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Climate governance and carbon risk in the global energy sector: Insights into corporate environmental initiatives

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ABSTRACT

This study examines the influence of sustainable governance, specifically climate governance, on carbon risk within the global energy sector. Additionally, we investigate the role of eco-innovation as a mediating factor in this relationship. By analyzing a dataset comprising 13,376 publicly listed energy companies from 91 different countries and employing Baron and Kenny's (1986) four-step mediation model, our research shows that improved climate governance mechanisms result in decreased carbon emissions from energy firms. This reduction can be primarily attributed to their increased participation in eco-innovation initiatives. Furthermore, these main findings are more pronounced in companies with robust environmental, social, and governance (ESG) practices. Our results also reveal various firm-level and country-level characteristics that moderate our identified relationship. Moreover, our results remain consistent even after addressing potential concerns related to endogeneity and sample selection bias. This research provides valuable insights for policymakers and managers who seek to mitigate carbon emissions within the global energy sector while fostering environmentally responsible practices to combat the impacts of climate change.

1. Introduction

The global energy industry is at the forefront of addressing urgent issues related to climate change, carbon risk, and environmental sustainability (Rao et al., 2023). In a world increasingly confronted by the escalating consequences of rising greenhouse gas emissions, businesses face significant pressure from diverse stakeholders, including the global community, management, consumers, media, suppliers, and professionals (Chithambo et al., 2022). All of these stakeholders demand greater accountability for businesses' contributions to climate change impacts (see Albitar et al., 2023; Bui et al., 2020). The energy firms are particularly encountering formidable challenges from rising demand and the urgent call for a transition to renewable energy sources, fostering a sustainable global environment. Therefore, the interconnection between climate governance, co-innovation, and carbon risk within the energy sector has garnered heightened scrutiny, particularly as numerous countries commit to reducing their reliance on fossil fuels (Rao et al., 2023; Taghizadeh-Hesary et al., 2021).

Notably, the 2015 (Paris: COP21[1]) and 2021 (Glasgow: COP26[2]) United Nations (UN) Climate Change Conference stands out among these commitments, encompassing a wide range of pledges made by nations concerning emissions reduction, renewable energy targets, energy efficiency, innovation, and technology transfer (Albitar et al., 2023). These agreements play a pivotal role in driving transformative changes within countries, regulatory frameworks, and corporate practices, compelling them to embrace new commitments and shoulder responsibility for their social and environmental impact (Bui et al., 2020). These commitments gained even greater prominence following the latest 2023 UN Climate Change Conference (Dubai: COP28), during which countries reached a historic consensus on the imperative to transition away from fossil fuels within their energy systems for the first time. Remarkably, groups including the United States, European nations, and

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[1] See https://www.un.org/sustainabledevelopment/cop21/
[2] see https://www.un.org/en/climatechange/cop26

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others highly susceptible to the effects of climate change advocated for even more ambitious commitments, pushing for a complete phase-out of fossil fuels.[3]

Therefore, comprehending the intricate linkage between climate governance and carbon risk within the global energy sector while considering the mediating influence of eco-innovation holds the potential to make substantial contributions to policymakers and corporate leaders. Note that while climate risk, which includes both physical risks and transition risks,[4] pertains to the broader impacts of climate change on the business environment (as discussed by Rao et al., 2023), carbon risk is a more specific concept that focuses on the measurement and management of carbon emissions levels (see Bolton and Kacperczyk, 2021; Bauer et al., 2022). Carbon risk and carbon premium are also distinct concepts within the realm of financial markets. The former represents the threshold of carbon emissions a firm can produce, whereas the latter pertains to the expected higher returns one can obtain when holding additional climate risk, as explained by Bauer et al. (2022).

Several vital factors drive our investigation into the carbon risk associated with energy-related firms. Firstly, the energy sector is significantly intertwined with carbon emissions, making it highly susceptible to their impacts. It is profoundly affected by Environmental, Social, and Governance (ESG) regulations and the commitments outlined in the COP21 agreement (Ramírez-Orellana et al., 2023). Second, energy firms are expected to drive eco-innovation within transitioning economies, facilitating the shift from conventional energy sources to renewable and environmentally friendly alternatives (Xu et al., 2023). Given these considerations, understanding the interplay between eco-innovation, climate governance, and carbon risk is academically valuable and highly practical.

With the related concern, the existing literature primarily focuses on examining three key relationships: (i) climate governance and carbon risk, (ii) climate governance and eco-innovation, and (iii) eco-innovation and carbon risk. The first research branch on climate governance and carbon risk presents conflicting views. Berrone and Gomez-Mejia (2009) and Orazalin et al. (2023) suggest that explicit environmental policies and committees may symbolize stakeholder legitimacy rather than yield more significant rewards for eco-strategies. In contrast, Bui et al. (2020), Albitar et al. (2023), and Cordova et al. (2021) provide robust evidence supporting the positive impact of climate governance on environmental performance, with Oyewo (2023) finding a positive relationship between board independence, ESG-based compensation, and carbon emissions. The second branch, addressing corporate governance and eco-innovation, remains uncertain about the influence of corporate governance in organizations pursuing eco-innovation. Mixed results from earlier research suggest that higher board independence or gender diversity can lead to carbon reduction initiatives (Haque, 2017). Zaman et al. (2023) highlight the positive effects of diversity on corporate eco-innovation, while Albitar et al. (2023) suggest a positive link between climate governance and commitment to addressing climate change. Focusing on the relationship between eco-innovation and carbon risk, the third branch reveals varied perspectives. Despite some studies indicating an adverse long-term effect of eco-innovation on carbon emissions (Fethi and Rahuma, 2019), others propose integrating natural standards into patents for sustainable innovations (Ganda, 2019), emphasizing the crucial role of eco-innovation and climate governance in addressing carbon emissions and advancing sustainable development agendas. However, the connection between climate change and carbon risk concerning eco-innovation remains underexplored. Consequently, our study aims to address this gap by examining the impact of sustainable governance (focusing on climate governance) on carbon risk within the global energy sector and investigating the mediating role of eco-innovation within this framework.

Underlying a combination of multiple theories, including legitimacy theory (Suchman, 1995), stakeholder theory (Freeman, 2010), and resource-based theory, our study uses a global sample encompassing 13,376 publicly listed energy companies across 91 countries for a period from 2000 to 2022. Applying Baron and Kenny (1986) four-step mediation model, we find the following results: (i) enhanced climate governance mechanisms are associated with reduced carbon emissions; (ii) climate governance leads to a higher level of eco-innovation activities; (iii) eco-innovation engagement is related to lower carbon emissions; and (iv) the better climate governance mechanisms are more likely to reduce carbon emissions through their higher engagement in eco-innovation activities. Extended tests reveal that our primary findings toward the mediating role of eco-innovation on the association between climate governance and carbon emissions are more pronounced in companies that maintain strong environmental, social, and governance practices. Our results also uncover firm- and country-level characteristics that moderate the observed relationship. Our findings remain robust even after addressing potential concerns related to endogeneity and sample selection bias.

Our study makes significant contributions to both literature and practice. Firstly, we establish a noteworthy association between climate governance and carbon risk mitigation in global energy firms. Furthermore, we identify eco-innovation as a mediating factor that facilitates the influence of climate governance on carbon risk. In other words, eco-innovation acts as the conduit through which climate governance affects carbon risk, underscoring the efficiency and effectiveness of energy firms' climate governance efforts in reducing carbon risk. These findings enrich the existing body of knowledge on climate risks, sustainable governance, and eco-innovation, particularly emphasizing the pivotal role of climate governance in the energy sector in mitigating climate-related risks (Bai et al., 2023; Bui et al., 2020).

Additionally, our study extends the prior research that examines the impact of climate governance on carbon risk. For instance, Xu et al. (2020) identify four potential pathways through which eco-innovation can affect carbon emission performance, including influences from energy consumption structure, industrial structure, urbanization, and foreign direct investment (FDI). Our study delves deeper into this subject by elucidating the underlying mechanisms. It elucidates how climate governance leads to a reduction in carbon risk, highlighting the mediating role of eco-innovation. This contribution enhances our understanding of the role of eco-innovation, revealing it as a mediating factor that amplifies the impact of climate governance on carbon risk.

Finally, from a practical standpoint, our study emphasizes the pivotal role of eco-innovation in mediating the relationship between climate governance and carbon risk. Previous studies primarily focused on the direct links between climate governance and carbon risk or between eco-innovation and carbon risk (Albitar et al., 2023; Bui et al., 2020). However, to the best of our knowledge, our study is the first to uncover the intricate interplay among these three elements: eco-innovation, climate governance, and carbon risk. Our findings also underscore the close relationship between ESG performance and climate governance, suggesting that robust ESG performance can positively incentivize carbon emission reduction. Consequently, our research provides valuable insights for policymakers and businesses, informing them about the energy industry's potential to align with climate governance policies and programs, thereby mitigating carbon risk.

The rest of our paper is structured as follows. The next section presents a literature review, theories and hypotheses. Section 3 discusses the data and research methodology. Section 4 presents the main empirical results, which are followed by additional tests and robustness

[3] see https://unfccc.int/cop28

[4] Specifically, physical risks refer to the events caused by climate change, hurricanes, flooding, and heat waves, for instance. In contrast, transition risks refer to the changes in government policy, technologies, or taxation to control carbon-intensive assets that result in potential losses in business because of the connectedness in the financial system.

checks in Section 5. Section 6 concludes the paper.

2. Literature review

2.1. Climate governance and carbon risks

Corporate governance mechanisms are fundamental concepts that help us comprehend how organizations handle their operations, risks, and responsibilities (Ali et al., 2023). They play a crucial role in overseeing a company's management of environmental and climate-related risks, as well as its involvement in carbon-related initiatives (Peters and Romi, 2014). In the context of climate change and environmental challenges, there has been a shift toward a climate governance approach, departing from traditional governance.[5] This approach has emerged as a distinct subset focusing on how organizations address climate-related risks. However, the role of climate governance in managing carbon risk is academically under-explored. Prior studies show that climate policies positively impact the overall factor productivity of energy firms, and this effect tends to persist over time. However, the benefits of implementing renewable energy policies, which include increased productivity, can be outweighed by their impacts on resource allocation efficiency and technological innovation (Zhang and Kong, 2022). Wen et al. (2021) indicate that formal manufacturers significantly reduce their energy intensity in response to competitive pressure from informal producers due to the level of corporate governance.

Our research applies two primary theories (i.e., legitimacy and stakeholders) to hypothesize the association between climate governance and carbon risk. While the legitimacy theory (Suchman, 1995) suggests that organizations must act according to societal norms and expectations to maintain their legitimacy, stakeholder theory (Freeman et al., 2010) emphasizes the importance of considering the interests of various stakeholders. In the context of climate governance, organizations prioritizing robust governance mechanisms are better equipped to respond to diverse stakeholder demands and concerns related to carbon risks. This alignment fosters an environment where organizations are motivated to enhance their carbon performance to meet societal and stakeholder expectations. To gain societal acceptance, climate governance may play a key role in eliminating the carbon risk thereby maintaining its legitimacy and fulfilling diverse stakeholder demands. Nevertheless, given that the primary objective of companies may be profit maximization rather than environmental preservation, adherence to these standards may be more symbolic than substantial. As a result, companies may choose to superficially align with specific societal norms while continuing to operate according to their core profit-driven principles (Perego and Kolk, 2012).

Furthermore, the legitimacy theorist argues that firms may employ disclosure practices to present a facade of environmental responsibility and obscure their inadequate ecological performance (Deegan and Gordon, 1996; Patten, 2002; Michelon et al., 2019). Notably, the choice to disclose corporate carbon emissions reduces the idiosyncratic volatility of firms that disclose their emissions compared to those that do not (Perera et al., 2023). On the other side, stakeholders also push pressure back on corporate governance to improve climate governance (Yunus et al., 2020). Moreover, pressure from the regulators is also associated with the firms' propensity to adopt innovation strategies (Yunus et al., 2020). In particular, the impact of internal and external stakeholders is diverse and related to the industry. For industries close to consumers, media exposure, and government pressure groups, stakeholders positively affect carbon emission disclosure. Meanwhile, stakeholders may hurt carbon emission disclosure in employee-oriented industries and creditor pressure (Nuriyani and Dewi, 2023).

