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Article

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Assessing the influence of climate risk, carbon allowances, and technological factors on the ESG market in the European union

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ABSTRACT

Environmental, Social, and Governance (ESG) is a market for environmental criteria that has recently attracted the attention of policymakers and in particular European Union (EU) countries to improve environmental quality. In the context of the EU Sustainable Development Goals, this study aims to examine the impact of climate risk uncertainties (transitional (TRI) and physical (PRI)), carbon allowances (EU ETS), and technology index (MSCI) on the ESG market. To this end, the study uses a quantile-on-quantile regression and its multivariate version for the period from November 28, 2007, to January 05, 2023. The results show that TRI and PRI increase ESG market development at higher quantiles, while EU ETS and technological progress reduce ESG progress. This shows that the risk of climate change requires the introduction of stricter environmental standards in EU countries, while the EU ETS and technological progress provide environmental benefits that reduce the need for the ESG market.

1. Introduction

At the heart of today's corporate expansion was originally corporate social responsibility (CSR), which was based on leveraging the expertise of managers and professionals to drive business growth and diversify investments. However, this significant expansion has led to an increasing dependence on fossil petroleum hydrocarbons, which has proven to be the main catalyst for escalating global temperatures and the associated adversities of climate change. The global community has recognized this phenomenon and has taken action to mitigate its effects,

most notably through the 2015 Paris Agreement (Bataille et al., 2018; Mensah et al., 2019). This agreement has set ambitious goals, such as limiting global temperature rise and achieving carbon neutrality by 2050 (Chen et al., 2022; Huang & Zhai, 2021; Mohammed & Pata, 2023). Internationally coordinated efforts driven by the Conference of the Parties (COP) under the United Nations Framework Convention on Climate Change (UNFCCC) express similar viewpoints. COP27's emphasis on climate action, particularly for major economies, underscores the need to move away from conventional economic models with negative environmental impacts (Guan et al., 2023; UNFCCC,

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2022).

Historic agreements such as the Kyoto Protocol and initiatives, such as the European Union Emissions Trading System (EU ETS) have been instrumental in creating the world's first carbon markets. These mechanisms have facilitated the reduction of climate-related risks by allowing companies to trade emission allowances and thus effectively manage and regulate their emissions. Climate initiatives are beneficial, but they impose a financial burden on companies. Nordhaus (2018) has developed frameworks that enable the assessment of these costs associated with carbon emissions. In conjunction with these advances, the technology industry is at an interesting point to emerge as a prominent participant in ESG markets and reduce climate risk by taking a leadership role in areas (Chen, Khurram, et al., 2023; Tan & Zhu, 2022) that encounter difficulties, such as the generation of electronic waste and the operation of energy-intensive processes (Asif et al., 2023). This industry significantly influences the overall ESG framework through digital innovation (Wang & Esperança, 2023).

Incorporating satellite imagery for environmental assessments, the use of artificial intelligence and machine learning, and the implementation of blockchain for supply chain governance and transparency are changing the way ESG factors are evaluated and addressed dramatically. (Aydoğmuş et al., 2022; Agnese et al., 2023a-b; Kazachenok et al., 2023; Kulkarni et al., 2023). This change involves evaluating and implementing measures as companies currently utilize these advanced technologies to improve their carbon efficiency and overall performance due to financial constraints. Investments are being channeled into green technologies and carbon markets, serving as a mechanism for companies to maintain their CSR and improve the broader ecological ecosystem (Bhatnagar & Sharma, 2022). Looking at these interlinked developments, one prominent overarching theme becomes clear: the interplay between ESG considerations, climate risks, carbon trading allowances, and the technology market is significantly influencing corporate behavior and investment decisions. It can therefore be concluded that climate change has led to considerable and irreversible financial losses for companies.

The introduction of advanced technologies and the adoption of efficient mechanisms for emissions trading can have a positive impact on companies. In this regard, this study examines the complex interactions between climate risk uncertainties, carbon allowance, technological progress and European ESG markets from 2007 to 2023. The integration of economic growth and the introduction of financial technologies in the consolidation of financial markets have contributed significantly to reducing climate risk. The combination of these factors increases the effectiveness of sustainable practices.

Although the relationship between green financial markets and climate risks has already been analyzed to some extent, there is little research on how different ESG markets respond to technological and carbon market risks. Investigating the interplay between these factors is of paramount importance for the development of an environmentally sustainable financial system that is consistent with the intention of achieving net zero emissions targets.

ESG firms need to fully understand the complicated dynamics of market forces and their interactions in order to effectively manage risks. Policymakers and fund managers are increasingly focusing on the factors that contribute to ESG valuations. However, there is a research gap regarding the influence of climate risks and technology on ESG markets. Based on this, the current study makes three main contributions: First, this study examines the impact of carbon allowances (CAE), technology, and climate risks on the ESG market, taking into account economic (EPU) and energy (OVX) uncertainties. Given Europe's prominent position in the ESG market and its pioneering role in carbon allowances, it is crucial to understand the interaction between the Europe's ambition to move to a green economy, various equity markets, uncertainties, and ESG corporate markets. Second, to the best knowledge, this study is the first attempt to examine the collective impact of climate risks and technology on ESG factors. Third, from a methodological perspective,

this study differs in that it includes an analysis of the tail dependency between ESG and climate risks. To achieve this, the study employs a refined multivariate quantile-on-quantile regression (QQR) approach of Sinha et al. (2023). The QQR approach represents an advance over the bivariate method proposed by Sim and Zhou (2015).

The rest of the article is structured as follows. Section 2 gives an overview of the related literature. Section 3 describes the methods. Section 4 presents and discusses the results and explains the implications for hedging. Section 5 concludes the paper.

