−5.544***
$\Delta lnCE_{it}$	−10.000***	−38.411***	−9.023***	
$ln\ GCSI_{it}$	−2.324**	1.992**	−0.676	−6.337***
$\Delta ln\ GCSI_{it}$	−9.746***	30.243***	−9.023***	
$ln\ RE_{it}$	−5.214***	2.527***	−1.261	−6.259***
$\Delta ln\ RE_{it}$	−8.669***	39.887***	−8.949***	
$ln\ FDI_{it}$	−5.666***	20.534***	−7.105***	−10.230***
$\Delta ln\ FDI_{it}$	−21.146***	60.081***	−10.418***	
$ln\ UP_{it}$	−1.573*	10.970***	1.944	−5.793***
$\Delta ln\ UP_{it}$	−2.601***	1.900**	1.404	
$ln\ GDP_{it}$	3.509	−3.173	6.937	−20.347***
$\Delta ln\ GDP_{it}$	−15.789***	23.245***	−7.888***	

Note: Lags are chosen by the AIC. *** & ** shows the significance level at 1% & 5%. Bartlett kernel is used for LR variance, with an average of 1.00 lags chosen by the LLC method. The time trend is included in the test. Null Hypothesis of LLC H_0: Panels contain unit roots. Null hypotheses are rejected at 1% significance level.

model. To further validate this, we conducted a Variance Inflation Factor (VIF) test, which shown VIF values ranging from 1.07 to 10.45, with a mean value of 4.80. Hence, the results in Table 3 confirms that all variables have VIF values under the standard threshold of 10 (Kennedy, 2008), supporting that there is no evidence of multicollinearity in the model.

4.1. Hausman test

This study employs the Hausman test to determine whether a fixed or random effects model is more appropriate. The heteroscedasticity may be existed; we also examine the robust regression results. The following hypotheses are presented:

Null Hypothesis (H_0): The random effects model is not correlated with the explanatory variables.

Alternative Hypothesis (H_1): There is a correlation between the individual-specific effects and the explanatory variables.

Table 5 presents the results of the Hausman test, indicating a p-value <0.005 ($p = 0.000$). This leads to the rejection of the alternative hypothesis *(H_1)*. This implies strong statistical evidence that the random effects model is correlated with the explanatory variables. Consequently, in practical terms, we prefer a fixed effects model over a random effects model for our panel data set, specifically in the context of country-specific data.

In order to check the relationship among the variables using panel model, we employ Pedroni's cointegration and Kao's residual tests. The results are reported in Tables 6 and 7 respectively. In values of Pedroni's cointegration test, it shows that if the results of 7 test (four within dimension and three between dimensions) are significant, it reflects the existence of cointegration relationship among the variables. In Table 6, the five out of seven tests are statistically significant which means there is no cointegration relationship. While in the literature review, it

Table 2
Summary of descriptive statistics.

Variables	$lnCE_{it}$	$ln\ EPSI_{it}$	$ln\ GCSI_{it}$	$ln\ RE_{it}$	$ln\ FDI_{it}$	$ln\ UP_{it}$	$ln\ GDP_{it}$
Mean	1.911	0.929	7.538	4.210	19.971	15.813	26.423
Median	1.960	1.080	7.789	4.249	23.040	15.801	26.411
Maximum	3.142	1.591	10.214	6.467	27.322	17.991	28.921
Minimum	1.090	0.000	0.000	0.574	0.000	12.947	23.665
Std. Dev.	0.397	0.466	1.445	1.261	8.201	1.370	1.448
Skewness	0.392	−1.228	−0.492	−0.379	−1.924	−0.122	−0.068
Kurtosis	3.011	3.112	3.887	2.770	4.980	2.153	2.153
Obs.	352	352	352	352	352	352	352

Table 4
Pairwise correlation and VIF.

No.	Variables	1	2	3	4	5	6	7	VIF
1	CE	1.000							/
2	EPS	−0.146*	1.000						2.26
3	GSCI	0.012	0.481*	1.0000					2.69
4	RE	−0.277*	0.581*	0.714*	1.0000				3.18
5	GDP	−0.0713	0.727*	0.741*	0.746*	1.0000			9.16
6	UP	−0.221*	0.684*	0.764*	0.810*	0.934*	1.0000		10.45
7	FDI	−0.011	0.001	0.134*	0.121*	0.151*	0.183*	1.0000	1.07
Mean VIF									**4.80**

Note: Own calculation "*" indicates significance at 5% level.