Besides the above theories, resource-based research suggests that organizations equipped with valuable resources have a greater capacity to address complex challenges (Qiu et al., 2016). Strong governance provides organizations financial, human, and relational capital, allowing them to invest in carbon reduction efforts (Phung et al., 2022). This theory underscores how corporate governance can facilitate organizations to allocate resources effectively toward carbon risk mitigation. Qiu et al. (2016) suggest that firms with more significant economic resources make more extensive disclosures, yielding net positive economic benefits. Whereas resource shortages may constrain a firm management's carbon decisions (Luo et al., 2013). However, the connection between resource efficiency and carbon efficiency is more intricate, demonstrating an interactive effect where changes in one factor have a dynamic and interconnected impact on the other (Wang et al., 2021).

Prior literature shows mixed results on the role of climate governance. One stream, including Berrone and Gomez-Mejia (2009) and Orazalin et al. (2023), finds that specific climate governance structures, such as explicit environmental policies and committees, did not necessarily correlate with greater rewards for environmentally oriented strategies. Some organizations adopt climate change initiatives symbolically to maintain their legitimacy in the eyes of stakeholders.

However, another stream of research, which includes more robust evidence, supports the positive impact of climate governance concerning environmental performance (Bui et al., 2020; Albitar et al., 2023; Cordova et al., 2021). For instance, Cordova et al. (2021) indicate that corporate social responsibility (CSR) committees, larger board sizes, and executive compensation policies based on environmental and social performance positively relate to carbon reduction management strategies. Bui et al. (2020) highlight the intricate relationship between climate governance and carbon disclosure. They find that robust climate governance mechanisms enhance the link between carbon disclosure and performance. This suggests that effective governance promotes transparency and accountability, facilitating a stronger correlation between an organization's carbon disclosure efforts and its actual carbon performance. Albitar et al. (2023) underscore the synergistic relationship between environmental innovation and enhanced governance in reducing CO2 emissions. This convergence suggests that an organization's commitment to innovation and effective climate governance can drive meaningful reductions in carbon risks. Furthermore, carbon strategy and managerial awareness of carbon risk significantly influence the relationship between corporate governance and carbon performance (Luo and Tang, 2021).

The mixed results above could stem from several factors, including the motivation of capable managers to disclose climate change information. Weak governance structures could impede the willingness of competent managers to disclose such information, thereby limiting transparency in this critical area (Nguyen et al., 2023). Additionally, the relationship between corporate governance and carbon performance is multifaceted. While traditional corporate governance mechanisms might not directly correlate with carbon performance, climate governance, which concentrates on specialized board committees addressing climate risk, appears to have a stronger association with carbon disclosure (Albitar et al., 2023). Moreover, the different results in the prior studies may come from the diversity in measurements and definitions used to measure climate governance and carbon performance. Hence, we utilize a composite climate governance index measurement that incorporates environmental committee effectiveness, CSR sustainability reporting, and sustainability compensation incentives. This holistic approach, in conjunction with the earlier discussion and the foundational principles of legitimacy theory, stakeholder theory, and the resource-based view, strongly indicates that climate governance plays a crucial role in reducing carbon risks. As a result, our hypothesis, in the alternative form below, asserts that proficient climate governance is inversely correlated with carbon risks, underscoring its pivotal role in addressing challenges related to carbon-related issues.

[5] The Intergovernmental Panel on Climate Change (IPCC) has emphasized the potential of governance in strengthening climate mitigation and adaptation efforts (Pachauri et al., 2014).

Hypothesis 1. ***Climate governance is negatively associated with carbon risks.***

2.2. The mediating effect of eco-innovation on the relation between climate governance and carbon risk

As mentioned, earlier research has demonstrated a range of corporate governance impacts on carbon risk, as evidenced by studies such as Luo and Tang (2021) and Peters and Romi (2014). However, the influence of corporate governance on carbon risk in the context of organizations actively pursuing eco-innovation remains uncertain. This uncertainty arises from the growing imperative for organizations to commit to eco-innovation activities to mitigate the adverse effects of climate change, as highlighted by recent work by Phung et al. (2022) and Zaman et al. (2023).

On the one hand, previous studies have examined the impact of corporate governance on either carbon emissions or eco-innovation (e.g., Asni and Agustia, 2022; Ma et al., 2022). For example, Haque (2017) finds that firms with higher levels of board independence or board gender diversity are more likely to adopt comprehensive carbon-reduction initiatives. This finding is complemented by Zaman et al. (2023), showing that an increase of one standard deviation in demographic and structural diversity corresponds to a respective increase of 4.66% and 7.11% in corporate eco-innovation. Ma et al. (2022) also explore that female managers demonstrate heightened caution in making eco-innovation decisions, particularly in situations characterized by high risk and financial constraints. Phung et al. (2022) further find that corporate governance significantly impacts eco-innovation strategies. Albitar et al. (2023) recently indicate a positive link between climate governance and climate change commitment.

On the other hand, some studies have started exploring the impact of eco-innovation on carbon emissions. Fethi and Rahuma (2019) uncover a significant and adverse long-term effect of eco-innovation (particularly environmental research and development – R&D activities) on carbon emissions, highlighting its potential to address ecological challenges. Expanding on this, Ganda (2019) propose that incorporating natural environmental standards into patents and equipping researchers with green skills and knowledge would facilitate the achievement of zero-emission targets, underscoring the importance of intellectual property and human capital in driving sustainable innovations. Hashmi and Alam (2019) further elucidate this understanding by revealing that even a marginal 1% increase in environmentally friendly patents could lead to a substantial reduction of 0.017% in carbon emissions, while a corresponding 1% rise in environmental tax revenue per capita could contribute to a 0.03% decrease in OECD countries.

Furthermore, Lee and Min (2015) find that green R&D investments have a dual effect of reducing carbon emissions and increasing firm value. Also, environmental performance encompasses the efficient utilization of resources, waste reduction, energy conservation, and mitigation of environmental risks (Aragón-Correa et al., 2008). To enhance ecological performance through eco-innovation, companies must invest in novel environmental technologies to reduce pollution and carbon emissions. Eco-innovation is vital in identifying inefficiencies in production processes and existing environmental technologies, thereby improving energy efficiency and fostering product innovations (Sambasivan et al., 2013).

Interestingly, investing in eco-innovation has been under consideration by organizations due to limited resources and adverse impact, as Khezri et al. (2021) argue that the influence of R&D investment on the advancement of green resources varies across countries and at different developmental stages. In addition, Mongo et al. (2021) indicate that while environmental innovations generally lower CO2 emissions in the long run, there can be a short-term reversal, suggesting the existence of a rebound effect that warrants further exploration. Nevertheless, Albitar et al. (2022) affirm the positive influence of environmental innovation in conjunction with improved ecological governance in mitigating CO2 emissions, emphasizing the significance of comprehensive strategies encompassing technological advancements and effective management approaches. These studies underscore the critical role of eco-innovation and climate governance in addressing carbon emissions and advancing sustainable development agendas.

Given the critical role of climate governance and eco-innovation in reducing carbon risk, our study fills the gap in the literature by exploring the mediating effect of eco-innovation on the relationship between climate governance and carbon risk. For several reasons, we contend that climate governance's impact on carbon emissions is reflected through eco-innovation. First, in line with stakeholder theory, effective climate governance typically involves engaging stakeholders in decision-making processes, including businesses, civil society, and other relevant actors. Stakeholder involvement enables advocacy and pushes for eco-innovation as a strategy to tackle climate-related challenges (Liao et al., 2015; Luo, 2019). Climate governance mechanisms that facilitate stakeholder engagement and integrate their perspectives into decision-making influence the direction of eco-innovation efforts. Consequently, eco-innovation emerges as a response to the demands and expectations of diverse stakeholders, functioning as a mediating factor that bridges the gap between climate governance and the mitigation of carbon risk.

Relatedly, the legitimacy theorists argue that organizations behave in line with social norms, values and beliefs to demonstrate their legitimacy and accountability (Nguyen et al., 2023). Also, environmental legitimacy is related to the perception that the firm's environmental performance is desirable and appropriate (Bansal and Clelland, 2004). It is an external and informal factor affecting the firms' actions regarding climate change issues. Zhou et al. (2021) suggest that environmental legitimacy, which includes formal and informal institutional pressure, positively impacts senior management cognition and the green strategic orientation of businesses. Therefore, companies often increase their investment in eco-innovation to gain, maintain, and repair environmental legitimacy (Li et al., 2018).

Building upon the theoretical arguments and empirical evidence presented above, we assert that eco-innovation within the energy sector is a mediator for the effectiveness of climate governance in mitigating carbon risk. Consequently, we put forward the following hypothesis.

H2: Eco-innovation mediates the relationship between climate governance and carbon risk.

3. Research methodology

3.1. Data and sample

Our study is based on an initial sample of energy firms globally over a twenty-three-year period from 2000 to 2022. To imply for the whole energy market, we select only related sectors, including Electricity, Gas, Water, and Multiutilities, and Oil and Gas Procedure Sectors. The selection includes 299,692 firm-year observations from 13,376 unique energy firms. We collect data samples from two primary database sources, Thomson Reuters's Refinitiv Eikon and World Development Indicators of the World Bank. The sample distribution by country is illustrated in Appendix B. The top five countries with more recorded observations are the United States (13,78%), Canada (13,78%), Australia (9.77%), China (4,23%) and the United Kingdom (3,09%).

Variable measurement

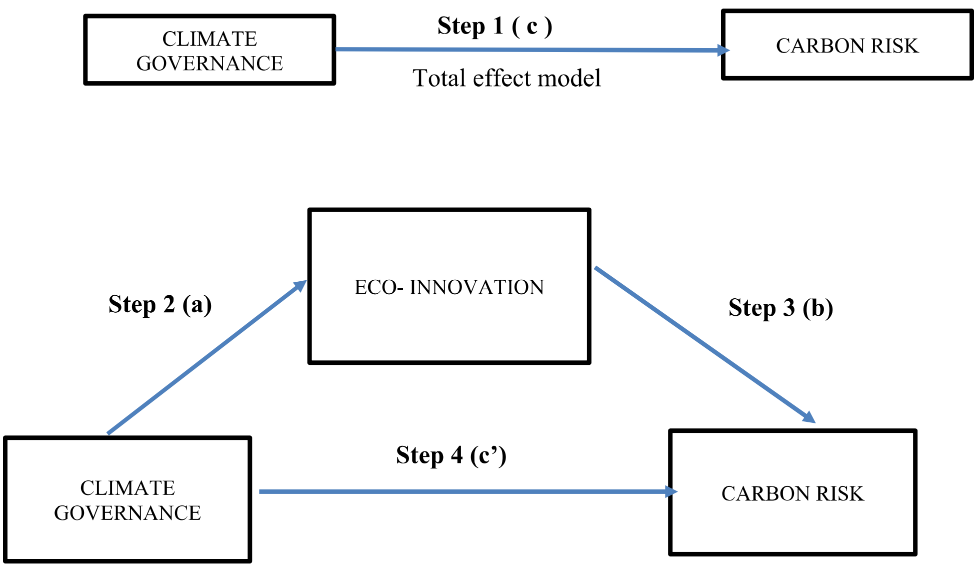
Our study employs *Carbon risk* as our primary dependent variable and *Climate Governance* as the main independent variable. To explore further the association between *Climate Governance* and *Carbon risk*, we also include *Eco-innovation* as the main mediating variable. This implies that we are investigating whether and how climate governance affects a firm's carbon risk indirectly through its impact on corporate eco-innovation activities and performance. All detailed variable definitions and measurements in our study are presented in Appendix A.