2. Literature review

Financial development instruments (Aytun et al., 2024; Pata & Fareed, 2023) and governance practices (Aureli et al., 2020; Erdogan et al., 2023; Meng et al., 2023) have become important areas of research for environmental policies and continue to attract the attention of researchers. As a sub-component of corporate governance practices, the importance of ESG criteria has escalated due to social recognition in the financial and sustainability discourse. ESG encompass more than just a company's social commitment and reputation. The concept of governance refers to a company's compliance with legal regulations, established guidelines, and stakeholder expectations. Companies listed on the financial markets are now required to disclose ESG information as it is very comprehensive (Khan, 2022; Pedersen et al., 2021). Many studies have shown that investors clearly prioritize ESG ratings when formulating their investment strategies (Cepni et al., 2023). ESG factors have a significant impact on the evaluation of corporate performance, especially with regard to carbon neutrality and green financing (Wu & Huang, 2022).

The interrelationships between scientific sustainability factors (i.e., ESG factors), climate risks, and the combined impact of carbon prices and technologies form a complex and multi-layered framework that significantly influences international environmental, financial, and economic policies. This framework is constantly evolving to meet the ever-changing challenges of today's society. The European Union, China, and the United States (US), characterized by advanced economic growth, is strategically well-positioned to transition from conventional to sustainable economic systems (Cui et al., 2022; He et al., 2023; Naqvi et al., 2023). This transition can be facilitated by utilizing their established sustainable financial market, which includes ESG firms with a comprehensive framework that can effectively incorporate the various dimensions of sustainability (Fichtner et al., 2023; Zhang, 2023; Zhou et al., 2022).

The consideration of climate risk is also of great importance in the context of investment strategies, corporate decisions, and environmental policy. Engle et al. (2020) have recognized climate risk as a crucial factor in corporate investment decisions, while Rodriguez Lopez et al. (2017) have highlighted its significant influence on companies' strategic efforts to reduce carbon emissions. Faccini et al. (2021) emphasized the relevance of transition climate risk, particularly in assessing the dynamics of stock returns in the United States. Similarly, Cepni et al. (2023) documented that climate uncertainty plays a significant role in information spillover effects in the ESG market, providing valuable insights into the effective management of climate change-related risks. The study emphasizes the influence of policy-related risks rather than the direct impact of climate change. In a recent academic review paper, Ozkan et al. (2022) explain the intricate relationship between a country's vulnerability to climate-related difficulties and its propensity to engage in CSR efforts, paying particular attention to cultural and religious factors. Carbon pricing has become an important sustainability tool, particularly due to its effectiveness in mitigating greenhouse emissions.

The effectiveness of the carbon market in tackling excessive emissions has been demonstrated in large emitters such as the US, China, and Europe, as shown in the studies by Liu et al. (2023), Ozturk et al. (2022), and Qiao et al. (2023). Asl et al. (2022) highlight the dependence of the

traditional, Islamic, and ESG equity markets on carbon credits and show how sensitive the ESG market is to carbon pricing and the green agenda. Regardless, the influence of technology on the ESG market is significant, especially for corporate environmental performance. A study by [Chuang and Huang \(2018\)](#) found that the incorporation of ESG factors in the Taiwanese environment had a remarkably positive impact on corporate environmental performance. In contrast, the research conducted by [Kraus et al. \(2020\)](#) in Malaysia noted that green technology and environmental strategies have an impact on CSR, but no direct impact of CSR on the environmental performance of manufacturing companies. Recently, [Aliani et al. \(2024\)](#) reported that board structure policies improve ESG ratings of 2988 firms from G7 countries. [Galeone et al. \(2024\)](#) concluded that financial technology helps banks to support ESG development in 65 countries. [Kartal et al. \(2024\)](#) noted that the common principle is the most effective ESG principle regarding 66 companies at Borsa Istanbul. [Pinheiro et al. \(2024\)](#) argued that institutional quality has a major influence on the ESG in 412 companies in 19 countries.

Although studies have analyzed various determinants of CSR and ESG, none have yet examined the impact of technology, EPU, ETS, and climate risk uncertainties on ESG. Moreover, previous studies have not considered the multiple effects of factors that have a potential impact on ESG on a quantile basis using the multivariate QQR method. The existing literature is incomplete in this regard and this study aims to contribute to the existing knowledge by analyzing the determinants of ESG, particularly on the basis of the EU region.

3. Methods

This section describes the variables used in this study and their sources. This section also explains the empirical approaches deployed to estimate the outcomes.

3.1. Data harvesting mechanism

As mentioned above, this study examines the impact of climate risk uncertainty, in particular transition risks (TRI) and physical risks (PRI), as well as carbon allowances within the EU ETS and the technologies represented by the MSCI Europe Information Technology Index, on the MSCI ESG market. The analysis also considers the presence of economic policy uncertainty (EPU) and the potential influence of exogenous shocks on EPU. The analysis covers the period from November 28, 2007 to January 05, 2023, and focuses on the European region. After collecting raw data, the study applies the multivariate QQR method to return data through calculating logarithmic differences in line with the recent literature ([Pata et al., 2024](#)).

The study is based on daily data and directly uses MSCI's established indices. The MSCI Europe ESG Leaders Index comprises companies from the MSCI Europe Index that have a solid ESG track record. The constituents of the index are weighted based on their respective market capitalization. The index comprehensively evaluates ESG performance, controversies, and business activities to determine the inclusion of its constituents. The composition of the company's constituent index includes prominent industry leaders and thus reflects the sectoral distribution.

The ESG performance of proxy companies in the European stock market is assessed using the MSCI Europe ESG Index. This assessment is based on the results of recent academic work by [Gavrilakis and Floros \(2023\)](#), [Gubareva et al. \(2023\)](#), and [Kumar \(2023\)](#). In other words, the study utilizes the MSCI Europe ESG Index from Bloomberg Terminal as the European ESG benchmark. Details and definitions of the MSCI Europe ESG Index can be found in [Asia Pacific Equity Research \(2023\)](#) and [MSCI \(2024\)](#).