Table 5
Correlated random effects – Hausman test.

Test Summary	Chi-Sq Statistic	Chi-Sq. (d.f)	Probability	Recommend Model
Cross-section random	140.32***	5	0.000	FE

Note: *** indicates significance level at 1%.

Table 6
Pedroni's Cointegration test.

Within dimension	Test Statistics	Between Dimension	Test Statistics
Panel V-Statistic	−1.640	Group RHO-Statistic	5.896***
Panel RHO-Statistic	−1.696	Group PP-Statistic	−6.793***
Panel PP-Statistic	−2.547***	Group ADF-Statistic	−2.963***
Panel ADF-Statistic	−2.286***	–	–

Note: All test statistics are distributed N (0, 1, 2), under a null H0 of no cointegration. *** shows the significance level at 1% level. Lags are selected based on SIC.

Table 7
Kao's residual cointegration test.

Test	Test Statistic	Prob.
Modified Dickey–Fuller t	3.294	0.001***
Dickey–Fuller t	6.523	0.000***
Augmented Dickey–Fuller t	−0.031	0.488
Unadjusted modified Dickey–Fuller t	1.039	0.149
Unadjusted Dickey–Fuller t	3.751	0.000***

Note: (1) 1.86 lags are selected based on AIC. (2) Newey-West fixed bandwidth and Bartlett kernel method used to estimate covariance matrix of the residuals. (3) ***, **, and * shows the significance level at 1%, 5%, and 10% level respectively (4) Null hypothesis: No cointegration.

predicts that if one test is significant the other will be insignificant, this study examines the most commonly used test. We have used another Kao's residual cointegration test and results are reported in Table 7. Table 6 shows that all tests are statistically significant and ensure the cointegration relationship among the variables except unadjusted modified Dicky-Fuller and Augmented Dickey–Fuller tests. The results show that variables affect each other in long run. In this study, Carbon Emissions, environmental policy stringency, government climate significant investment, renewable energy, foreign direct investment, urbanization and GDP output influence each other in long term. Whereas the cointegration test does not disclose the direction effect of one variable to other. Thus, we use regression analysis.

For regression analysis, we have used fixed effect, and GMM models for panel data techniques. Later we have used the two stage least square method to avoid the endogeneity problem in the panel data. The findings based on the panel regression models are most appropriate and valid for the policy design. This study uses the Hausman test and conclude that fixed effect model is better and best fit for the analysis.

In order to check the promoting effect of environmental policy stringency on Carbon Emissions, this study uses the fixed effect model at first for regression of all sample data. The results are presented in Table 8. The results show that estimated coefficients are statistical negative significant at 1% statistical level which indicates that environmental policy stringency reduces the Carbon Emissions in European countries, therefore, promoting the environmental policy stringency stimulates government climate significant investment and renewable energy transformation. In the fixed effect model, the results of M2 show the controlled variables are also significant and have a negative impact on Carbon Emissions. The foreign direct investment, urbanization, and GDP have negatively significant impact which means if the urbanization, FDI and GDP increase, the Carbon Emissions decreases due to best use of natural resources and aware for depletion of limited resources. In the fixed effect model, the adjusted R-square shows the strong goodness of fit and high explanatory for the results.

Furthermore, to check the accuracy of the variables and process, we employ the Differential Generalized Movement Method (D-GMM). The estimated results of differential GMM has passed the second order sequence correlation test (AR (2)) which reflects that second order does not pass the correlation sequence. The model has also passed the Sargan Hansen test which shows the rationality of selecting D-GMM model and confirms the validity of instrumental variables. The test prove that D-GMM estimations are consistent and instrumental variables are reasonable.