Carbon risk. While climate risk presents the general climate change effects on the business environment, including physical and transition risks (Rao et al., 2023), carbon risk refers specifically to the level of carbon emissions. We choose carbon risk because prior literature argues that emission data is considered more consistent than the *E*-scores (Busch et al., 2022) when studying the E (Environment) element of ESG score (Pástor et al., 2022). Accordingly, following Bolton and Kacperczyk (2021) and Bauer et al. (2022), we estimate the carbon intensity risk as the total carbon dioxide (CO2) and CO2 equivalents emissions in tones of each firm scaled by its total assets (*CO2/TA*) or total revenues (*CO2/Rev* - which can avoid the impact of firm size on carbon emission levels). As such, all gases, including carbon dioxide (CO2), methane (CH4), nitrous oxide (N20), hydrofluorocarbons (HFCS), perfluorinated compound (PFCS), sulfur hexafluoride (SF6), nitrogen trifluoride (NF3) are related. The total CO2 emissions are combined with the direct carbon intensity of Scope 1 and the indirect carbon intensity of Scope 2, following the greenhouse gas (GHG) protocol for all our emissions classifications by type. The higher number of *CO2/TA* and *CO2/Rev* implies a higher carbon intensity risk.

Climate Governance. Following previous studies such as Albitar et al. (2023), Bui et al. (2020), and Phung et al. (2022), we measure climate governance by the composite index (score ranging from 0 to 3) constructed from three individual indicators: (i) environmental committee (*CSR_committee*) – measured by a dummy factor denoting the value of one if there exists a board-level environmental committee, and zero otherwise; (ii) sustainability report (*SUS_report*) - measured by a dummy factor denoting the value of one if the sustainability report(s) is published by the observed firm, and zero otherwise; and (iii) climate incentive (*Climate_incentive*) - measured by a dummy factor denoting the value of one if there exists incentives for individual management of climate change, and zero otherwise.

Eco-innovation. Following previous studies such as Albitar et al. (2023), we employ an eco-innovation index (*Ecoin_Index*), which is constructed by five individual proxies of eco-innovation from Thomson Reuters's Eikon databases, including (i) Environmental product indicator taking a value of 1 if the company reports on at least one product line or service that is designed to have a positive effect on the environment, 0 otherwise; (ii) Environmental asset under management taking a value of 1 if the company reports on assets under management which employ environmental screening in the investment selection process, 0 otherwise; (iii) Product environmentally responsible use: taking a value of 1 if the company reports on product features or services that will promote responsible, efficient, cost-effective and environmentally preferable use, 0 otherwise; (iv) Renewable/clean energy product taking a value of 1 if the company develops products or technologies for use in the clean renewable energy sector, 0 otherwise; and (v) Eco-design product taking a value of 1 if the company reports on specific products which are designed for reuse and recycling, 0 otherwise. Hence, the index ranges from 0 to 5 showing the corporate efforts to reduce its impact on the environment by using natural resources including energy and developing a service or product offering a better quality of life for all. In a robustness check, we also use eco-innovation score (*Ecoin_Score),* ranging from 0 to 100, constructed by Thomson estimating the corporate capacity to eliminate environmental costs and burdens for its customers and thereby creating new market opportunities through new environmental technologies and processes or eco-designed products. This score is widely used in recent research (e.g., Albitar et al., 2023; Nadeem et al., 2020; Zaman et al., 2023).

Control variables. We employ a comprehensive set of control variables including corporate governance, firm-level and country-level characteristics. These variables are selected from previous studies related to carbon risk and eco-innovation (e.g. Marquis and Qian, 2014; Tavakolifar et al., 2021; Phung et al., 2022; Acheampong et al., 2021). Their definitions are described in Appendix A.



Step 1: $Carbon\ risk_{it} = \beta_0 + \beta_1 \cdot Climate\ governance_{it} + \beta_k \sum controls_{it} + \sigma$
Step 2: $Eco - innovation_{it} = \alpha_0 + \alpha_1 \cdot Climate\ governance_{it} + \alpha_k \sum controls_{it} + \varepsilon$
Step 3: $Carbon\ risk_{it} = = \gamma_0 + \gamma_1 \cdot Eco - innovation_{it} + \gamma_k \sum controls_{it} + \tau$
Step 4: $Carbon\ risk_{it} = \theta_0 + \theta_1 \cdot Climate\ governance_{it} + \theta_1 \cdot Eco - innovation_{it} + \theta_k \sum controls_{it} + \epsilon$

c = c' + ab
c'= the direct effect of climate governance on carbon risk after controlling for eco- innovation
c'=c-ab
ab= indirect effect of climate governance on carbon risk

Table 1
Descriptive Statistics.

Variable	N	Mean	Sd	Min	p25	p50	p75	max
CO2/TA	17,664	0.415	0.647	0.000	0.034	0.218	0.476	3.883
CO2/Rev	17,586	1.173	1.992	0.000	0.111	0.460	1.180	11.520
Cli_gov_Index	32,994	1.643	1.054	0.000	1.000	2.000	2.000	3.000
Ecoin_Index	32,797	1.321	1.252	0.000	0.000	1.000	2.000	4.000
Ecoin_Score	32,827	25.805	32.665	0.000	0.000	0.000	54.550	97.230
Duality	33,018	0.396	0.489	0.000	0.000	0.000	1.000	1.000
Excomp/TA	20,931	2.836	6.109	0.002	0.245	0.732	2.425	41.049
Ex_board	31,354	6.417	2.879	1.190	4.250	6.150	8.250	14.980
lnBSize	32,909	10.563	3.680	3.000	8.000	10.000	12.000	22.000
lnMeeting	29,642	2.221	0.417	1.386	1.946	2.197	2.485	3.401
lnTA	116,459	13.268	4.051	3.258	10.305	13.344	16.306	22.373
%Female	32,645	14.700	12.753	0.000	0.000	13.330	22.220	50.000
EBIT/interest	97,420	−64.126	437.963	−3642.645	−4.506	1.972	6.336	610.600
Quick ratio	113,342	3.508	9.329	0.000	0.500	0.930	2.050	69.400
CF/TA	113,640	−0.093	0.657	−5.000	−0.050	0.046	0.106	0.416
Dividend yield	192,604	1.431	3.784	0.000	0.000	0.000	0.710	26.510
Debt/Equity	114,555	69.150	174.930	−620.030	0.000	32.110	99.340	998.280
ROA	110,173	−20.164	87.655	−669.140	−12.050	2.020	6.300	63.590
M/B	72,896	0.002	0.010	−0.029	0.000	0.001	0.002	0.079
Fixed Assets/TA	113,060	0.526	0.307	0.000	0.268	0.591	0.787	0.974
Urban	145,656	1.293	0.860	−0.430	0.912	1.136	1.503	4.198
GDP	145,422	1.799	3.042	−7.096	0.690	1.603	2.644	10.741
Inflation	143,888	2.735	2.417	−0.732	1.488	2.138	3.226	13.913
WGI_index	138,008	1.018	0.750	−0.771	0.863	1.272	1.567	1.792

The table reports descriptive statistics of all variables employed in our empirical models. See definitions and measurements of those variables in appendix A.
A significant portion of the data used in this paper is missing due to the combination of various database sources. The missing observations are either excluded from the computations or treated as zeroes.

3.2. Empirical model

In this study, we use fixed effect (FE) regression, in which firm group means are fixed (non-random), to test our hypotheses H1–H2. This method is used to avoid omitted variable bias. We leverage Baron and Kenny (1986) 4-step mediating model to examine the mediating role of eco-innovation on the relationship of climate governance on carbon risk. In the first step (Eq. 1), we demonstrate a primary correlation between the initial value and the outcome, where the dependent variable (*Carbon risk*) is regressed against the main independent variable (*Climate governance*). This step confirms the presence of an effect that could potentially be influenced by mediating factors. In the second step (Eq. 2), we examine the correlation between the initial variable and the mediator, where the dependent variable (*Eco-innovation*) is regressed against the independent variable (*Climate governance*). The mediator is treated as if it were an outcome variable, providing insights into the relationship between the initial variable and the mediator.

In the third step (Eq. 3), we next demonstrate the influence of the mediator (Eco-innovation) on the primary outcome variable (*Carbon risk*) through a regression equation. In this process, the initial variable is controlled to establish the effect of the mediator on the outcome variable, emphasizing the need to account for the initial variable in understanding the impact of the mediator. In the final (fourth) step (Eq. 4), we examine whether the mediator (*Eco-innovation*) influences the outcome variable in a regression equation where both main independent variable (*Climate governance*) and the mediator (*Eco-innovation*) are considered as predictors. In order to establish complete mediation of the independent factor (*Climate governance*) – outcome factor (*Carbon risk*) relationship by the mediator (*Eco-innovation*), it is necessary to examine the effects of *Climate governance* on *Carbon risk* while controlling for *Eco-innovation*. This implies that in the regression model, the relationship between the independent and dependent variables should either vanish entirely (indicating full mediation) or significantly diminish (indicating partial mediation) once the mediator is introduced (Baron and Kenny, 1986). Our models (Eq. (1) to Eq. (4)) are specified as follows:

$$Carbon\ risk_{it} = \beta_0 + \beta_1 \bullet Climate\ governance_{it} + \beta_k \sum controls_{it} + \sigma \quad (1)$$

$$Eco - innovation_{it} = \alpha_0 + \alpha_1 \bullet Climate\ governance_{it} + \alpha_k \sum controls_{it} + \varepsilon \quad (2)$$

$$Carbon\ risk_{it} == \gamma_0 + \gamma_1 \bullet Eco - innovation_{it} + \gamma_k \sum controls_{it} + \tau \quad (3)$$

$$Carbon\ risk_{it} = \theta_0 + \theta_1 \bullet Climate\ governance_{it} + \theta_2 \bullet Eco - innovation_{it} + \theta_k \sum controls_{it} + \epsilon \quad (4)$$

In all models, our control variables include three groups: corporate governance variables (i.e., *Excomp/TA, Duality, Ex_board, lnBSize, lnMeeting, lnTA, %Female*); firm-level factors (i.e., *EBIT/interest, Quick ratio,* CF/TA, *Dividend yield, Debt/Equity, ROA, M/B, Fixed Assets/TA*); and country-level characteristics (*Urban, GDP, Inflation, WGI_index*). In general, a mediation model tests a causal relationship in which one variable (*Climate governance*), influences a second variable – mediator (*Eco-innovation*), and consequently, that variable impacts a third variable (*Carbon risk*). This differs from a moderating model which analyzes the influence of a third variable on the relationship between two factors. Notably, a moderating model cannot indicate the causal link between these other variables, while our mediating model could do. In this study, we propose the hypothesis that investigates the role of climate governance system on a firms' eco-innovation performance. In other words, we explore how the enhancements in eco-innovation are associated with shifts in firms' carbon risk. Specifically, we focus on the mediating effect of eco-innovation on the relationship between climate governance and carbon risk. Therefore, we find that a mediation model is the most appropriate method to address our research question.