The MSCI Technological Index (TECH) is a benchmark for the evaluation of European technology companies. This index is the first study conducted in the field of environmental economics. In addition, the European carbon market, represented by the Carbon Allowances Europe

Index (ETS), is used as a benchmark in this study. This index serves as a liquid and investable benchmark for tracking global carbon credits and monitoring carbon emissions in Europe. Carbon credits have attracted interest due to their effectiveness as a trading mechanism and their role in facilitating carbon credit transactions and environmental governance ([Aid & Biagini, 2023](#); [Chen, Geng, & Liu, 2023](#); [Houque & Khan, 2023](#)).

This study also includes the novel categorization of physical risk index (PRI) and transitional risk index (TRI) as outlined by ([Bua et al., 2022](#)). The term 'physical risk' refers to the potential for financial repercussions due to direct consequences arising from tangible events. In contrast, the concept of 'transition risk' refers to the financial impact of the transition to a decarbonized economy. [Bernanke \(1983\)](#) has had a decisive influence on the determination of economic cycles and investment decisions. Previous research has neglected this variable due to the lack of reliable and quantitative measures of policy uncertainty, despite its importance in economics and environmental risk. To address this issue, [Baker et al. \(2022\)](#) developed an EPU index using newspaper sources, a method that has been well-received in academic circles. The indicator has been employed as an exogenous variable in analyzing the relationship between ESG, ETS, climate risk, and technological indices.

The data for the TECH and ESG are obtained from the Bloomberg Terminal, in particular from the Market Data section of Bloomberg Professional Services. The data for EPU is computed and gathered from the St. Louis Federal Reserve Bank. The time courses for each of these variables are depicted in [Fig. 1](#), with the vertical axis showing the index values for each variable. PRI and TRI have remained stable over time. EPU appears to have increased dramatically during the COVID-19 period, particularly in 2020. ETS values have decreased since 2010, while the ETS index has started to increase since 2020. ESG and TECH indices have increased significantly over 10 years.

3.2. Model estimation with M-QQR approach

Quantile regression is a precious tool, allowing researchers to effectively examine relationships with specific quantiles of a dependent variable. This is in contrast to traditional ordinary least squares (OLS) regression, which focuses primarily on average outcomes ([Sim & Zhou, 2015](#)). The use of regression techniques requires careful consideration of assumptions, such as the independence of observations. In the context of empirical research, a comprehensive understanding of the subtleties of the relationships between the different quantiles provides a more nuanced view of possible nonlinearities or heteroscedastic relationships between variables ([Mohammed & Mellit, 2023](#); [Yi & Demirel, 2023](#)).

The behavior of a variable that is dependent on quantiles is influenced by the quantiles of a separate reference set, as opposed to a variable that is independent of quantiles and exhibits consistent behavior across these quantiles ([Fernández-López et al., 2022](#)). These distinctions are important in various scientific disciplines. Pollutant concentrations and health effects can vary across different quantiles, suggesting that health effects may be more pronounced at higher pollutant concentrations ([Quito et al., 2023](#)). The use of quantile analysis has become increasingly important in empirical studies due to the continuous development of research methods and the availability of big data.

The QQR method proposed by [Sim and Zhou \(2015\)](#) is widely used in academic research to evaluate the dynamic and nonlinear influence of a quantile-dependent variable on a quantile-independent variable under different market conditions. The first stage of the QQR approach can be exemplified in Eq. (1):

$$ESG_t = \delta^\theta(ETS_t) + v_t^\theta \quad (1)$$

where v_t^θ illustrates the error term, and $\delta^\theta(\cdot)$ denotes the effect of the θ quantile of ETS. In the second stage, the independent variable (ETS) is linearized considering the first-order Taylor rule, which is shown in Eq. (2):

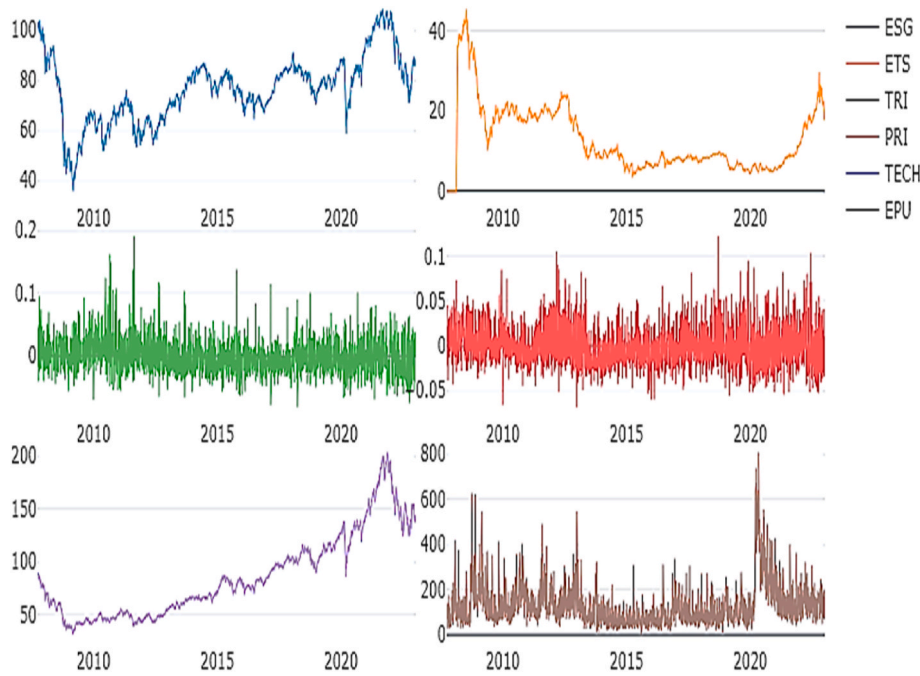


Fig. 1. Data trend from November 28, 2007 to January 05, 2023.