According to the results of the differential GMM estimation reported in Table 8, the environmental policies stringency has a negative impact on Carbon Emissions. The condition of D-GMM are fulfilled through AR (1), AR (2) Sargan, and Hansen and Wald chi square tests. The results of D-GMM in M3 is tested without effect of controlled variables. The D-GMM results also confirms that environmental policy stringency has a significant and negative impact on mitigation of Carbon Emissions. Whereas, in M4 of D-GMM, the controlled variables are tested to confirm the results whether these variables have impact on Carbon Emissions. The results reveal statistical significant at 1% and 10% significance level of urbanization and FDI. The GDP has not a significant impact that shows if the GDP increases or decreases, it has not impact on Carbon Emissions. The urbanization has a negative relationship with Carbon Emissions, the results are consistent with the findings of Al-Mulali et al. (2013). The urbanization potential leads to industrial and more use of renewable energy. These essentials are harmful for the environmental policy stringency and renewable energy Sun et al. (2022). Therefore, the hypothesis H1 is proved and accepted which states that environmental policy stringency reduces the Carbon Emissions and have a significant negative impact in European economies.

4.2. *Mitigating endogeneity concerns*

4.2.1. *2SLS instrumental variables*

This study has employed the two stage least square (2SLS) method to examine the endogeneity issue in the empirical estimation. In M5 to M7 of Table 8, we have taken instrumental variables urban population without lag period, environmental policy stringency, renewable energy,

Table 8
Regression results for EU-22 economies.

Variables	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10
	FE-1	FE-2	D-GMM	D-GMM	2SLS-IV	2SLS-IV	2SLS-IV	2SLS-IV	2SLS-IV	2SLS-IV
					(CE)	*(CE)*	*(CE)*	*RE)*	*(RE)*	*(GDP)*
$lnCE_{it(-1)}$	0.456*** 4.290	0.453*** 5.770	0.313*** 3.250	0.412*** 8.800	–	–	–	–	–	–
$ln\ EPSI_{it}$	−0.762*** −7.930	−0.456*** −6.210	−0.893*** −6.040	−0.242*** −2.290	−0.042* −1.666	0.134 0.726	−0.056* −1.959	0.026 0.045	4.608 0.546	0.105*** 3.134
$ln\ FDI_{it}$	–	−0.001* −1.930	–	−0.001* −1.920	–	0.089 1.037	–	–	–	–
$ln\ UP_{it}$	–	−2.135*** −12.790	–	−2.841*** −3.940	–	–	–	–	–	0.848*** 13.587
$ln\ GDP_{it}$	–	−0.169*** −2.910	–	−0.261 −1.170	0.069* 1.795	−0.144 −0.583	0.123** 2.144	0.481*** 4.684	−16.334 −0.530	–
$lnRE_{it}$	–	–	–	–	−0.113*** −2.787	−0.126 −1.483	−0.111** −2.580	–	–	0.101* 1.861
$ln\ GCSI_{it}$	–	–	–	–	–	–	−0.056 −1.201	0.275*** 3.046	17.454 0.554	0.071 1.214
Time Dummy	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Sectional Dummy	Yes	Yes	–	–	–	–	–	–	–	–
Adj. R^2	0.226	0.583	–	–	–	–	–	–	–	–
AB Test AR (1)	–	–	0.384	0.018	–	–	–	–	–	–
AB Test AR (2)	–	–	0.159	0.375	–	–	–	–	–	–
Sargan Test	–	–	0.000	0.000	–	–	–	–	–	–
Hansen Test	–	–	1.000	1.000	–	–	–	–	–	–
Wald Chi square	–	–	41.73	265.34	–	–	–	–	–	–

1***, **, * show the significance level at 1%, 5% and 10% respectively.
2First column of FE-1 represents results without control variables while FE-2 shows results with control variables.
3White period (period correlation) instrument weighting matrix method used for D-GMM Estimation.
4All values are converted into logarithmic.
5Null hypothesis of "No second order autocorrelation" tested.
6Null hypothesis of "Instruments are valid instruments" tested.