4. Empirical results

4.1. Summary statistics

Table 1 reports the descriptive statistics of all variables utilized in this study. It shows that for carbon risk, the mean (median) value of carbon emission over total assets (*CO2/TA*) is 0.415 (0.218), while the mean (median) value of carbon emission by total revenues is 1.173 (0.460). In addition, the climate corporate governance index

Table 2
Correlation Matrix.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
1. *Cli_gov_Index*	1																					
2. *Ecoin_Index*	0.43*	1																				
3. *Ecoin_Score*	0.36*	0.77*	1																			
4. *Duality*	−0.02*	−0.04*	−0.01*	1																		
5. *Excomp/TA*	−0.29*	−0.23*	−0.19*	−0.07*	1																	
6. *Ex_board*	0.06*	−0.04*	−0.04*	0.29*	−0.05*	1																
7. *lnBSize*	0.26*	0.33*	0.30*	0.09*	−0.37*	−0.00	1															
8. *lnMeeting*	0.05*	0.06*	0.06*	−0.10*	−0.01*	−0.25*	−0.01	1														
9. *lnTA*	0.31*	0.41*	0.34*	0.04*	−0.61*	−0.07*	0.57*	0.12*	1													
10. *%Female*	0.40*	0.28*	0.29*	0.01*	−0.12*	0.01*	0.03*	0.04*	0.02*	1												
11. *EBIT/interest*	0.04*	0.02*	0.02*	0.02*	−0.24*	0.00	0.07*	0.01	0.21*	0.00	1											
12. *Quick ratio*	−0.11*	−0.09*	−0.08*	−0.06*	0.20*	−0.05*	−0.16*	0.01	−0.22*	−0.06*	−0.15*	1										
13. *CF/TA*	0.05*	−0.12*	−0.13*	0.05*	−0.31*	0.10*	0.04*	−0.07*	0.45*	−0.03*	0.13*	0.00	1									
14. *Dividend yield*	0.16*	0.16*	0.16*	−0.03*	−0.26*	−0.04*	0.17*	0.08*	0.31*	0.11*	0.09*	−0.08*	0.13*	1								
15. *Debt/Equity*	0.02*	0.16*	0.15*	−0.00	−0.13*	−0.05*	0.14*	0.06*	0.26*	0.02*	0.06*	−0.10*	0.11*	0.07*	1							
16. *ROA*	0.06*	0.05*	0.03*	0.03*	−0.40*	0.04*	0.12*	−0.05*	0.46*	−0.02*	0.16*	0.02*	0.72*	0.14*	0.13*	1						
17. *M/B*	0.01*	0.01	0.01	0.04*	0.04*	0.01	−0.00	−0.02*	−0.03*	0.02*	−0.03*	0.01*	0.05*	0.06*	0.22*	0.06*	1					
18. *Fixed Assets/TA*	−0.00	−0.29*	−0.23*	0.08*	−0.14*	0.14*	−0.07*	−0.09*	0.26*	−0.02*	0.11*	−0.28*	0.26*	0.07*	0.11*	0.19*	−0.04*	1				
19. *Urban*	−0.15*	−0.18*	−0.14*	−0.03*	0.01	−0.08*	−0.02*	−0.05*	0.07*	−0.17*	0.00	0.02*	0.02*	0.03*	0.04*	0.03*	−0.02*	−0.00	1			
20. *GDP*	−0.10*	−0.03*	−0.04*	0.00	−0.03*	−0.06*	0.05*	−0.08*	0.16*	−0.08*	0.05*	−0.03*	0.06*	−0.00	0.06*	0.08*	0.01*	−0.00	0.34*	1		
21. *Inflation*	−0.03*	−0.02*	−0.06*	−0.06*	0.02*	−0.03*	−0.00	0.02*	0.14*	−0.05*	0.02*	−0.01*	0.05*	0.06*	0.00	0.06*	0.01*	−0.03*	0.14*	0.26*	1	
22. *WGI_index*	−0.00	−0.16*	−0.08*	0.06*	0.14*	0.23*	−0.25*	−0.12*	−0.43*	0.16*	−0.12*	0.12*	−0.14*	−0.17*	−0.14*	−0.15*	0.02*	0.01*	−0.48*	−0.45*	−0.48*	1

The table reports correlation matrix among independent variables used in all our models. * denotes the significance level of 5%.

(*Cli_gov_Index*) ranges from 0 to 3. Its average is 1.643 based on the 32,994 firm-year observation sample. In other words, on average, the observed firms employ more than one climate governance policy. Regarding the mediating factor [eco-innovation index (*Ecoin_Index*) and eco-innovation score (*Ecoin_Score*)], we find the following: (i) there is no firm-year observation having utilized five eco-innovation components within the *Ecoin_Index* (mean of 1.321) since the maximum index recorded is 4, and (ii) The mean value of the eco-innovation score is 25.805, ranging from 0 to 97.230.

Table 2 reports the Pearson correlations among independent variables in our empirical models. We find no evidence of severe multicollinearity issues since the significant coefficients of independent factor pairs are much lower than 0.8, supported by unreported individual (far from 10) and mean Variance Inflation Factor (VIF) (far from 6) values.

4.2. Effects of climate governance on carbon risk

Using fixed-effect models (with different control variables), we examine the association between the climate governance index and carbon emissions (the first step of the mediation model). The results are reported in Table 3, demonstrating a statistically significant and negative relationship across all models (1–8) using *CO2/TA* or *CO2/Rev* as the proxies for emissions. The findings suggest that energy firms with better climate governance systems exhibit lower levels of carbon risk, supporting our first hypothesis $\boldsymbol{H_1}$. Regarding economic significance, for every 1 unit increase in the climate governance index, the CO2 emissions relative to total assets decrease by 0.022, while the CO2 emissions relative to revenue decrease by 0.108. Our findings align with previous studies (Aragón-Correa et al., 2008; Lee and Min, 2015; Sambasivan et al., 2013) that emphasize the importance of eco-innovation in reducing carbon emissions. By embracing eco-innovation, energy firms enhance their market competitiveness, seize business opportunities in the growing sustainable energy sector, and contribute to a more sustainable and resilient energy future.

Our findings imply that the interconnections among eco-innovation, carbon risk, and climate governance hold great significance in the energy sector. Eco-innovation assumes a vital role in mitigating carbon risk for energy companies. Through investments in the research and development of environmentally friendly energy technologies, enhancements in energy efficiency, and adopting sustainable practices, companies can reduce their carbon emissions and minimize exposure to regulatory and financial risks associated with carbon-intensive activities. Eco-innovation empowers energy companies to adapt to evolving climate governance frameworks, meet targets for reducing emissions, and proactively address regulatory requirements. Additionally, it enables companies to seize emerging opportunities in the expanding market for renewable energy and low-carbon solutions, thereby mitigating the risks linked to potential shifts in consumer preferences and demand for sustainable energy sources.

Furthermore, climate governance in the energy sector establishes the policy framework and regulatory guidelines that shape the industry's transition toward a low-carbon economy. These governance mechanisms, encompassing carbon pricing mechanisms, mandates for renewable energy, and targets for emissions reduction, provide incentives and requirements for energy companies to embrace eco-innovation practices. Climate governance measures encourage and support the development, deployment, and diffusion of eco-innovative technologies and practices by offering financial incentives, research funding, and fostering supportive policy environments. Consequently, climate governance acts as a catalyst for eco-innovation in the energy sector, propelling the adoption of cleaner energy sources, stimulating energy efficiency, and nurturing sustainability. The relationship between eco-innovation, carbon risk, and climate governance in the energy sector thus operates in a mutually reinforcing manner, with eco-innovation serving as a conduit between the imperative to manage carbon risk and the regulatory framework provided by climate governance.

Table 3
Effects of Climate Governance on Carbon Risk.

	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]
VARIABLES	CO_2/TA	CO_2/TA	CO_2/TA	CO_2/TA	CO_2/Rev	CO_2/Rev	CO_2/Rev	CO_2/Rev
Cli_gov_Index	**−0.123*****	**−0.043*****	**−0.034*****	**−0.022****	**−0.244*****	**−0.139*****	**−0.133*****	**−0.108*****
	[0.000]	[0.000]	[0.000]	[0.016]	[0.000]	[0.000]	[0.000]	[0.001]
Duality		−0.008	0.006	−0.003		0.250***	0.257***	0.216***
		[0.648]	[0.778]	[0.873]		[0.000]	[0.000]	[0.000]
Excomp/TA		−0.012***	−0.013***	−0.012***		−0.022***	−0.024***	−0.021***
		[0.000]	[0.000]	[0.000]		[0.000]	[0.000]	[0.001]
Ex_board		0.002	0.006	0.006		−0.017*	−0.000	−0.005
		[0.635]	[0.149]	[0.211]		[0.082]	[0.968]	[0.667]
lnBSize		−0.007**	0.000	0.000		−0.054***	−0.033***	−0.028**
		[0.045]	[0.968]	[0.900]		[0.000]	[0.007]	[0.028]
lnMeeting		0.032*	0.022	0.046**		0.162***	0.074	0.051
		[0.082]	[0.290]	[0.033]		[0.001]	[0.193]	[0.328]
lnTA		−0.373***	−0.330***	−0.331***		−0.554***	−0.605***	−0.542***
		[0.000]	[0.000]	[0.000]		[0.000]	[0.000]	[0.000]
%Female		−0.004***	−0.004***	−0.002***		−0.008***	−0.005***	−0.003*
		[0.000]	[0.000]	[0.003]		[0.000]	[0.003]	[0.086]
EBIT/interest			−0.000**	−0.000			0.001***	0.001***
			[0.043]	[0.125]			[0.001]	[0.001]
Quick ratio			−0.006***	−0.006**			−0.015	−0.031
			[0.006]	[0.041]			[0.529]	[0.181]
CF/TA			0.293***	0.205**			−2.516***	−1.980***
			[0.000]	[0.015]			[0.000]	[0.000]
Dividend yield			−0.001	−0.000			0.008	0.011
			[0.730]	[0.882]			[0.288]	[0.125]
Debt/Equity			−0.000	−0.000			−0.000	−0.000
			[0.175]	[0.340]			[0.218]	[0.384]
ROA			0.001*	0.001*			−0.000	0.000
			[0.081]	[0.065]			[0.783]	[0.934]
M/B			−0.481	−0.327			−4.052	−3.327
			[0.588]	[0.705]			[0.146]	[0.185]
Fixed Assets/TA			0.089	0.078			−0.465	−0.262
			[0.447]	[0.496]			[0.375]	[0.615]
Urban				0.033**				0.181***
				[0.012]				[0.000]
GDP				−0.002***				−0.008**
				[0.007]				[0.016]
Inflation				0.009**				−0.018
				[0.010]				[0.144]
WGI_index				0.596***				0.793***
				[0.000]				[0.001]
Constant	0.671***	7.066***	6.112***	5.309***	1.681***	11.593***	12.718***	10.342***
	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]
Observations	17,664	13,412	9175	8649	17,586	13,344	9138	8626
R-squared	0.077	0.233	0.221	0.243	0.044	0.113	0.128	0.156
Number of firms	1998	1630	1394	1303	1986	1623	1387	1299
Wald Chi 2 (p-value)	0.000***	0.000***	0.000***	0.000***	0.000***	0.000***	0.000***	0.000***

*The table reports fixed effect (FE) regression results (with robust standard errors) on the association between climate governance and carbon risk. See appendix A for all detailed definitions and measurements of the variables. P-values can be found in square brackets. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.*

In terms of control variables, we observe that firms' cash flow (CF/TA), profitability (*ROA*), urbanization, inflation, and the World Governance Indicator (WGI) index are positively and significantly associated with higher levels of CO2 emissions relative to total assets (*CO2/TA*). Conversely, top-management compensation (*Excomp/TA*), firm size (*lnTA*), board gender diversity (*%Female*), liquidity (*quick ratio*), and GDP have significant negative impacts on the level of CO2 emissions relative to total assets. These findings suggest that larger firms with more female representation on boards, higher top-management compensation, and greater liquidity tend to engage more in carbon-reducing activities.

At the country level, our analysis reveals that countries with higher GDPs tend to exhibit lower levels of carbon risk. However, we also observe that higher levels of urbanization and a higher WGI index are associated with increased carbon emissions. The influences of macro-factors, such as GDP, WGI index, and inflation, on carbon emissions have been examined in various studies, but the findings have been inconclusive (Abouie-Mehrizi et al., 2012; Nabi et al., 2020; Zhao et al., 2021). Specifically, Nabi et al. (2020) identify a U-shaped relationship between economic growth and carbon emissions within a given period, suggesting that the impact of macro factors can vary depending on the level of economic growth. Notably, inflation is positively related to higher CO2 emissions relative to total assets (*CO2/TA*), but it has no significant effect on CO2 emissions relative to revenue (*CO2/REV*) in column 8. Similarly, the quick ratio is negatively and significantly associated with CO2 emissions relative to total assets (*CO2/TA*). Still, it has no significant relationship with CO2 emissions relative to revenue (*CO2/REV*). Lastly, while firms' cash flow (CF/*TA*) is positively related to *CO2/TA*, it has a negative impact on *CO2/REV*.

When we replace the carbon emissions by the ratio of CO2 emissions to revenue (*CO2/Rev*), we find that CEO duality (*Duality*), cash-flow (CF/*TA*), interest coverage ratio (*EBIT/interest*), urbanization, and World Governance Indicator (*WGI_index*) are all positively and significantly associated with higher levels of CO2 emissions relative to total assets. Conversely, top-management compensation (*Excomp/TA*), board size (*lnBSize*), firm size (*lnTA*), board gender diversity (*%Female*), and GDP have significant negative impacts on the level of CO2 emissions relative to total assets. Notably, CEO duality (*Duality*) is positively related to higher levels of CO2 emissions relative to total assets (*CO2/TA*) but does not have a significant association with CO2 emissions

Table 4
Climate Governance-Carbon Risk Nexus: The Mediating Effects of Eco-Innovation.

