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Is Climate Risk a Priced Factor in Fixed Income Markets?

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ABSTRACT (English)

This study examines the impact of climate risk in the US and European corporate bond markets. By analyzing the significant changes in a few bonds' characteristics before versus after the announcement of the Paris Agreement (i.e., the materialization of a climate risk of transition type), it can be observed that bonds' prices as well as their price volatilities significantly decreased after such announcement, where the price drop for European bonds appears more pronounced. Spreads bid-ask, on the other hand, seem to have remained unaffected. Investigating whether such changes can be explained by a number of the issuing firms' sustainability characteristics, it becomes clear that neither the ESG- nor the Environmental-scores (E-Score) have any predictive power in this context, although higher values for these scores, especially for the E-score, should imply a lower exposure to such climate risks. On the other hand, in the attempt to correlate the price changes with the levels of greenhouse gas (GHG) emissions of the issuing firms, different results are obtained depending on whether parametric or non-parametric tests are used. While the non-parametric tests show no significant relationship between firms' emission levels and their respective bond price changes, the parametric tests detect a statistically significant negative correlation between the two variables, which would allow to conclude that climate risk is a priced factor in the fixed-income market of corporate bonds, as the bonds' price changes turn out to be significantly negatively correlated with the level of emissions of the issuing companies, corresponding specifically to a 1-basis-point decrease bond prices for each additional 896,057.35 tons of total GHG emissions (i.e., Scopes 1+2+3) in the US market and a 1-basis-point decrease in bond prices for each additional 311,411.86 of GHG emissions of Scopes 1+2 for European bonds.

Keywords: *Climate Change, Climate Risk, Transition Risk, ESG, Carbon Risk.*

ABSTRACT (German)

In dieser Studie werden die Auswirkungen des Klimarisikos auf die US-amerikanische und europäischen Märkte für Unternehmensanleihen untersucht. Durch die Analyse der signifikanten Veränderungen einiger Anleihensmerkmale vor und nach der Ankündigung des „Paris Agreement" (d.h. der Verwirklichung eines Klimarisikos vom Typ „Transition Risk") lässt sich feststellen, dass die Kurse der Anleihen sowie ihre Kursvolatilität nach dieser Ankündigung deutlich zurückgegangen sind, wobei der Kursrückgang bei europäischen Anleihen ausgeprägter zu sein scheint. Die Spreads bid-ask hingegen scheinen unbeeinflusst geblieben zu sein. Bei der Untersuchung, ob solche Veränderungen durch eine Reihe von Nachhaltigkeitsmerkmalen der emittierenden Unternehmen erklärt werden können, wird deutlich, dass weder der ESG- noch der Environmental-Score (E-Score) in diesem Zusammenhang eine Vorhersagekraft haben, obwohl höhere Werte für diese Scores, insbesondere für den E-Score, eine geringere Exposition gegenüber solchen Klimarisiken implizieren sollten. Bei dem Versuch, die Preisveränderungen mit den Treibhausgasemissionen der emittierenden Unternehmen zu korrelieren, werden hingegen unterschiedliche Ergebnisse erzielt, je nachdem, ob parametrische oder nicht-parametrische Tests verwendet werden. Während die nicht-parametrischen Tests keine signifikante Beziehung zwischen den Emissionsniveaus der Unternehmen und ihren jeweiligen Anleihekursänderungen zeigen, stellen die parametrischen Tests eine statistisch-signifikante negative Korrelation zwischen den beiden Variablen fest. Dies führt zu dem Schluss, dass Klimarisiko ein Faktor ist, der auf dem Markt für festverzinsliche Unternehmensanleihen eingepreist wird. Die Kursänderungen der Anleihen korrelieren signifikant negativ mit dem Emissionsniveau der emittierenden Unternehmen, was konkret einem Rückgang der Anleihekurse um 1-Basispunkt für jede zusätzliche 896.057,35 Tonnen Gesamt-Treibhausgasemissionen (d.h. entspricht, Scopes 1+2+3) auf dem US-Markt und einem Rückgang der Anleihekurse um 1-Basispunkt für jede zusätzliche 311.411,86 Tonnen Treibhausgasemissionen der Scopes 1+2 bei europäischen Anleihen bedeutet.

Stichwörter: *Climate Change, Climate Risk, Transition Risk, ESG, Carbon Risk.*

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1. Introduction

1.1. Motivation

Climate change undoubtedly represents one of the most arduous challenges of the 21st century, both from a social and political standpoint, but also from a financial perspective (see for example Krueger et al., 2020; Ginglinger and Moreau, 2023; Hartzmark and Sussman, 2019).