foreign direct investment, and government climate significant investment with lag effect. The selection of instrumental variables from M5-M7 is valid and explanatory variable is significant and have negative impact with carbon emissions. However, the foreign direct investment is not valid as an instrumental variable in M5-M7 models of Table 8. Moreover, from M8-M9 of Table 8, we have changed response variable as a renewable energy and used GCSI and FDI as instrumental variables. In M8 of Table 8, the GCSI is valid instrument but FDI is not a valid instrument variable. In M10 of Table 8, we have again changed the response variable as a GDP and placed urban population, environmental policy stringency, renewable energy and GCSI with 1 lag period, all variables are valid instruments and explanatory variable is positively significant with carbon emissions except GCSI. The study shows that taking lags of the instrument variables up to one period to explore the endogeneity issue is valid and have a significant effect on explanatory variable. The study shows that the more reliable and efficient models are M5 and M8 of Table 8, the results reveal that renewable energy and GDP as an instrument variables are valid and environmental policy stringency statistically negatively significant at 1% with carbon emissions and have same results as mentioned in M2 and M4 regression.

In this study, the fixed effect model was selected based on the Hausman test (Yirong, 2022), which provides more appropriate and efficient estimated coefficients. Notably, the regression result from the fixed effect model indicate that environmental policy stringency reduces carbon emission by 0.456 percent. Furthermore, prior literature evidences that Differential GMM can analyze the long-term relationship between independent and dependent variables while taking into consideration the issue of endogeneity and heteroscedasticity in panel data (Bhattacharya et al., 2017). Hence, we employ D-GMM model to find better estimates for policy recommendation.

The result from the D-GMM model indicates that a 1 percent increase in environmental policy stringency reduces 0.242 percent of carbon emissions. This finding is congruous with the findings of Wolde-Rufael and Weldemeskel (2020), who evidence that EPS decreases pollution (CE). Similar results are indicated by Ahmed (2020) for OECD countries, Sezgin et al. (2021) for the G7, Yirong (2022) for high-polluting economies (e.g. Russia, USA, China, Japan, and India), and Li et al. (2023) for BRICS economies.

4.3. Processing of cross-sectional dependence test

We conducted the cross-sectional dependence (CSD) test for all variables in the model. Table 9 presents the results, indicating a 1% significance level in the interdependence among countries, as evidenced by the CSD test results. Consequently, we rejected the null hypothesis (H0) of no cross-sectional dependence among Carbon Emissions, environmental policy stringency, renewable energy, government climate significant investment, foreign direct investment, urban population, and gross domestic product. Due to the presence of CSD, this study employs the second-generation panel test procedure.

An environmental stringency policy can protect the natural environment and mitigate Carbon Emissions. Academicians often study environmental policies to promote future environmental protection. Increased greenhouse gas emissions or economic pressures may lead to greater investment in eco-technology. Once industries implement green technology, energy efficiency will improve, and the environment will be

Table 9
Cross-sectional dependence (CSD).

Series	CD-test	P-value	Corr.	Abs(corr.)
$lnCE_{it}$	41.028***	0.000	0.67	0.71
$ln\ EPSI_{it}$	15.72***	0.000	0.26	0.35
$lnRE_{it}$	45.405***	0.000	0.75	0.75
$lnGCSI_{it}$	6.126***	0.000	0.10	0.48
$ln\ FDI_{it}$	3.627***	0.000	0.06	0.22
$ln\ UP_{it}$	24.789***	0.000	0.41	0.83
$ln\ GDP_{it}$	42.151***	0.000	0.69	0.78

Note: *** shows the 1% significance level under null hypothesis of cross section independence CD ∼ N (0, 1).

safeguarded. This study examines the emissions reduction market from both the suppliers and consumer perspectives. To provide a better understanding of the cross-sectional dependence test, the detailed results are reported in Table 9.

4.4. Mediation analysis

Following the regression analysis, the study scrutinizes the direct and indirect impacts of stringent environmental regulations on carbon mitigation strategies. Specifically, the Government's Climate Significant Investment (GCSI) is posited as a mediator between environmental regulations and carbon emissions, while renewable energy development is postulated as a mediator between GCSI and carbon emissions. The graphical illustration of the models is given by Fig. 6.

The results, delineated in Table 10, column (1), reveal that both Environmental Policy Stringency (EPS) and GCSI significantly mitigate carbon emissions. Similarly, findings in column (II) demonstrate that EPS exerts a statistically significant and positive influence on GCSI. The Sobel test results, detailed in Tables 11 and 13, elucidate the following:

1. The relationship between the independent variable and the mediator.
2. The relationship between the mediator and the dependent variable.
3. The direct relationship between the explanatory and response variables.