$$\delta^{\theta}(ETS_t) \approx \delta^{\theta} ETS^{\tau} + \delta^{\theta}(ETS^{\tau})(ETS_t - ETS^{\tau}) \quad (2)$$

where δ^{θ} denotes the partial derivative of $\delta^{\theta}(ETS_t)$. $\delta^{\theta} ETS$ and $\delta^{\theta}(ETS^{\tau})$ are converted into $\delta_0(\theta, \tau)$ and $\delta_1(\theta, \tau)$, respectively. The third stage comprises the quantile-based modeling of the independent variable and is represented by Eq. (3):

$$\delta^{\theta}(ETS) \approx \delta_0(\theta, \tau) + \delta_1(\theta, \tau)(ETS_t - ETS^{\tau}) \quad (3)$$

In the last stage, the QQR approach calculates the quantile-based effects of ETS on ESG as in Eq. (4), where $\forall$ shows the θ th conditional quantile of ETS_t , and z_t^{θ} illustrates the quantile-based error term.

$$ESG_t = \underbrace{\delta_0(\theta, \tau) + \delta_1(\theta, \tau)(ETS_t - ETS^{\tau})}_{\forall} + z_t^{\theta} \quad (4)$$

The QQR approach can be used to graphically represent the interaction between two variables. However, the ESG may have more than one determinant. In this case, the QQR estimation cannot fully explain the ESG. To overcome this shortcoming, the study uses the novel multivariate QQR approach.

Sinha et al. (2023) have developed the multivariate QQR method, which incorporates the moderating effects of additional exogenous variables via interactions and potentially overcomes the omitted variable bias of the bivariate QQR. These models effectively overcome

problems such as heteroscedasticity, skewness, serial correlation, and structural breaks. The mathematical equations of M-QQR are estimated as in Eqs. (5)–(8):

$$ESG = \beta^{\theta}(ETS) + \sum_n \beta^{\theta}(x_t) + \sum_n \gamma^{\theta}(EST * EPU_t) + \epsilon^{\theta} \quad (5)$$

$$ESG = \beta^{\theta}(PRI) + \sum_n \beta^{\theta}(x_t) + \sum_n \gamma^{\theta}(pri * EPU_t) + \epsilon^{\theta} \quad (6)$$

$$ESG = \beta^{\theta}(TRI) + \sum_n \beta^{\theta}(x_t) + \sum_n \gamma^{\theta}(TRI * EPU_t) + \epsilon^{\theta} \quad (7)$$

$$ESG = \beta^{\theta}(TECH) + \sum_n \beta^{\theta}(x_t) + \sum_n \gamma^{\theta}(TECH * EPU_t) + \epsilon^{\theta} \quad (8)$$

where ϵ denotes the error term, and θ shows a particular quantile, respectively.

4. Main findings and discussion

4.1. Summary statistics

This section discusses the preliminary results of the descriptive statistics analysis, as shown in Table 1.

Table 1
Descriptive statistic.

	EPU	ESG	ETS	PRI	TECH	TRI
Mean	124.2161	76.34832	12.88910	−0.001046	85.95028	−0.000544
Median	101.5650	77.12050	9.163895	−0.003466	76.87500	−0.003066
Maximum	807.6600	108.3790	45.33787	0.122507	203.4300	0.190732
Minimum	3.320000	35.78600	0.014570	−0.068305	31.74000	−0.081479
Std. Dev.	84.93895	13.32522	8.357977	0.021209	39.60481	0.024130
Skewness	2.340271	−0.038098	1.291013	0.717595	0.895074	0.959689
Kurtosis	11.31926	3.049845	4.726859	4.370757	3.021768	6.794500
Jarque-Bera	15125.51	1.376184	1601.718	653.8313	532.0474	3001.652
Probability	0.000000	0.502534	0.000000	0.000000	0.000000	0.000000
Sum	494876.9	304171.7	51350.16	−4.165815	342425.9	−2.168831
Sum Sq. Dev.	28735851	707227.6	278235.6	1.791591	6247498.	2.319139
Observations	3984	3984	3984	3984	3984	3984

In addition to the basic summary statistics, the study also tests for non-normality, skewness, and kurtosis of the selected series. The median values of the data are derived from their corresponding mean values. This means that the presence of outliers in the data set is not limited, with the exception of the climate risk data, which show relatively small fluctuations. All the time series given show positive values, except for climate risk. This suggests that the shock experienced by the data during various financial turmoils, such as the US subprime crisis, the European debt crisis, the COVID-19 pandemic, and the military conflict between Russia and Ukraine, varies.

All selected series are positively and significantly skewed, except for ESG, which is statically significant but has a negative value. The kurtosis coefficients show excessive kurtosis when the number exceeds three, indicating the deviation of these series from the normal distribution. All series pass the Jarque-Bera test and fail the normality test, as can be seen from the probability values, indicating that time series do not follow a normal distribution. The Jarque-Bera test statistics also show that the quantile-based framework is the most appropriate approach to deal with the non-linearity in the data series (Kartal et al., 2023; Pata et al., 2022).

Fig. 2 presents the results of the pairwise correlation analysis carried out between the series. The outcomes show a clear correlation weakness compared to the other selected series. On closer inspection, it becomes clear that the ESG factor has a positive relationship with the ETS, PRI, and TRI. The correlation coefficients for these associations are 0.02, 0.001, and 0.0002, respectively. Conversely, there is a negative correlation between ESG and TECH as well as EPU, with correlation coefficients of 0.02 and 0.03, respectively. Overall, Fig. 2 shows that the interaction for the TECH & ESG and EPU & ESG pairs is stronger than for the others.

Before presenting the results of the model, it is essential to evaluate the test for nonlinearity proposed by Broock et al. (1996) for the time series. The Brock, Dechert, and Scheinkman (BDS) test is a statistical method for detecting nonlinearity in time series data. This method is used to determine whether a particular time series has deterministic or stochastic characteristics. In the analysis, the correlation sum of the time series data at different embedding dimensions is compared with the expected sum, assuming that the data points are independent. The presence of deterministic structures in the data can be inferred from notable deviations. The test takes into account essential variables such as the embedding dimension and the distance threshold. The results of the BDS analysis are shown in Table 2. The null hypothesis is rejected in favor of H_1 , indicating the potential of utilizing a nonlinear method.