Four-step mediation model of Baron and Kenny								
	[Step 1]	*[Step 2]*	*[Step 3]*	*[Step 4]*	*[Step 1]*	*[Step 2]*	*[Step 3]*	*[Step 4]*
VARIABLES	CO_2/TA	*Ecoin_Index*	CO_2/TA	CO_2/TA	CO_2/Rev	*Ecoin_Index*	CO_2/Rev	CO_2/Rev
Cli_gov_Index	**−0.022****	**0.211*****		**−0.013**	**−0.108*****	**0.211*****		**−0.088****
	[0.016]	[0.000]		[0.208]	[0.001]	[0.000]		[0.018]
Ecoin_Index			**−0.050*****	**−0.048*****			**−0.119*****	**−0.101****
			[0.000]	[0.000]			[0.001]	[0.011]
Duality	−0.003	−0.095*	−0.007	−0.008	0.216***	−0.095*	0.220***	0.206***
	[0.873]	[0.062]	[0.747]	[0.674]	[0.000]	[0.062]	[0.000]	[0.001]
Excomp/TA	−0.012***	0.012***	−0.010***	−0.010***	−0.021***	0.012***	−0.020***	−0.018***
	[0.000]	[0.000]	[0.000]	[0.000]	[0.001]	[0.000]	[0.002]	[0.003]
Ex_board	0.006	−0.007	0.005	0.005	−0.005	−0.007	−0.009	−0.006
	[0.211]	[0.416]	[0.277]	[0.231]	[0.667]	[0.416]	[0.433]	[0.595]
lnBSize	0.000	−0.019**	0.000	0.000	−0.028**	−0.019**	−0.028**	−0.028**
	[0.900]	[0.012]	[0.987]	[0.972]	[0.028]	[0.012]	[0.030]	[0.029]
lnMeeting	0.046**	−0.081***	0.040*	0.039*	0.051	−0.081***	0.045	0.040
	[0.033]	[0.004]	[0.055]	[0.059]	[0.328]	[0.004]	[0.382]	[0.429]
lnTA	−0.331***	0.379***	−0.308***	−0.301***	−0.542***	0.379***	−0.525***	−0.482***
	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]
%Female	−0.002***	0.004***	−0.002***	−0.002***	−0.003*	0.004***	−0.003**	−0.002
	[0.003]	[0.003]	[0.002]	[0.005]	[0.086]	[0.003]	[0.044]	[0.109]
EBIT/interest	−0.000	0.000	−0.000	−0.000	0.001***	0.000	0.001***	0.001***
	[0.125]	[0.266]	[0.113]	[0.129]	[0.001]	[0.266]	[0.001]	[0.001]
Quick ratio	−0.006**	0.002	−0.005*	−0.005*	−0.031	0.002	−0.030	−0.030
	[0.041]	[0.679]	[0.068]	[0.068]	[0.181]	[0.679]	[0.206]	[0.215]
CF/TA	0.205**	−0.716***	0.176**	0.189**	−1.980***	−0.716***	−2.119***	−2.028***
	[0.015]	[0.000]	[0.037]	[0.023]	[0.000]	[0.000]	[0.000]	[0.000]
Dividend yield	−0.000	−0.001	−0.000	0.000	0.011	−0.001	0.011	0.012
	[0.882]	[0.825]	[0.937]	[0.994]	[0.125]	[0.825]	[0.170]	[0.105]
Debt/Equity	−0.000	−0.000	−0.000	−0.000	−0.000	−0.000	−0.000	−0.000
	[0.340]	[0.575]	[0.489]	[0.430]	[0.384]	[0.575]	[0.594]	[0.450]
ROA	0.001*	−0.001***	0.001	0.001	0.000	−0.001***	−0.000	−0.000
	[0.065]	[0.003]	[0.114]	[0.110]	[0.934]	[0.003]	[0.881]	[0.910]
M/B	−0.327	3.580*	−0.093	−0.191	−3.327	3.580*	−2.407	−3.051
	[0.705]	[0.073]	[0.904]	[0.812]	[0.185]	[0.073]	[0.302]	[0.213]
Fixed Assets/TA	0.078	−0.097	0.064	0.065	−0.262	−0.097	−0.303	−0.288
	[0.496]	[0.443]	[0.580]	[0.568]	[0.615]	[0.443]	[0.571]	[0.583]
Urban	0.033**	−0.246***	0.028**	0.027**	0.181***	−0.246***	0.177***	0.169***
	[0.012]	[0.000]	[0.030]	[0.034]	[0.000]	[0.000]	[0.000]	[0.000]
GDP	−0.002***	−0.019***	−0.003***	−0.003***	−0.008**	−0.019***	−0.007*	−0.009**
	[0.007]	[0.000]	[0.005]	[0.001]	[0.016]	[0.000]	[0.054]	[0.011]
Inflation	0.009**	−0.014*	0.008**	0.008**	−0.018	−0.014*	−0.020	−0.019
	[0.010]	[0.063]	[0.022]	[0.019]	[0.144]	[0.063]	[0.103]	[0.112]
WGI_index	0.596***	−0.911***	0.559***	0.542***	0.793***	−0.911***	0.765***	0.656***
	[0.000]	[0.000]	[0.000]	[0.000]	[0.001]	[0.000]	[0.000]	[0.003]
Constant	5.309***	−3.431***	5.027***	4.956***	10.342***	−3.431***	10.139***	9.656***
	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]
Observations	8649	11,667	8597	8597	8626	11,667	8574	8574
R-squared	0.243	0.248	0.252	0.253	0.156	0.248	0.158	0.162
Number of firms	1303	1588	1303	1303	1299	1588	1299	1299
Wald Chi 2 (p-value)	0.000***	0.000***	0.000***	0.000***	0.000***	0.000***	0.000***	0.000***

*The table reports 4-step mediation results on the mediating effect of eco-innovation on the association between climate governance and carbon risk. See appendix A for all detailed definitions and measurements of the variables. P-values can be found in square brackets. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.*

relative to revenue (*CO2/Rev*). Additionally, the board size (*lnBSize*) is negatively related to CO2 emissions relative to revenue (*CO2/Rev*) but does not impact CO2 emissions relative to total assets (*CO2/TA*). Overall, the findings support our hypothesis and are consistent with prior studies (Albitar et al., 2022; Albitar et al., 2023) examining the relationship between climate governance and carbon risk.

4.3. Climate governance-carbon risk nexus: the mediating effects of eco-innovation

We next investigate the second hypothesis using Baron & Kenny's (1986) 4-step models. Indeed, we check whether eco-innovation (meditating factor) impacts the relationship between climate governance quality and carbon emissions (evident in the first hypothesis). We report the results in Table 4. Regardless of the proxies of carbon risk, we consistently find evidence supporting the mediating role of eco-innovation. However, we find the full mediating effect when employing *CO2/TA* to measure carbon risk. At the same time, the results reveal a partial mediating impact when utilizing *CO2/Rev* as the alternative proxy for carbon emissions.

More specifically, in Columns [1] to [4], we conduct a 4-step model with *CO2/TA* as the dependent variable. Our findings reveal a significant negative relationship between climate governance and carbon risk in the total effect model [STEP 1] (−0.022**). The [STEP 2] demonstrates a positive association between climate governance and the eco-innovation index (mediator) (0.211***). The [STEP 3] indicates that eco-innovation (mediator) significantly reduces carbon risk (−0.050***). Finally, [STEP 4], which controls for eco-innovation (mediator), shows that climate governance no longer predicts carbon risk, suggesting that eco-innovation fully mediates this relationship. In Columns [5] to [8], we use *CO2/Rev* as the dependent variable. We find consistent results across all steps; however, when controlling for eco-innovation (mediator), climate governance continues to decrease carbon risk (Y) but is still significant in the final step. Therefore, in this case,

Table 5
Alternative Measures of Eco-Innovation.

Four-step mediation model of Baron and Kenny								
	[Step 1]	*[Step 2]*	*[Step 3]*	*[Step 4]*	*[Step 1]*	*[Step 2]*	*[Step 3]*	*[Step 4]*
VARIABLES	CO_2/TA	*Ecoin_Score*	CO_2/TA	CO_2/TA	CO_2/Rev	*Ecoin_Score*	CO_2/Rev	CO_2/Rev
Cli_gov_Index	**−0.022****	**4.479*****		**−0.009**	**−0.108*****	**4.479*****		**−0.091*****
	[0.016]	[0.000]		[0.290]	[0.001]	[0.000]		[0.006]
Ecoin_Score			**−0.002*****	**−0.002*****			**−0.004*****	**−0.003*****
			[0.000]	[0.000]			[0.000]	[0.000]
Duality	−0.003	0.977	0.001	−0.001	0.216***	0.977	0.237***	0.220***
	[0.873]	[0.373]	[0.975]	[0.960]	[0.000]	[0.373]	[0.000]	[0.000]
Excomp/TA	−0.012***	0.485***	−0.009***	−0.009***	−0.021***	0.485***	−0.020***	−0.018***
	[0.000]	[0.000]	[0.000]	[0.000]	[0.001]	[0.000]	[0.001]	[0.003]
Ex_board	0.006	−0.433*	0.004	0.004	−0.005	−0.433*	−0.010	−0.007
	[0.211]	[0.093]	[0.381]	[0.338]	[0.667]	[0.093]	[0.378]	[0.545]
lnBSize	0.000	−0.788***	−0.001	−0.001	−0.028**	−0.788***	−0.030**	−0.029**
	[0.900]	[0.000]	[0.870]	[0.890]	[0.028]	[0.000]	[0.020]	[0.021]
lnMeeting	0.046**	−1.523*	0.040*	0.040*	0.051	−1.523*	0.046	0.041
	[0.033]	[0.051]	[0.056]	[0.059]	[0.328]	[0.051]	[0.371]	[0.417]
lnTA	−0.331***	10.619***	−0.297***	−0.293***	−0.542***	10.619***	−0.534***	−0.490***
	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]
%Female	−0.002***	0.149***	−0.002***	−0.002**	−0.003*	0.149***	−0.003*	−0.002
	[0.003]	[0.000]	[0.007]	[0.010]	[0.086]	[0.000]	[0.063]	[0.139]
EBIT/interest	−0.000	−0.000	−0.000*	−0.000*	0.001***	−0.000	0.001***	0.001***
	[0.125]	[0.924]	[0.081]	[0.088]	[0.001]	[0.924]	[0.001]	[0.001]
Quick ratio	−0.006**	−0.068	−0.006**	−0.006**	−0.031	−0.068	−0.031	−0.031
	[0.041]	[0.410]	[0.042]	[0.042]	[0.181]	[0.410]	[0.178]	[0.189]
CF/TA	0.205**	−32.736***	0.106	0.116	−1.980***	−32.736***	−2.211***	−2.106***
	[0.015]	[0.000]	[0.224]	[0.177]	[0.000]	[0.000]	[0.000]	[0.000]
Dividend yield	−0.000	0.073	0.001	0.001	0.011	0.073	0.011	0.013*
	[0.882]	[0.541]	[0.832]	[0.787]	[0.125]	[0.541]	[0.130]	[0.079]
Debt/Equity	−0.000	−0.001	−0.000	−0.000	−0.000	−0.001	−0.000	−0.000
	[0.340]	[0.554]	[0.353]	[0.314]	[0.384]	[0.554]	[0.518]	[0.376]
ROA	0.001*	−0.042***	0.001	0.001	0.000	−0.042***	−0.000	−0.000
	[0.065]	[0.001]	[0.135]	[0.133]	[0.934]	[0.001]	[0.933]	[0.954]
M/B	−0.327	25.206	−0.410	−0.470	−3.327	25.206	−3.008	−3.569
	[0.705]	[0.610]	[0.615]	[0.573]	[0.185]	[0.610]	[0.212]	[0.149]
Fixed Assets/TA	0.078	−1.155	0.091	0.092	−0.262	−1.155	−0.262	−0.247
	[0.496]	[0.752]	[0.434]	[0.426]	[0.615]	[0.752]	[0.625]	[0.639]
Urban	0.033**	−3.800***	0.032**	0.031**	0.181***	−3.800***	0.190***	0.179***
	[0.012]	[0.000]	[0.015]	[0.018]	[0.000]	[0.000]	[0.000]	[0.000]
GDP	−0.002***	−0.470***	−0.003***	−0.003***	−0.008**	−0.470***	−0.007**	−0.009***
	[0.007]	[0.000]	[0.002]	[0.001]	[0.016]	[0.000]	[0.048]	[0.008]
Inflation	0.009**	−0.203	0.009***	0.009***	−0.018	−0.203	−0.019	−0.018
	[0.010]	[0.291]	[0.009]	[0.009]	[0.144]	[0.291]	[0.134]	[0.146]
WGI_index	0.596***	−12.226***	0.560***	0.547***	0.793***	−12.226***	0.861***	0.730***
	[0.000]	[0.001]	[0.000]	[0.000]	[0.001]	[0.001]	[0.000]	[0.001]
Constant	5.309***	−124.407***	4.834***	4.786***	10.342***	−124.407***	10.100***	9.631***
	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]
Observations	8649	11,713	8626	8626	8626	11,713	8603	8603
R-squared	0.243	0.182	0.263	0.264	0.156	0.182	0.157	0.161
Number of firms	1303	1585	1303	1303	1299	1585	1299	1299
Wald Chi 2 (p-value)	0.000***	0.000***	0.000***	0.000***	0.000***	0.000***	0.000***	0.000***

*The table reports 4-step mediation results on the mediating effect of eco-innovation on the association between climate governance and carbon risk. Green Innovation is measured by environmental innovation scores. See appendix A for all detailed definitions and measurements of the variables. P-values can be found in square brackets. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.*

we conclude that the relationship between climate governance and carbon risk remains mediated (but partially) by eco-innovation.