All these relationships are statistically significant, albeit the indirect effect exhibits marginal statistical significance. This denotes partial mediation at a 10% level of statistical significance. Additionally, the RIT results indicate that 35% of the effect of EPS on carbon mitigation is mediated through GCSI. The RID results suggest that the mediation effect is 0.3 times the magnitude of the direct effect of EPS on carbon mitigation. Consequently, GCSI partially mediates the relationship between EPS and carbon mitigation.

Meanwhile, renewable energy demonstrates a statistically significant mediating effect between GCSI and carbon mitigation, thereby corroborating the indirect influence of GCSI on carbon mitigation via renewable energy adoption. For instance, the coefficients in column (III) of Table 10 reveal a substantial positive impact, indicating that GCSI fosters the adoption of renewable energy, which in turn results in significant reductions in carbon emissions.

To substantiate the mediation effect, we estimated the combined impact of GCSI and renewable energy within the same model. Employing the approach delineated by Baron, Kenny, Zhao, Lynch, and Chen, we observe that GCSI significantly enhances renewable energy adoption, as evidenced by the results in column (IV) of Table 10, affirming statistical significance at the 1% level.

The results, reported in Table 10, column (III), indicate that GCSI is significant with a direct effect. Additionally, Table 12 demonstrates that all steps represent significant effects. The RIT results reveal that the relationship between GCSI and carbon emissions reduction is 33.5% mediated by renewable energy. Furthermore, the RID results elucidate that the relationship between the regressor and the response variable is 1.0 times as large as the direct effect of GCSI on carbon emissions reduction. This substantiates the high mediation impact of GCSI and

Table 10
Mechanism test of mediation model.

Variable	(CE)	(GCSI)	(CE)	(RE)
Structural	I	II	III	IV
$lnGCSI_{it}$	0.029*	–	–	–
	1.79			
$ln\ RE_{it}$	–	–	−0.091***	–
			−4.60	
$ln\ EPS_{it}$	−0.168***	1.491***	0.019	1.573***
	−3.30	10.28	0.36	13.39
Constant	1.845***	6.153***	2.278***	2.748***
	16.56	40.82	32.12	22.52
Time Dummy	Yes	Yes	Yes	Yes
Sectional Dummy	Yes	Yes	Yes	Yes
Log likelihood Max	−980.718		−897.816	

Note: ***, **, * show the significance level at 1%, 5% and 10% respectively. Values below coefficients are t-statistics.

Table 11
Testing indirect effect.

Estimates	RE	GCSI
	Sobel test	Sobel test
Indirect effect	−0.144	0.044
Std Err.	0.033	0.025
z-value	−4.354	1.766
p-value	0.000	0.077
Conf. Interval	−0.208 to −0.079	−0.005 to 0.093

Table 12
Baron, Kenny, Zhao, Lynch & Chen's approach to testing mediation.

Paths	Renewable energy	
	Beta	P-value
Step 1 lnRE:lnEPS (X - > M)	1.573	0.000
Step 2 lnCE:lnRE (M - > Y)	0.091	0.000
Step 3 lnCE:lnEPS (X - > Y)	0.019	0.722
RIT	1.154	
RID	7.510	

Note: Step 1 and 2 are significant at 1% whereas step3 is insignificant. Thus there is a full mediation.

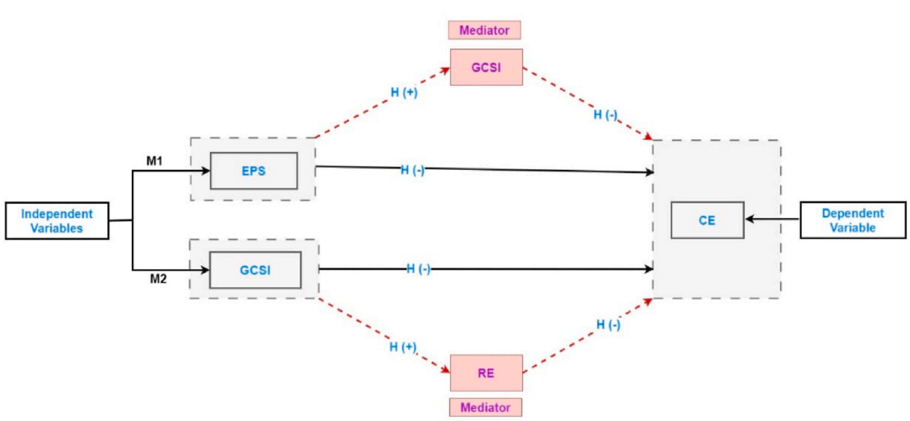

Fig. 6. Graphical illustration of Mediation Models.