To advance the development of quantile-based estimates, it is essential to identify the presence of time-varying correlations within the series. To achieve this goal, this study performs calculations on the moving window correlation and dynamic conditional correlation of the

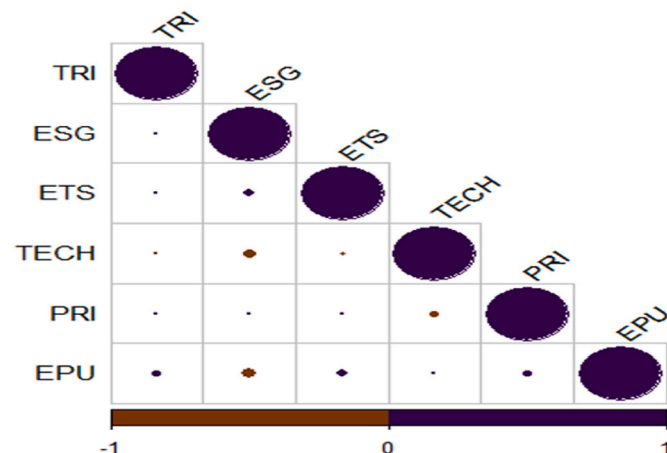


Fig. 2. Correlation outcomes.

Table 2
BDS analysis.

	Dimension				
	2	3	4	5	6
EPU	0.082	0.140	0.173	0.191	0.198
z-Statistic	52.862*	56.537*	58.892*	62.376*	66.931*
ESG	0.197	0.334	0.430	0.496	0.541
z-Statistic	168.508*	181.183*	196.592*	218.617*	248.504*
ETS	0.201	0.341	0.438	0.506	0.552
z-Statistic	155.976*	167.325*	181.511*	201.952*	229.790*
PRI	0.007	0.014	0.020	0.021	0.023
z-Statistic	6.056*	7.596*	8.713*	8.871*	10.149*
TRI	0.010	0.018	0.025	0.029	0.032
z-Statistic	8.401*	9.230*	10.609*	11.953*	13.778*

Note: * refers to significance at the 1% level.

relationship between ESG market factors and the determinants, in particular the PRI, TRI, ETS, and TECH variables. The results are shown graphically in Fig. 3. The analysis of the correlation between these two variables over a 200-month rolling window shows a fluctuating correlation that is clear in both direction and magnitude. It is noteworthy that EGS is positively correlated with TECH in many time periods and that the level of this interaction is higher than for other variables.

Moreover, the correlation between these series could depend on external factors that influence the nature of their relationship. The results of the exogeneity tests are shown in Table 3. The exogeneity test provide information on the independence of the selected moderators, namely the EPU.

Table 4 provides additional evidence of the robustness of parameter selection by comparing the results of the least angle regression.

On the basis of the diagnostic findings, an empirical investigation now begins. The results of the QQR and *m*-QQR tests are explained in detail in the following sections.

4.2. QQR regression results

In Figs. 4 and 5, the QQR and M-QQR plots show a convergent correlation as they approach positive values and a divergent correlation as they approach negative values. The values approaching “0” mean that there is no relationship between the variables.

The estimated results of the model obtained with the QQR are illustrated in Fig. 4 below in panels a,b,c, and. The slope coefficients of the QQR in the given diagram represent the impact of the τ th quantile of the explanatory variable on the λ th quantile of the ESG index.

Panel (a) in Fig. 4 shows a persistent negative effect of TRI on ESG in the lower quantiles. This negative value is consistently in the range of -0.01 to -0.05 . Nevertheless, there is a balancing effect in the transition to the upper quantiles. The visual representation of the intensity increase within the medium range is characterized by the prevalence of warm colors in the green spectrum, ranging from 0.14 to 0.25. However, as one progresses to the upper percentiles of the TRI, a clear intensification of the phenomenon is observed, with an approximate increase of 0.4 in the upper quantile, resulting in a dominance of the yellow spectrum. This shows that the results of the QQR approach indicate that the TRI increases the ESG in the upper quantiles.

The effects of TRI are particularly detrimental in the lower quantiles of the ESG stock market. This phenomenon can be attributed to the fact that companies falling into these quantiles may exhibit lower levels of preparedness or adaptability in response to the ongoing transition to a low-carbon economy. Certain companies may still rely significantly on carbon-intensive practices or have limited resources and expertise to enable a rapid transition. These companies face significant financial vulnerabilities, such as penalties imposed by regulators and technological obsolescence, leading to a decline in the value of their stocks (Krueger et al., 2020). As investors realize these vulnerabilities, they may be reluctant to invest in or divest from these companies,