5. Robustness and sensitivity test

5.1. Alternative measures of eco-innovation

Table 5 presents the results of Baron and Kenny (1986) 4-step model with the mediating effect using environmental innovation scores as an alternative measure for eco-innovation. We generally find consistent results in Table 4 that eco-innovation mediates the relationship between climate governance and carbon risk. This demonstrates the robustness of our conclusions on the significant role of climate governance in reducing carbon risk and the mediating effect of eco-innovation.

5.2. High-ESG vs low-ESG firms

In this subsection, we retest our predictions using sub-groups of high-ESG firms and low-ESG firms. The firms are divided into two subgroups based on the median value of their ESG score (*ESG_score*). Specifically, firms with an ESG score greater than the median are classified as high-ESG firms, while the remaining firms are classified as low-ESG firms. Results are reported in Table 6 (Panel A and Panel B). Panel A presents the results of a 4-step model for the high-ESG firms group and shows that eco-innovation fully mediates the relationship between climate governance and carbon risk for high-ESG firms. Panel B shows the results for the low-ESG firms group; however, we do not find significant results from step 1, so the 4-step mediation results cannot be concluded. In other words, our main results in Table 4 (i.e., mediating role of eco-innovation on the relationship between climate governance and carbon risk) are more pronounced in the sub-sample of high-ESG firms.

Table 6
High-ESG vs Low-ESG Firms.

	Panel A: High-ESG Firms				Panel A: Low-ESG Firms			
	[Step 1]	*[Step 2]*	*[Step 3]*	*[Step 4]*	*[Step 1]*	*[Step 2]*	*[Step 3]*	*[Step 4]*
VARIABLES	CO_2/TA*	Ecoin_Index	CO_2/TA*	CO_2/TA*	CO_2/TA*	Ecoin_Index	CO_2/TA*	CO_2/TA*
Cli_gov_Index	**−0.023***	**0.212*****		**−0.017**	0.012	0.185***		0.016
	[0.083]	[0.000]		[0.271]	[0.251]	[0.000]		[0.158]
Ecoin_Index			**−0.042*****	**−0.039*****			−0.043**	−0.046**
			[0.001]	[0.006]			[0.023]	[0.019]
Governance controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Firm-level controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Country-level controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Constant	5.810***	−6.329***	5.593***	5.486***	3.308***	−1.662***	3.102***	3.163***
	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.005]	[0.000]	[0.000]
Observations	6394	6663	6349	6349	2255	5004	2248	2248
R-squared	0.256	0.244	0.263	0.264	0.147	0.179	0.155	0.158
Number of firms	998	1027	998	998	712	1041	708	708
Wald Chi 2 (p-value)	0.000***	0.000***	0.000***	0.000***	0.000***	0.000***	0.000***	0.000***

*** For brevity, results on CO_2/Rev will be provided upon request.**
*The table reports 4-step mediation results on the mediating effect of eco-innovation on the association between climate governance and carbon risk for two sub-samples: High-ESG (ESG_score > mean) vs Low-ESG Firms (ESG_score ≤mean). See appendix A for all detailed definitions and measurements of the variables. P-values can be found in square brackets. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.*

Table 7a
The Moderating Role of Firm Characteristics.

PART I: Large vs Small Firms								
	Panel A Large Firms				Panel B Small Firms			
	[Step 1]	*[Step 2]*	*[Step 3]*	*[Step 4]*	*[Step 1]*	*[Step 2]*	*[Step 3]*	*[Step 4]*
VARIABLES	CO_2/TA*	Ecoin_Index	CO_2/TA*	CO_2/TA*	CO_2/TA*	Ecoin_Index	CO_2/TA*	CO_2/TA*
Cli_gov_Index	**−0.021****	**0.202*****		**−0.012**	−0.019**	0.130***		−0.028***
	[0.029]	[0.000]		[0.257]	[0.040]	[0.001]		[0.006]
Ecoin_Index			**−0.050*****	**−0.048*****			0.012	0.029**
			[0.000]	[0.000]			[0.167]	[0.013]
Governance controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Firm-level controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Country-level controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Constant	5.596***	−6.396***	5.285***	5.208***	3.894***	2.362***	3.654***	3.779***
	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.001]	[0.000]	[0.000]
Observations	8269	10,316	8217	8217	380	1351	380	380
R-squared	0.247	0.269	0.256	0.257	0.724	0.153	0.717	0.732
Number of firms	1192	1314	1192	1192	157	396	157	157
Wald Chi 2 (p-value)	0.000***	0.000***	0.000***	0.000***	0.000***	0.000***	0.000***	0.000***
PART II: Profitable vs Loss Firms								
	Panel A Profitable Firms				**Panel B Loss Firms**			
	[Step 1]	***[Step 2]***	***[Step 3]***	***[Step 4]***	***[Step 1]***	***[Step 2]***	***[Step 3]***	***[Step 4]***
VARIABLES	**CO_2/TA***	**Ecoin_Index**	**CO_2/TA***	**CO_2/TA***	**CO_2/TA***	**Ecoin_Index**	**CO_2/TA***	**CO_2/TA***
Cli_gov_Index	**−0.021****	**0.237*****		**−0.012**	0.010	0.018		0.010
	[0.028]	[0.000]		[0.275]	[0.150]	[0.444]		[0.129]
Ecoin_Index			**−0.049*****	**−0.046*****			0.032***	0.032***
			[0.000]	[0.000]			[0.001]	[0.001]
Governance controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Firm-level controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Country-level controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Constant	6.249***	−4.852***	5.969***	5.869***	1.758***	1.897***	1.779***	1.751***
	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.006]	[0.000]	[0.000]
Observations	7219	9317	7170	7170	1430	2350	1427	1427
R-squared	0.276	0.279	0.284	0.285	0.207	0.173	0.214	0.216
Number of firms	1253	1471	1253	1253	628	878	628	628
Wald Chi 2 (p-value)	0.000***	0.000***	0.000***	0.000***	0.000***	0.000***	0.000***	0.000***

*** For brevity, results on CO_2/Rev will be provided upon request.**
*The table reports the role of firm size and firm profitability. See appendix A for all detailed definitions and measurements of the variables. P-values can be found in square brackets. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.*

Nevertheless, there are no significant differences between the two groups (High-ESG vs Low-ESG firms) regarding the effect of climate governance on eco-innovation [STEP 2], as well as the impact of eco-innovation on carbon risk [STEP 3].

Notably, we highlight that the role of climate governance in reducing carbon emissions is non-significant in low-ESG firms (STEP 1, Panel B). This suggests that in low ESG enterprises, the impact of climate governance on carbon emissions is still unclear, potentially due to pressures prioritizing short-term financial performance, lack of awareness and understanding of climate change risks and opportunities, and ineffective governance structures.

Table 7b
The Moderating Role of Firm Characteristics (continued).

PART III: High-levered vs Low-leveraged Firms								
	Panel A: High-levered Firms				Panel A: Low-levered Firms			
	[Step 1]	*[Step 2]*	*[Step 3]*	*[Step 4]*	*[Step 1]*	*[Step 2]*	*[Step 3]*	*[Step 4]*
VARIABLES	CO_2/TA*	Ecoin_Index	CO_2/TA*	CO_2/TA*	CO_2/TA*	Ecoin_Index	CO_2/TA*	CO_2/TA*
Cli_gov_Index	**−0.023*****	**0.192*****		**−0.020****	0.013	0.271***		0.031**
	[0.003]	[0.000]		[0.018]	[0.184]	[0.000]		[0.011]
Ecoin_Index			**−0.037*****	**−0.035*****			−0.055***	−0.063***
			[0.001]	[0.002]			[0.000]	[0.000]
Governance controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Firm-level controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Country-level controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Constant	6.437***	−4.904***	6.188***	6.060***	4.798***	−1.325	4.344***	4.563***
	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.183]	[0.000]	[0.000]
Observations	6575	8631	6526	6526	2074	3036	2071	2071
R-squared	0.282	0.261	0.285	0.287	0.355	0.254	0.388	0.397
Number of firms	1157	1356	1157	1157	470	706	467	467
Wald Chi 2 (p-value)	0.000***	0.000***	0.000***	0.000***	0.000***	0.000***	0.000***	0.000***
PART IV: High-MTB vs Low-MTB Firms								
	Panel A: High-MTB Firms				**Panel A: Low-MTB Firms**			
	[Step 1]	***[Step 2]***	***[Step 3]***	***[Step 4]***	***[Step 1]***	***[Step 2]***	***[Step 3]***	***[Step 4]***
VARIABLES	**CO_2/TA***	**Ecoin_Index**	**CO_2/TA***	**CO_2/TA***	**CO_2/TA***	**Ecoin_Index**	**CO_2/TA***	**CO_2/TA***
Cli_gov_Index	**−0.022****	**0.209*****		**−0.016**	−0.007	0.219***		−0.002
	(0.038)	(0.000)		(0.171)	(0.459)	(0.000)		(0.820)
Ecoin_Index			**−0.041*****	**−0.038*****			−0.029**	−0.028**
			(0.001)	(0.004)			(0.010)	(0.011)
Governance controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Firm-level controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Country-level controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Constant	5.899***	−3.574***	5.592***	5.471***	3.685***	−2.626***	3.617***	3.608***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.006)	(0.000)	(0.000)
Observations	4781	6373	4744	4744	3868	5294	3853	3853
R-squared	0.335	0.299	0.339	0.340	0.125	0.196	0.133	0.133
Number of firms	883	1145	883	883	875	1113	875	875
Wald Chi 2 (p-value)	0.000***	0.000***	0.000***	0.000***	0.000***	0.000***	0.000***	0.000***

*** For brevity, results on CO_2/Rev will be provided upon request.**

*The table reports the role of firm financial leverage and firm market value. See appendix A for all detailed definitions and measurements of the variables. P-values can be found in square brackets. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.*

5.3. The moderating role of firm characteristics

We next examine the role of firm characteristics in the tested relationship. Specifically, we conduct a mediating analysis on subgroups based on firm size, profitability, leverage level, and market-to-book (MTB) value to examine the impact of firm characteristics on the relationship between carbon risk and eco-innovation. We employ the median value of such variables as the cutoff to classify large- vs small firms, high-levered vs low-levered firms, and high MTB vs low MTB firms. We classify profitable and loss firms by using zero as the cutoff. Results for firm size, firm profitability, leverage level, and market-to-book (MTB) are reported in Table 7a, 7b (PARTS I-IV, respectively). We find that our main results shown in Table 4 (i.e., the mediating role of eco-innovation on the relationship between climate governance and carbon risk) are more pronounced in the sub-samples of large firms (relatively compared to small ones), profitable firms (relatively compared to loss ones), high-levered firms (relatively compared to low-levered firms), and high-MTB firms (relatively compared to low-MTB ones).