Table 13
Baron, Kenny, Zhao, Lynch & Chen's approach to testing mediation.

Paths	GCSI	
	Beta	P-value
Step 1 lnGCSI:lnEPS (X - > M)	1.491	0.000
Step 2 lnCE:lnGCSI (M - > Y)	0.029	0.073
Step 3 lnCE:lnEPS (X - > Y)	−0.168	0.001
RIT	0.353	
RID	0.261	

Note: Step 1 and 3 are significant at 1% whereas step2 is significant at 10%. Thus there is a partial mediation.

renewable energy in aiding European countries to reduce carbon emissions. Table 11 provides a summary of the mediation effects. Consequently, the results corroborate Hypotheses 2 and 3. Detailed mediation results are provided in Tables 10–13.

The findings of the mediation analysis complement the regression analysis in a way that GCSI remains a critical factor of policy instrument aimed at mitigating the carbon dioxide through clean energy transition. In other words, the environmental regulations with a potential to boost GCSI result in faster renewable energy transition which in return reduces carbon footprints. Thus, countries with higher GCSI are more likely to achieve emissions reduction targets than those with less or no GCSI. These results are consistent with and supported by previous research (Saqib and Dincă, 2024; Oyewo et al., 2024; Dechezleprêtre et al., 2023; Barra and Falcone, 2024a,b). The summary of the mediation models with numerical values is given in Fig. 7.

5. Conclusions and policy implications

Despite Europe's global preeminence in developing and enforcing environmental regulatory frameworks and achieving climate change targets, a burgeoning discourse has emerged regarding the heterogeneity across European nations. This debate focuses on whether this variance pertains to the stringency of environmental policies or their efficacy in fulfilling climate commitments. This study pioneers an examination of the impact of environmental regulations through the lens of Government's Climate Significant Investment (GCSI) and the transition to renewable energy on carbon mitigation efforts within the EU-22. Given the low foreign direct investment (FDI) in these countries, the study incorporates FDI, GDP, and urbanization as control variables. Employing dynamic panel data estimation techniques for regression analysis, the study subsequently utilizes Structural Equation Modeling (SEM) for mediation analysis.

The results show that stricter environmental regulations help mitigate carbon emissions. However, the effectiveness of these regulations is significantly influenced by GCSI, while renewables mediate the impact of GCSI on carbon mitigation. Since GCSI complements environmental regulations and renewable energy complements GCSI, these factors emerge as key indicators of effective environmental regulations. Now, in the light the revised 'Renewable Energy Directive' under the 'European Green Deal', which has increased the EU's binding renewable energy target to at least 42.5% by 2030 and its aspirational goal of 45%, the study findings suggest that reducing GCSI gap across EU-22 nations can help to narrow the clean energy transition gap, thereby reducing environmental performance disparity as well.

Europe's ambition to become a climate-neutral continent by 2050 relies heavily on accelerating clean energy transitions across sectors like power generation, industry, buildings, and transport (Fetting, 2020). However, existing gaps in meeting these targets—such as slow deployment rates, regulatory delays, and insufficient integration of renewables into energy systems—pose significant obstacles. The study's findings suggest that stringent environmental regulations play an indirect yet crucial role in promoting carbon mitigation through GCSI, which acts as a catalyst for developing renewable energy infrastructure. By addressing regulatory bottlenecks and enhancing GCSI, the EU can significantly reduce its dependency on fossil fuels, thereby aligning with the 'REPowerEU' plan's goal of diversifying energy supplies and diminishing reliance on Russian energy sources (European Commission, 2023).