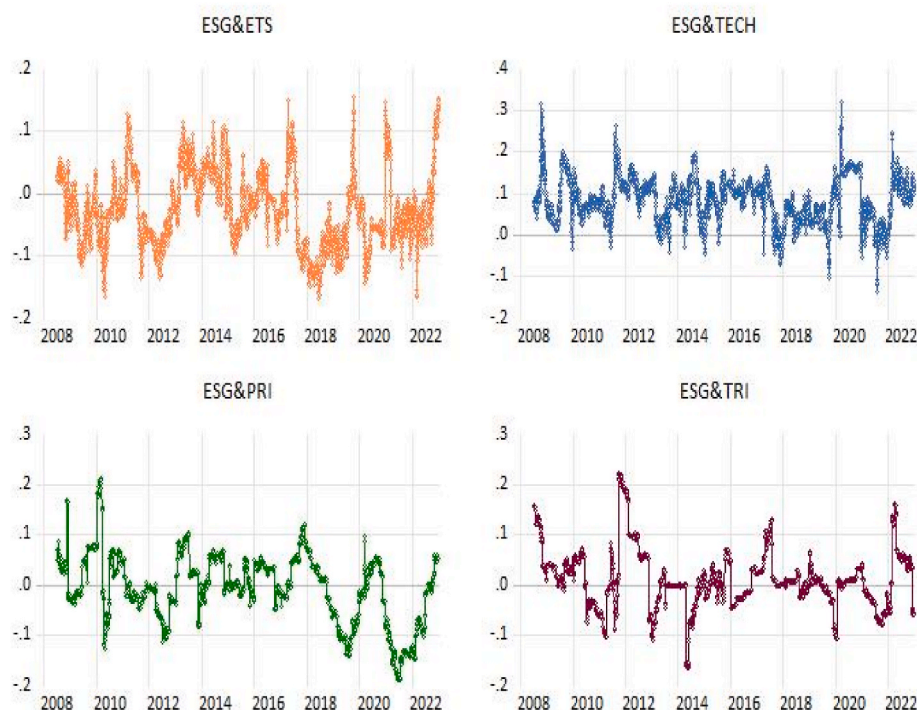


Fig. 3. Moving-Window correlation (200 days W-rolling).

Table 3

Exogeneity results.

	Wu-Husman ST	pvalue	Durbain & Wu-Husman	Pvalue
EPU	260.76963	0.00	244.92283	0.00

Table 4

Least angle regression.

step	Mallow's Cp	R-square	Action
1	8262.8164	0.00	+
2	1124.4689	0.5831	+TECH
3	334.9820	0.6478	+EPU
4	3.9744 ^a	0.6750	+ETS
5	5.1161	0.6750	+PRI
6	6.0000	0.6751	+TRI

^a show the optimum value selection of the minimum M-Cp based on the lasso Algorithm.

exacerbating the decline in their stock prices.

In the upper quantiles of the ESG stock market, despite the rise of TRI, the ESG market shows remarkable success in linking TRI to favorable outlooks and rising market demand for these stocks. Companies that fall into these quantiles tend to exhibit higher levels of proactivity, have greater resources, and are strategically positioned to effectively manage and potentially benefit from the climate risks associated with the transitions. During a high TRI, individuals and organizations often adopt innovative practices, expand their scope of operations, and redefine their brand image. This finding is consistent with the study by Cepni et al. (2023), as with increased climate uncertainty, the integration of ESG equity portfolios can be used to mitigate the risks associated with actual climate-related events.

Panel (b) in Fig. 4 shows an initial positive impact of about 0.03 within the lower quantiles of the PRI on the ESG market. However, the observed impact becomes negative in other ESG quantiles and the lower quantile of the PRI. In the higher quantiles of the ESG and PRI, the observed value remains consistently negative at around -0.11 .

However, in the upper PRI quantile and the lower ESG quantile, there is a notable positive impact of around 0.8. This finding indicates a more pronounced negative correlation between PRI and ESG compared to TRI and ESG. The initial positive impact of PRI on ESG suggests that companies that are strongly aligned with ESG principles may receive a slight premium when they are exposed to moderate physical risk. However, the complexity of this situation increases when comparing the quantiles of the ESG factors with those of the PRI.

The negative impact of the PRI on ESG means that companies that face lower physical risks but adhere strongly to ESG principles do not necessarily show positive stock performance. Investors expect companies to be more proactive in addressing ESG concerns given the temporary reduction in immediate physical risks. In the given constellation, a notable positive impact of PRI on ESG can be observed, which is around 0.8. The result is in line with previous studies by Fichtner et al. (2023), and Zhou et al. (2022), who concluded that ESG firms that provide a comprehensive framework can effectively address sustainability and reduce climate risks.

Panel (c) in Fig. 4 indicates that the effect of TECH on ESG is consistently positive in the various segments of the data distribution. This trend is reflected in the slope coefficients of 1.77 in the QQR analysis. It is worth noting that companies with strong ESG performance, particularly those ranked in the highest ESG quantile, appear to have significant advantages even with limited technology exposure. This is evident when these companies are positioned in the lower quantile of TECH. The favorable effect of TEC on ESG is consistent with the study by Ozkan et al. (2022). Technological progress can help to set higher environmental standards, as advances in energy efficiency, energy production, and renewable energy deployment technologies include environmental benefits. Companies that produce with advanced technology can contribute to ESG development by making their production processes cleaner, which is consistent with the findings of this study.

Panel (d) in Fig. 4 illustrates the quantitative relationship between the slope of carbon trading and its impact on the ESG market. A positive effect of 0.8 to almost 1.9 is observed across different ETS quantiles and within the lower range of ESG (0.05–0.35). This effect in the higher quantile can be traced by examining economic incentives and strategic