5.4. The moderating role of country characteristics

Besides the firm characteristics of firms, the country-level characteristics may also affect firms' climate governance and eco-innovation activities. Specifically, GDP and economic growth have been identified as factors that could increase carbon risk and carbon emissions (Ji et al., 2021; Amin et al., 2022; You et al., 2022). Moreover, good institutional and political governance positively contributes to sustainable development, allowing nations to mitigate the negative impacts of CO2 emissions on overall development (Leal Filho et al., 2019). Thus, in this analysis, we conduct mediating research on subgroups based on GDP and WGI (Worldwide Governance Indicators) to examine the impact of firm characteristics on the relationship between carbon risk and eco-innovation. Results are reported in Table 8 (PART I AND PART II, respectively). Similar to firm characteristics, we use the median value of GDP and WGI as the cutoff to classify High-GDP vs Low-GDP countries and High-WGI vs Low-WGI countries. Generally, we find that our main results reported in Table 4 (i.e., the mediating role of eco-innovation on the relationship between climate governance and carbon risk) are more pronounced in the sub-samples of high-GDP countries (relatively compared to low-GDP ones) and low-WGI countries (relatively compared to Low-WGI ones).

5.5. Endogeneity treatments

To treat endogeneity issue and sample selection bias, we utilize the two-step system Generalized Method of Moments (GMM) and the propensity score matching (PSM), respectively.

5.5.1. Two-step system generalized method of moments (GMM)

The GMM method captures unobserved influences by transforming the variables into first differences. This way, we can mitigate unobserved heterogeneity and other problems like omitted variable bias (Arellano and Bover, 1995; Trinh et al., 2020a, 2020b). In addition, the approach uses lagged values as the instrument variables (IVs) for the potentially endogenous factors such as climate governance and eco-innovation. This is because these IVs in earlier years could not have resulted from carbon emissions (STEP 1, 3–4) and eco-innovation (STEP 2) in subsequent years; consequently, it is unlikely to face endogeneity

Table 8
The Moderating Role of Country Characteristics.

Part 1 High-GDP vs Low-GDP Countries

	Panel A: High-GDP Countries				Panel B: Low-GDP Countries			
	[Step 1]	*[Step 2]*	*[Step 3]*	*[Step 4]*	*[Step 1]*	*[Step 2]*	*[Step 3]*	*[Step 4]*
VARIABLES	CO_2/TA*	Ecoin_Index	CO_2/TA*	CO_2/TA*	CO_2/TA*	Ecoin_Index	CO_2/TA*	CO_2/TA*
Cli_gov_Index	**−0.056***** [0.000]	**0.215***** [0.000]		**−0.045***** [0.001]	0.010 [0.402]	0.178*** [0.000]		0.017 [0.198]
Ecoin_Index			**−0.072***** [0.000]	**−0.063***** [0.000]			−0.038*** [0.005]	−0.041*** [0.006]
Governance controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Firm-level controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Country-level controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Constant	5.055*** [0.000]	−4.283*** [0.000]	4.838*** [0.000]	4.602*** [0.000]	5.111*** [0.000]	−3.066*** [0.000]	4.620*** [0.000]	4.714*** [0.000]
Observations	3763	5128	3746	3746	4886	6539	4851	4851
R-squared	0.292	0.323	0.299	0.305	0.224	0.223	0.231	0.232
Number of firms	1231	1490	1231	1231	1068	1323	1068	1068
Wald Chi 2 (p-value)	0.000***	0.000***	0.000***	0.000***	0.000***	0.000***	0.000***	0.000***
Part 2 High-WGI vs Low-WGI Countries								
	Panel A: High-WGI Countries				**Panel B: Low-WGI Countries**			
	[Step 1]	***[Step 2]***	***[Step 3]***	***[Step 4]***	***[Step 1]***	***[Step 2]***	***[Step 3]***	***[Step 4]***
VARIABLES	**CO_2/TA***	**Ecoin_Index**	**CO_2/TA***	**CO_2/TA***	**CO_2/TA***	**Ecoin_Index**	**CO_2/TA***	**CO_2/TA***
Cli_gov_Index	0.003 [0.880]	0.236*** [0.000]		0.012 [0.578]	**−0.034***** [0.000]	**0.189***** [0.000]		**−0.025***** [0.004]
Ecoin_Index			−0.045*** [0.008]	−0.047** [0.023]			**−0.051***** [0.000]	**−0.046***** [0.000]
Governance controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Firm-level controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Country-level controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Constant	4.677*** [0.000]	−1.917** [0.019]	4.132*** [0.000]	4.162*** [0.000]	5.478*** [0.000]	−5.102*** [0.000]	5.356*** [0.000]	5.229*** [0.000]
Observations	3939	5523	3906	3906	4710	6144	4691	4691
R-squared	0.252	0.222	0.256	0.256	0.273	0.258	0.282	0.285
Number of firms	698	858	698	698	796	956	796	796
Wald Chi 2 (p-value)	0.000***	0.000***	0.000***	0.000***	0.000***	0.000***	0.000***	0.000***

*** For brevity, results on CO_2/Rev will be provided upon request.**
*The table reports the role of country characteristics. See appendix A for all detailed definitions and measurements of the variables. P-values can be found in square brackets. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.*

Table 9
Dynamic panel-data estimation, two-step system GMM.

	[Step 1]	*[Step 2]*	*[Step 3]*	*[Step 4]*
VARIABLES	CO_2/TA	*Ecoin_Index*	CO_2/TA	CO_2/TA
CO_2/TA $_{t-1}$	0.880*** [0.000]		0.876*** [0.000]	0.884*** [0.000]
Ecoin_Index $_{t-1}$		0.745*** [0.000]		
Cli_gov_Index	**−0.018***** [0.000]	**0.089***** [0.000]		**0.000** [0.974]
Ecoin_Index			**−0.014**** [0.039]	**−0.006*** [0.085]
Governance controls	Yes	Yes	Yes	Yes
Firm-level controls	Yes	Yes	Yes	Yes
Country-level controls	Yes	Yes	Yes	Yes
Constant	0.018 [0.773]	−0.328** [0.033]	0.069 [0.261]	0.047 [0.130]
Observations	7759	10,969	7707	7707
Number of firms	1221	1525	1221	1221
Wald Chi 2 (p-value)	0.000***	0.000***	0.000***	0.000***

*** For brevity, results on CO_2/Rev will be provided upon request.**
*The table reports the results of the two-step system GMM regression. See appendix A for all detailed definitions and measurements of the variables. P-values can be found in square brackets. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.*

bias. We report GMM results for the 4-step model in Table 9. We find that climate governance is likely to reduce the carbon risk through their higher level of engagement in eco-innovation.

5.5.2. *Propensity score matching (PSM): regression on matched samples*

We next use the three-stage PSM estimation to check the sample selection bias and possible endogeneity for our main variables of interest, including climate governance and eco-innovation (Rosenbaum and Rubin, 1983; Trinh et al., 2020a, 2020b; Elnahass et al., 2020, 2021). In the first stage, we use the probit method to estimate propensity scores for firms having higher climate governance index (treatment group for STEP 1, 3–4) or for firms having higher eco-innovation index (treatment group for STEP 1), and those having lower climate governance index (control group for STEP 1, 3–4) or for firms having lower eco-innovation index (control group for STEP 1). To do so, we create two dummies: (i) a 'high climate governance index' dummy variable (*Treated_ Cli_gov_Index*) that takes the value of 1 if the climate governance score is equal to or higher than its median and (ii) a 'High eco-innovation index' dummy variable (*Treated_Ecoin_Index*) that takes the value of 1 if the eco-innovation score is equal to or higher than its median. We, therefore, obtain estimated propensity scores of treated and controlled groups. In the second stage of PSM, we match samples using 1–1 nearest neighbour matching without replacement technique,[6] which helps match each observation from the treatment group with each observation of the control group. In the final stage, we conduct the regression on the matched sample using the 4-step models. Results are reported in Table 10. We also explore the same findings as the main tests

[6] In unreported tests, we find consistent results when employing alternative matching techniques such as one-to-one nearest neighbour matching with a replacement and nearest neighbour matching with $n = 2$ and $n = 3$ with a replacement.

Table 10
Propensity Score Matching (PSM): Effect of Climate Governance on Carbon Risk.

	[Step 1]	[Step 2]	[Step 3]	[Step 4]
VARIABLES	CO_2/TA	*Ecoin_Index*	CO_2/TA	CO_2/TA
Treated_ *Cli_gov_Index*	**−0.034*****	**0.356*****		**−0.016**
	[0.001]	[0.000]		[0.107]
Treated_ *Ecoin_Index*			**−0.129*****	**−0.114*****
			[0.000]	[0.000]
Duality $_{t-1}$	0.013	−0.039	−0.027	−0.027
	[0.662]	[0.336]	[0.484]	[0.332]
Excomp/TA $_{t-1}$	−0.009***	0.008*	−0.038***	−0.008***
	[0.000]	[0.057]	[0.002]	[0.000]
Ex_board $_{t-1}$	0.007	0.024***	−0.004	0.006
	[0.101]	[0.000]	[0.470]	[0.181]
lnBSize $_{t-1}$	−0.002	−0.011	0.010*	−0.011***
	[0.642]	[0.108]	[0.082]	[0.003]
lnMeeting $_{t-1}$	0.098***	−0.088**	0.167***	0.045**
	[0.000]	[0.022]	[0.000]	[0.038]
lnTA $_{t-1}$	−0.245***	0.263***	−0.436***	−0.206***
	[0.000]	[0.000]	[0.000]	[0.000]
%Female $_{t-1}$	−0.002**	0.003*	−0.006***	−0.001
	[0.026]	[0.053]	[0.000]	[0.266]
EBIT/interest $_{t-1}$	−0.000	−0.000***	−0.001*	−0.000
	[0.515]	[0.001]	[0.071]	[0.632]
Quick ratio $_{t-1}$	−0.005	0.000	−0.010	−0.005*
	[0.111]	[0.948]	[0.638]	[0.064]
CF/TA $_{t-1}$	0.102	0.103	−0.653**	0.038
	[0.455]	[0.624]	[0.028]	[0.769]
Dividend yield $_{t-1}$	−0.010**	−0.001	0.019***	−0.004
	[0.011]	[0.829]	[0.001]	[0.356]
Debt/Equity $_{t-1}$	0.000*	−0.000***	0.000*	0.000
	[0.060]	[0.005]	[0.059]	[0.305]
ROA $_{t-1}$	−0.001	0.002**	0.010***	−0.000
	[0.421]	[0.031]	[0.000]	[0.582]
M/B $_{t-1}$	−3.689*	10.766***	−30.468***	−2.917
	[0.067]	[0.001]	[0.001]	[0.126]
Fixed Assets/TA $_{t-1}$	−0.208**	−0.187	0.019	−0.284***
	[0.011]	[0.122]	[0.897]	[0.000]
Urban $_{t-1}$	0.067***	−0.041	0.072**	0.068***
	[0.006]	[0.353]	[0.015]	[0.009]
GDP $_{t-1}$	0.001	−0.022***	−0.009**	0.002
	[0.710]	[0.000]	[0.028]	[0.501]
Inflation $_{t-1}$	−0.004	−0.025***	0.000	0.002
	[0.386]	[0.003]	[0.983]	[0.602]
WGI_index $_{t-1}$	0.531***	−0.867***	0.806***	0.376***
	[0.000]	[0.000]	[0.000]	[0.000]
Constant	4.173***	−2.025***	6.884***	3.914***
	[0.000]	[0.002]	[0.000]	[0.000]
Firm FE	Yes	Yes	Yes	Yes
Observations	2000	4260	2136	2000
R-squared	0.927	0.824	0.869	0.928
Wald Chi 2 (p-value)	0.000***	0.000***	0.000***	0.000***

*** For brevity, results on CO_2/Rev will be provided upon request.**
*The table reports the PSM results. See appendix A for all detailed definitions and measurements of the variables. P-values can be found in square brackets. *** $p < 0.01$, ** $p < 0.05$, * $p < 0$.*

and GMM.