Economic consequences of EU legislation on environmental governance is a common concern among EU lagging regions. While examining the economic repercussions of stringent environmental policies indicates that they do not hinder economic growth. In fact, renewable energy contributes positively to economic growth, albeit inelastic. Urbanization in the EU-22 also fosters economic growth, though it concurrently exacerbates carbon emissions. Nonetheless, ample investment in renewable energy offsets the emissions in the long run. The computed estimates are mostly positive and statistically significant but predominantly inelastic, highlighting a delayed return on policies in terms of economic costs while maintaining steady environmental benefits. This suggests that while some EU nations have achieved significant green growth milestones, there remains substantial progress to be made collectively. To fill these policy gaps, the study recommends that the EU intensifies its efforts to mobilize GCSI and FDI, particularly in countries that are currently underperforming in their renewable energy transition. Enhancing the integration of renewable energy in sectors beyond electricity—like transport and industry—remains a critical need for achieving a cohesive approach to the EU's overarching climate objectives. This strategy will ensure that environmental and economic goals are mutually reinforcing, creating a sustainable pathway for long-term growth and carbon neutrality. These recommendations also corroborate with "Leaders' Declaration on a Global Climate Finance Framework" at COP28 which reiterate the global climate finance gap. The recent COP29 pledge of $300 billion annually by 2035 provides a transformative opportunity to bridge the renewable energy transition gap in developing regions within the EU, unlocking critical financial flows to drive sustainable progress.

In nutshell, realizing the European Green Deal's vision demands a unified implementation strategy that leverages green innovations, substantial investments, and adaptive yet stringent regulatory frameworks to accelerate the energy transition in lagging regions. Bridging the identified gaps in policy execution is essential for the EU to achieve its ambitious climate goals while ensuring socio-economic stability across all member states.

Furthermore, for regulators, investors, firms, and policymakers, this study highlights key policy insights for reducing carbon consumption and fostering green transitions. Renewable energy and GCSI have proven critical in mitigating emissions. Regulators can enhance these impacts by facilitating access to capital for green firms, accelerating clean technology investments. The growing demand for renewable energy, driven by stringent environmental policies, presents lucrative opportunities for investors in green and sustainability bonds, offering substantial financial and environmental returns. Stricter policies

Fig. 7. Direct and Indirect Coefficient values.

incentivize renewable energy adoption, urging firms to prioritize green technologies and utilize corporate green bonds to secure funding and maintain competitiveness. To achieve net-zero goals by 2050, policymakers must combine regulations, escalating carbon penalties, and R&D investments to reduce renewable energy costs and ensure equitable green transitions.

6. Future research

This study presents two suggestions for future research. First, amidst data limitation this study has been conducted in only European economies. Hence, future researcher could explore this mechanism in a detail in other developed and developing countries. Furthermore, additional factors should be taken into consideration when distinguishing between countries and regions, along with distinct level of economic development.

CRediT authorship contribution statement

Abdul Khalique: Writing – original draft, Visualization, Investigation, Formal analysis, Conceptualization. **Yichen Wang:** Writing – original draft, Software, Resources, Investigation, Conceptualization. **Khalid Ahmed:** Writing – original draft, Validation, Supervision, Software, Methodology, Formal analysis, Data curation.

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.

Appendix A. List of countries

1. Austria
2. Belgium
3. Czech Republic
4. Denmark
5. Estonia
6. Finland
7. France
8. Germany
9. Greece
10. Hungary
11. Ireland
12. Italy
13. Latvia
14. Lithuania
15. Luxembourg
16. Netherlands
17. Poland
18. Portugal
19. Slovenia
20. Spain
21. Sweden
22. United Kingdom

Appendix B. Implications of Different Values of K

To evaluate the implications of different values of K, sensitivity analyses were performed by varying K from 2 to 5. These analyses revealed that increasing K led to a finer segmentation of the sample, with more nuanced subgroup-specific relationships emerging. However, beyond $K = 5$, additional classes provided diminishing returns in terms of interpretability and model stability. The findings indicate that the choice of K influences the granularity of subgroup insights but does not alter the overarching trends or key conclusions, ensuring the robustness of the study's main contributions.

Data availability

Data will be made available on request.

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