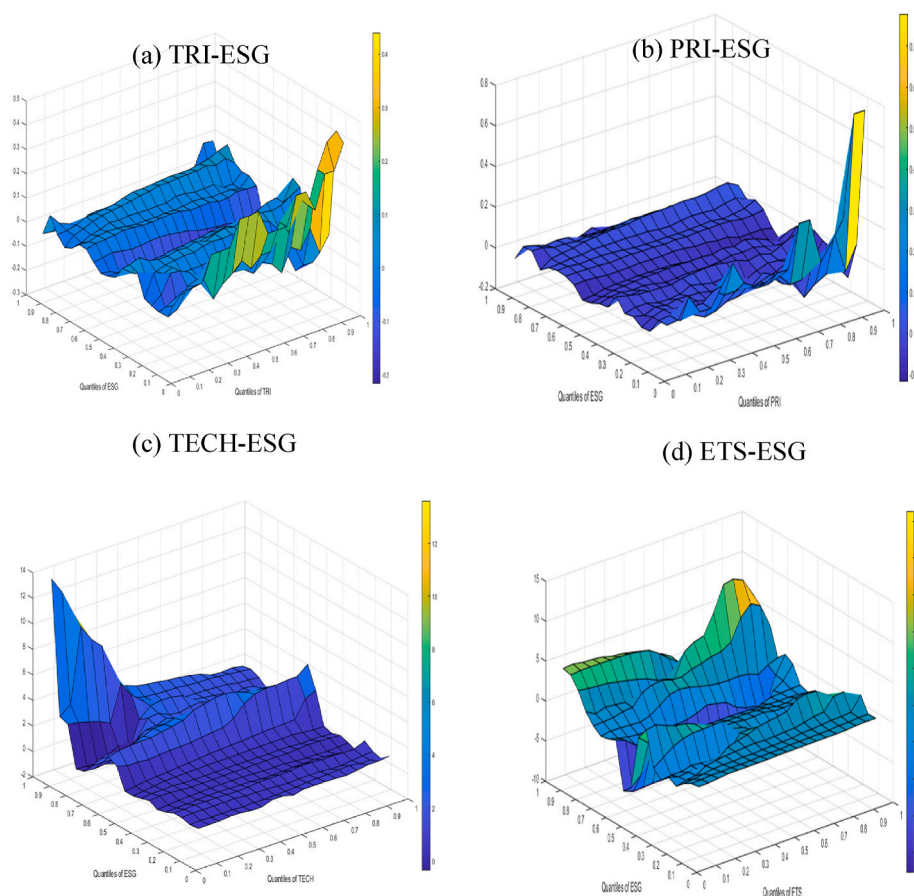


Fig. 4. QQR results.

foresight. Given their significant market influence and substantial capital reserves, companies operating in this space have a distinct advantage when it comes to taking advantage of the ETS, creating economic incentives for companies to reduce their emissions, and acting as a catalyst for strategic business transformation (Rodriguez Lopez et al., 2017). For these prominent companies, the practice of carbon trading is not just a means to meet regulatory requirements, but rather an opportunity to secure their operations for the future. The result regarding the link between ETS and ESG is consistent with the study by Siddique et al. (2021), which establishes a link between carbon pricing through carbon disclosure and ESG performance. However, the results of the current study contradict the research of Dewaelheyns et al. (2023), which showed that the observed increase in policy-induced carbon risk leads to a decline in firm value for companies that do not have sufficient carbon allowances.

4.3. M-QQR findings

The novel M-QQR method is used to investigate the subtleties of the exogenous shocks moderated by the EPU. In other words, the effects of TRI, PRI, TECH, and ETS on ESG are tested using the M-QQR approach by including the control variable (EPU) in the analysis. The results of this analysis are shown in Fig. 5.

The results in panel (a) of Fig. 5 indicate that TRI has a positive impact on the ESG market. The observed impact is more pronounced when the influence of the EPU is taken into account, compared to the results of the QQR analysis. Therefore, the importance of the EPU for the link between TRI and ESG should not be underestimated. This statement underlines the importance of the external economic and political environment in influencing the way transition risks manifest themselves in the market. Companies may be reacting to the immediate consequences

of climate risks and the broader uncertainties associated with the economic policies that regulate these risks. In an environment dominated by EPU, the ability of companies to skillfully manage TRI becomes more important. The presence of EPU strengthens the market's appreciation of effective risk management. Companies that demonstrate flexibility and foresight in dealing with TRI become attractive investment opportunities.

Panel (b) in Fig. 5 illustrates that the PRI principles have a significant and positive influence on the ESG market. The observed positive correlation is subject to considerable modulation by external factors, with a focus on the EPU level. The inclusion of the EPU has a significant impact on the extent and nature of the influence of the PRI on the ESG market. The presence of a low ESG level in combination with the influence of the EPU leads to a negative result. This means that the valuations of companies are negatively impacted by physical climate risks when lower ESG ratings and EPU are taken into account. The amplification of the vulnerability of companies facing direct climate challenges appears to be exacerbated by the turbulence resulting from uncertain politics. The dynamics change significantly in the higher quantiles. In Europe, there is a significant and positive impact when looking at the higher values of EPU, PRI, and the ESG indices simultaneously. This underscores the importance of the political landscape in determining market responses to physical climate risks. In situations where companies operate in an environment that exhibits high levels of EPU, their ability to effectively manage physical risks serves not only as a means of resilience but also as a factor that differentiates them in the marketplace. In these particular circumstances, companies that demonstrate expertise in managing PRI are praised for their ability to anticipate and adapt, which in turn has a positive impact on their ESG ratings.

Panel (c) in Fig. 5 reveals that TECH has a negative impact on ESG when the EPU is included in the analysis with M-QQR. In contrast to the