Our results from all the above endogenous treatment methods (i.e., GMM, PSM) confirm our robust results, which survive across various model specifications.

6. Conclusion

Under the pressure of Net Zero commitment involved by many countries around the world and in response to the call for further investigation into climate change and carbon greenhouse gas emission issues in the energy sector, this study examines the association between climate governance and carbon risk and the mediating effect of eco-innovation on such association. Using a global sample of energy firms, we initially found a negative link between climate governance and carbon risk. This result implies the critical role of climate governance in the energy sector in setting policies and guidelines for the transition to a low-carbon economy. The finding supports the recent discussions related to the impact of climate governance on carbon emissions (Bui et al., 2020; Albitar et al., 2023; Cordova et al., 2021). We then apply Baron & Kenny's 4-step mediation model to explore the mediating role of eco-innovation. Our findings show that enhanced climate governance mechanisms are associated with a reduction in carbon emissions by energy firms, and this decline is primarily attributed to their increased engagement in eco-innovation initiatives. Moreover, these key findings are particularly pronounced in companies with strong environmental, social, and governance (ESG) practices. Also, our results uncover several factors at both the firm and country levels that influence the identified relationship. Our findings remain robust even after addressing potential concerns related to endogeneity and sample selection bias.

Findings from our research have several contributions and implications for practice and policymakers. First, the negative association between climate governance and carbon risk indicates that policymakers should continue prioritizing and strengthening climate governance frameworks. Additionally, policies that promote and incentivize eco-innovation within the energy sector may yield even more significant carbon risk reduction benefits. Second, for energy firms, our findings on the positive effect of eco-innovation underscore the importance of integrating eco-innovation practices into their strategies. The commitment to reducing carbon emission go beyond the information disclosure in their annual report (Chithambo et al., 2022; Nguyen et al., 2024), it however implies that proactive efforts to reduce carbon emissions should be considered through innovation initiatives (i.e., eco-innovation), which consequently can be critical to corporate risk management and bringing businesses forward to the Net Zero target commitment.

In addition, stakeholders (i.e., investors) seeking sustainable and low-risk investments can consider ESG ratings and the presence of eco-innovation practices as crucial indicators of a company's ability to manage carbon risks. It emphasizes the potential financial advantages of investing in high-ESG and innovation-driven firms.

Overall, the study highlights the interconnectedness of climate governance, eco-innovation, and carbon risk reduction. It suggests that a holistic approach, combining regulatory measures with innovative practices, can play a pivotal role in the global effort to mitigate climate change and achieve environmental sustainability goals. Our study calls for further evidence on other underlying channels which explain or affect the relationship between climate governance and carbon risk.

CRediT authorship contribution statement

Minh-Lý Liêu: Conceptualization, Data curation, Formal analysis, Methodology, Writing – original draft, Writing – review & editing. **Thuy Dao:** Conceptualization, Data curation, Formal analysis, Methodology, Project administration, Validation, Writing – original draft, Writing – review & editing. **Tam Huy Nguyen:** Conceptualization, Methodology, Supervision, Validation, Writing – original draft, Writing – review & editing. **Vu Quang Trinh:** Conceptualization, Data curation, Formal analysis, Methodology, Software, Supervision, Validation, Writing – original draft, Writing – review & editing.

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Appendix A. Variable definition

Variable - Abbreviation		Definition	Source
Independent Variables			
Carbon risk	CO2/Rev	Carbon intensity risk is computed as the total of a firm's total carbon dioxide (CO2) and CO2 equivalents emission in tonnes [ENERDP023] scaled by the firm's total revenues in USD in million [WC1001].	Thomson Reuters' Refinitiv Eikon [formerly ASSET4]
	CO2/TA	Carbon intensity risk is computed as the total of a firm's total carbon dioxide (CO2) and CO2 equivalents emission in tonnes [ENERDP023] scaled by the firm's total asset in USD in million [WC02999].	Thomson Reuters' Refinitiv Eikon [formerly ASSET4]
Climate corporate governance			
Climate corporate governance index	CSR_committee	CSR committee CGVSDP005	Thomson Reuters' DataStream [TRDS]
	SUS_report	CSR Sustainability Reporting CGVSDP026	Thomson Reuters' DataStream [TRDS]
	Climate_incentive	Sustainability Compensation incentives CGCPO09V	Thomson Reuters' DataStream [TRDS]
Firm Eco-innovation			
Eco-innovation Score	Ecoin_Score	Eco-innovation Score	Thomson Reuters' DataStream [TRDS]
Eco-innovation Index	Ecoin_Index	Eco-design products: ENPIDP069 Environmental products ENPIDP019 Environmental assets under management ENPIDP034 Product environmental responsible use ENPIDP048 Renewable/clean energy products ENPISP066	Thomson Reuters' DataStream [TRDS]
Control variables			
Duality	Duality	Dummy variable, which denotes the value of 1 if a firm's CEO simultaneously acts as the chairman of the board and 0 otherwise [CGBSO09V].	Thomson Reuters' DataStream [TRDS]
Executives's compensation per total assets	ExComp/TA	Senior executives (top-management)' compensation is the total amount of compensation paid to a firm's all senior executives [CGCPDP054] reported by the firm scaled by its total assets [WC02999].	Thomson Reuters' DataStream [TRDS]
Independent Board	Ex_board	Percentage of a firm's independent board members [CGBSO07V].	Thomson Reuters' DataStream [TRDS]
Board Member Size	LnBSize	The logarithm value of the total numbers of a firm's board members at the fiscal year-end [CGBSDP060].	Thomson Reuters' DataStream [TRDS]
Board Meeting Number	LnMeeting	The logarithm value of a firm's number of board meetings within a specific year.	Thomson Reuters' DataStream [TRDS]
Total Assets	lnTA	The logarithm value of a firm's total assets.	Thomson Reuters' DataStream [TRDS]
Female on Board	%Female	A firm's percentage of females on board, also known as a proxy for board gender diversity for a firm [CGBSO03V].	Thomson Reuters' DataStream [TRDS]
EBIT/interest	EBIT/interest	Earnings Before Interest and Taxes for a firm scaled by its interest expense on debt [WC08291].	Thomson Reuters' DataStream [TRDS]
Quick ratio	Quick ratio	Quick ratio for a firm's liquidity ratio [WC08101] which is calculated as: Quick ratio = Cash & Equivalents + Receivables (Net)) / Current Liabilities-Total.	Thomson Reuters' DataStream [TRDS]
Operating net cash flow/ Assets	CF/TA	A firm's net cash flow earned from its operating activities [WC04860] scaled by its total assets [WC02999]. The net operating cash flow exhibits the firm's net cash receipts and disbursements resulting from its operations. This item is calculated as the total of the firm's funds from operations, funds used or for its other operating activities, and extraordinary items.	Thomson Reuters' DataStream [TRDS]
Dividend Yield	Dividend yield	Dividend Yield [DY]	Thomson Reuters' DataStream [TRDS]
Debt/Equity	Debt/Equity	Leverage proxy for a firm calculated as the percentage of total debt to its equity [WC08231]. The leverage ratio is calculated using the following formula: Debt/Equity = (Long Term Debt + Short Term Debt & Current Portion of Long Term Debt) / Common Equity * 100.	Thomson Reuters' DataStream [TRDS]
ROA	ROA	Return on assets for capturing a firm's profitability [WC08326] using the following formula: ROA = (Net Income – Bottom Line + ((Interest Expense on Debt-Interest Capitalized) * (1-Tax Rate))) / Average of Last Year's and Current Year's Total Assets * 100.	Thomson Reuters' DataStream [TRDS]
Market/Book	M/B	Market-to-Book value for] which is estimated as the firm's market value of the common (ordinary) equity scaled by its common (ordinary) equity reported in the firm's balance sheet [MTBV] with the item code in Worldscope is 03501.	Thomson Reuters' DataStream [TRDS]
Fixed Assets/Total Assets	Fixed Assets/TA	A firm's fixed assets, also known as tangibility, that represents the firm's net value of property, plant and equipment (PPE) less the firm's accumulated reserves for its amortization, depletion, and depreciation [WC02501] then scaled by its total assets [WC02999].	Thomson Reuters' DataStream [TRDS]
Urban population growth	Urban	A country's Urban population growth (annual %) for capturing its urbanization [SP.URB.GROW].	World Development Indicators of World Bank [WDIs-WB]
GDP Capita Growth	GDP	The annual growth rate of a country's GDP per capita to which a firm belongs [NY.GDP.PCAP.KD.ZG].	World Development Indicators of World Bank [WDIs-WB]
Inflation	Inflation	A country's inflation, GDP deflator (annual %).	World Development Indicators of World Bank [WDIs-WB]
Country governance quality	WBI_index	A country's aggregate governance quality index, which captures the aggregate likelihood value of the following sub-categories of the country: 1- Control of Corruption, 2- Government Effectiveness, 3- Political Stability and Absence of Violence/Terrorism, 4- Regulatory Quality, 5- Rule of Law, and 6- Voice and Accountability. Each of the sub-categories is ranging approximately from −2.5 to 2.5.	World Governance Indicators of World Bank [WGIs-WB]

Appendix B. Sample distribution by country

Country	N	%	Country	N	%	Country	N	%
Argentina	713	0.24%	Hungary	667	0.22%	Pakistan	621	0.21%
Australia	12,673	4.23%	Iceland	23	0.01%	Papua New Guinea	161	0.05%
Austria	460	0.15%	India	2875	0.96%	Peru	552	0.18%
Bangladesh	276	0.09%	Indonesia	598	0.20%	Philippines	874	0.29%
Barbados	46	0.02%	Ireland	1012	0.34%	Poland	1058	0.35%
Belgium	276	0.09%	Isle Of Man	115	0.04%	Portugal	437	0.15%
Bermuda	345	0.12%	Israel	1564	0.52%	Portugal	46	0.02%
Bolivia	207	0.07%	Italy	2001	0.67%	Puerto Rico	46	0.02%
Bosnia & Herzegovina	253	0.08%	Jamaica	46	0.02%	Romania	184	0.06%
Brazil	2530	0.84%	Japan	1817	0.61%	Russian Federation	2530	0.84%
British Virgin Islands	115	0.04%	Jordan	46	0.02%	Saudi Arabia	92	0.03%
Bulgaria	230	0.08%	Kazakhstan	253	0.08%	Senegal	23	0.01%
Canada	29,279	9.77%	Kenya	69	0.02%	Serbia	92	0.03%
Cayman Islands	46	0.02%	Kuwait	23	0.01%	Singapore	621	0.21%
Chile	782	0.26%	Lithuania	161	0.05%	South Africa	253	0.08%
China	10,028	3.35%	Luxembourg	276	0.09%	South Korea	690	0.23%
Colombia	437	0.15%	Malaysia	368	0.12%	Spain	3979	1.33%
Cote D Ivoire	46	0.02%	Mauritius	23	0.01%	Sri Lanka	322	0.11%
Croatia	46	0.02%	Mexico	69	0.02%	Sweden	2415	0.81%
Cyprus	138	0.05%	Mongolia	92	0.03%	Switzerland	782	0.26%
Czech Republic	414	0.14%	Montenegro	69	0.02%	Syrian Arab Republic	23	0.01%
Denmark	552	0.18%	Morocco	69	0.02%	Tanzania	207	0.07%
Ecuador	69	0.02%	Namibia	23	0.01%	Thailand	2185	0.73%
Egypt	23	0.01%	Netherlands	483	0.16%	Turkey	1081	0.36%
Estonia	46	0.02%	New Zealand	1058	0.35%	Ukraine	782	0.26%
Faroe Islands	115	0.04%	Nigeria	253	0.08%	United Arab Emirates	69	0.02%
Finland	414	0.14%	North Macedonia	115	0.04%	United Kingdom	9269	3.09%
France	2576	0.86%	Norway	2668	0.89%	United States	41,308	13.78%
Germany	3404	1.14%	Oman	207	0.07%	Vietnam	1541	0.51%
Greece	368	0.12%	Other Eastern European	138	0.05%	Zambia	46	0.02%
Hong Kong	3151	1.05%	Others	140,164	46.77%			

Appendix C. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eneco.2024.107782.

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