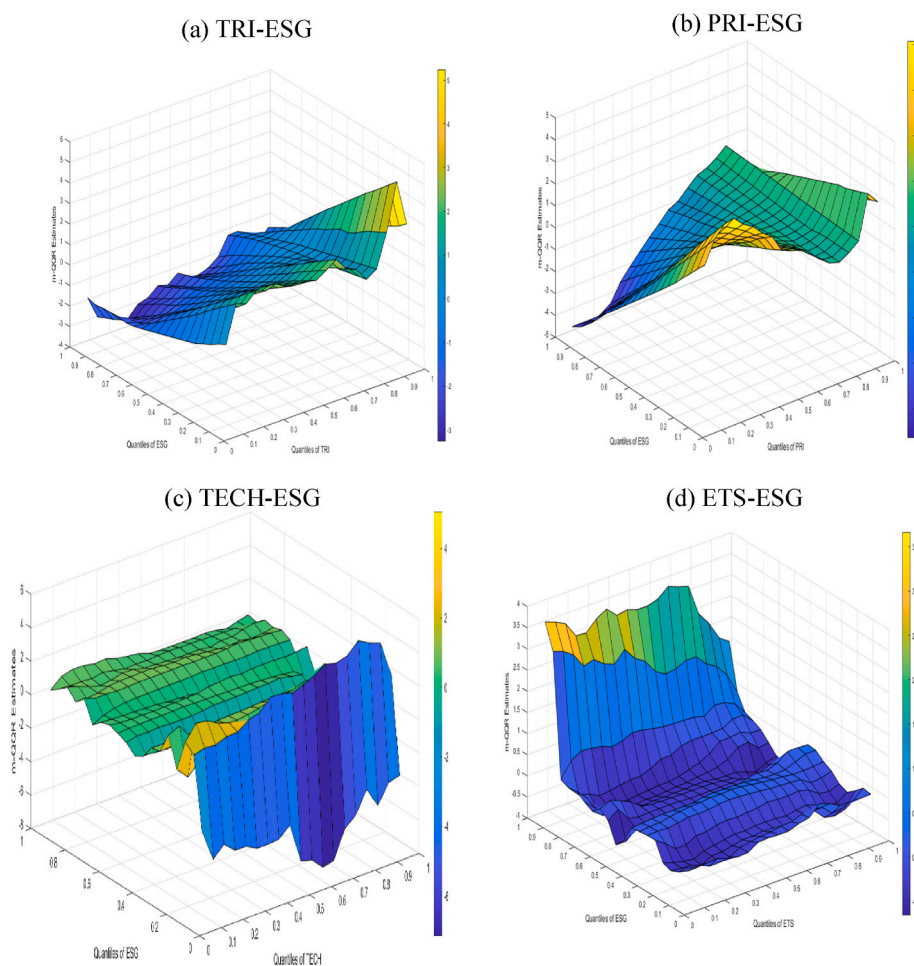


Fig. 5. M-QQR results.

QQR results, this shift that led to negative effects of the TECH variable can be attributed to the uncertainties associated with technology-related investments in an unpredictable policy environment. Companies at both ends of the technology spectrum may perceive greater risks due to unclear economic policies. Companies that invest little in technology may be reluctant to invest further, while companies that are heavily invested in technology may fear the potential negative impact of sudden policy changes. This implies that the EPU is hindering companies' environmental technological developments and progress in ESG, and shows that the EU countries need to eliminate economic uncertainties in order to improve environmental standards at a technological level.

In panel (d) of Fig. 5, the introduction of the EPU factor has led to a break in the previously observed positive correlation between the ETS and the ESG market. The impact of the ETS on the ESG market shows a detrimental trend across different ETS quantiles. In the higher ESG quantile, however, the effect reverses and becomes positive. This means that the EPU can influence the overall perspective of carbon trading for companies. The prevailing opinion of many people is that the ETS is associated with increasing uncertainty, leading to a generally negative perception. However, it is worth noting that companies with significant size and influence in the upper quantile of ESG rankings may have a different perspective on the matter. The company's extensive resources, strategic foresight, and skill in dealing with regulatory uncertainty enable it to generate revenue from carbon trading, which favors a positive association with the ESG market.

5. Conclusion and policy implications

5.1. Conclusion

This study aims to investigate the influence of green bonds on climate risk indices, with a particular focus on the EPU and the CSI, using the MQQR and QQR methods. The results emphasize that climate concerns, technological improvements, and carbon pricing have a significant and diverse influence on the ESG investment market. This impact is particularly evident when the degree of uncertainty in economic policy is taken into account.

5.2. Policy implications

Based on the research findings, it is clear that the ESG market operates in a complex network of interconnected factors, including climate risks, technological progress, and carbon regulations, all of which are embedded in the broader context of overarching economic policies. Policymakers occupy a central position in this complex network. They significantly influence the environment through the formulation of clear and well-designed policies, particularly in the areas of carbon pricing and climate risk disclosure.

Technology is driving change and innovation in the ESG sector. Given the revolutionary power of technology, policymakers need to create an environment that promotes green technologies. Incentivizing research into sustainable technologies and a robust digital infrastructure that supports data sharing can help ESG decision-makers make informed decisions. Creating interoperable technology standards is critical, as

standardization usually precedes mainstream adoption. Investors need to understand the long-term value proposition of technology-focused ESG companies to make them attractive targets. This, and a willingness to embrace new technologies, could benefit investors in a rapidly changing industry. Fund managers who combine policy and investing should use sophisticated analytics and AI for market insights and work with digital startups to innovate. However, policymakers should not ignore the fact that EPU is hindering the link between technology and ESG. Economic uncertainties prevent TECH from having a positive impact on ESG. Therefore, policymakers should take measures to minimize EPU or prevent its harmful effects before adopting a policy measure that improves ESG. In this context, regular financing schemes that are not affected by EPU can be developed for ESG-related technological investments. This TECH & ESG relationship, which is valid for EU countries, can also be global. Therefore, countries in the global world should make technological progress in ESG development while considering economic uncertainties. To this end, global ESG development can be achieved through global collaborations.

TRI and PRI support the development of the ESG market. The transitional and physical increase in climate risk uncertainties is prompting EU countries to diversify and expand ESG. Rising climate risks reinforce countries' environmental concerns and efforts. In this context, not only policymakers in the EU but also in other countries should take steps to support ESG as global climate risks increase. To this end, policymakers can grant tax exemptions to companies that implement ESG standards.

The EU ETS is the world's leading system for carbon allowances. Carbon allowances give companies the right to emit a certain amount of carbon emissions into the atmosphere. These rights can have a negative impact on ESG development. Carbon allowance prices have risen significantly, especially since 2021 (ECB, 2021). However, the results of the current study show that carbon allowances have a negative impact on ESG, suggesting that carbon allowance prices are not yet a deterrent. In this context, both EU policymakers and international institutions and organizations can support the development of ESG by raising carbon allowance prices to a level that discourages carbon emissions. With policies that simultaneously consider TECH, PRI, TRI, and ETS, policymakers can contribute to ESG development at regional and global levels.

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Availability of data and materials

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Ethics approval and consent to participate

Not applicable.

Consent for publication

The authors are willing to permit the Journal to publish the article.

CRediT authorship contribution statement

Ugur Korkut Pata: Conceptualization, Methodology, Writing – review & editing, Investigation. **Kamel Si Mohammed:** Data curation, Software, Writing – original draft. **Vanessa Serret:** Investigation, Writing – review & editing, Writing – original draft. **Mustafa Tevfik Kartal:** Formal analysis, Writing – review & editing, Writing – original draft.

Declaration of competing interest

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

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