A relatively young literature has been developing, especially over the past 15-20 years, with the aim of providing a more scientific approach for the estimation of the developments as well as the consequences related to such a phenomenon. Fundamental contributions from world-wide famous institutions, climate modelers, physicists and many other researchers have played a major role also for the financial industry when it comes to estimating how a number of companies and, more generally, financial assets can be impacted by it (see for example Bansal et al., 2016 and Krueger et al., 2020).

For this reason, when discussing about the future financial implications of climate change, it is of imperative importance to first understand the natural science behind it, as such analysis provides the basis for a better understanding (and anticipation) of the reactions of market participants and policy makers.

Once the natural science around climate change has been analyzed and comprehended, it is then possible to derive what possible financial risks and opportunities come along with it.

This thesis is therefore structured in the following way: First, it will be discussed what climate change is, its drivers, as well as its future estimated developments, as such aspects represent the building blocks needed to understand some concepts and reasonings that will follow shortly after. Next, a summary of the literature about the financial implications of climate change and its associated risks and opportunities will be presented.

Finally, the results of an empirical study about a specific type of climate risk, namely the transition risk represented by the announcement of the implementation of the Paris Agreement of 2015 and its reflections in the US and European corporate bond markets will be provided, after which a number of conclusions and possible interpretations can be derived.

The reason behind the choice of focusing on bonds is that the bond market is often underestimated and considered as the "backwater of capital markets", but its size speaks against such disregard. In fact, in 2020 its global value was approximately $128 trillion, out of which around 32% - i.e., $41 trillion ca. - was represented by corporate bonds (ICMA, 2020), while in the same year, the value of the global stock market was around $109 trillion (Statista, 2024). Keeping in mind the vastity of such a market, it becomes clear that a fair and correct pricing of climate risks can potentially reduce the possibility of wealth transfers between uninformed and sophisticated investors, as well as reducing the probability of extreme future price movements (Weikai Li– Singapore Management University, NGFS workshop), especially given that bond issuances by corporations and flows to bond funds on behalf of households have been increasing continuously in the past years (Duan et al., 2021).

The aim of this work, therefore, is to attempt providing more clarity within this complex topic and understand what reflections a climate risk of transition type can have for the corporate bond market, as well as exploring whether such a risk is also a priced factor within this market.

1.2. Understanding Climate Change

Many studies have been conducted in order to analyze whether climate change exists and whether it can consist of a real threat to our society as a whole (e.g., Van Vuuren et al. 2011, Levitus et al., 2017, Gasparrini et al., 2017).

Among the most predominant organizations operating in this field and attempting to provide guidance in this matter is the *Intergovernmental Panel on Climate Change (IPCC)*, a special United Nations body set up in 1988 in order to assess the science related to climate change, ultimately providing scientific basis for understanding what it is, its impacts and future risks, as well as options for the adaptation and mitigation (Intergovernmental Panel on Climate Change, 2024).

The scientific basis of the IPCC's outputs is the result of the contribution of thousands of researchers and experts throughout the world, who analyze and assess thousands of scientific papers which are published every year and, in the end, provide a *comprehensive summary* of the main findings and developments.

Another worldwide-famous organization active in this regard is NASA, which has dedicated a relatively new section of investments to climate change research with the aim of finding out more about its developments, as well as its present and expected future impacts.

NASA, among others, has identified evidence of climate change via nine different channels (*Evidence - NASA Science*, n.d.), namely:

- Global temperature rising: increase of 1°C since the late 1800's, mostly driven by human activities, especially through increased carbon dioxide emissions into the atmosphere.

- Ocean warming: since 1979 the top 100 meters of ocean have warmed-up by 0.33°C (Levitus et al., 2017).

- Ice sheets shrinking: between 1993 and 2019 Greenland has lost on average 279 billion tons of ice per year, whereas Antarctica around 148 billion tons per year (Velicogna et al., 2020).

- Retreating of glaciers, including the Alps, Himalayas, Andes and Alaska.

- Decrease in snow cover in the Northern Hemisphere.

- Rising of sea level: over the last 100 years the global sea level rose about 20 centimeters.

- Declining of Artic Sea ice in both extent and thickness (Zhang and Rothrock, 2003).

- Increased frequency of extreme weather events: since the 1950's, the number of record high temperatures as well as intense rainfall events has been increasing in the US, while the number of record low temperatures has shrunk (USGCRP, 2017). The same is true for Europe as well, according to the European Environment Agency (EEA Report, November 2017; Crespi et al., 2023).

- Increase in ocean acidification: ever since the beginning of the Industrial Revolution, the acidity levels of the water surfaces have increased by around 30%, mostly due to humankind emitting carbon dioxide into the atmosphere, which is later absorbed into the ocean (C.L. Sabine, et al., 2004; Pörtner et al., 2019).

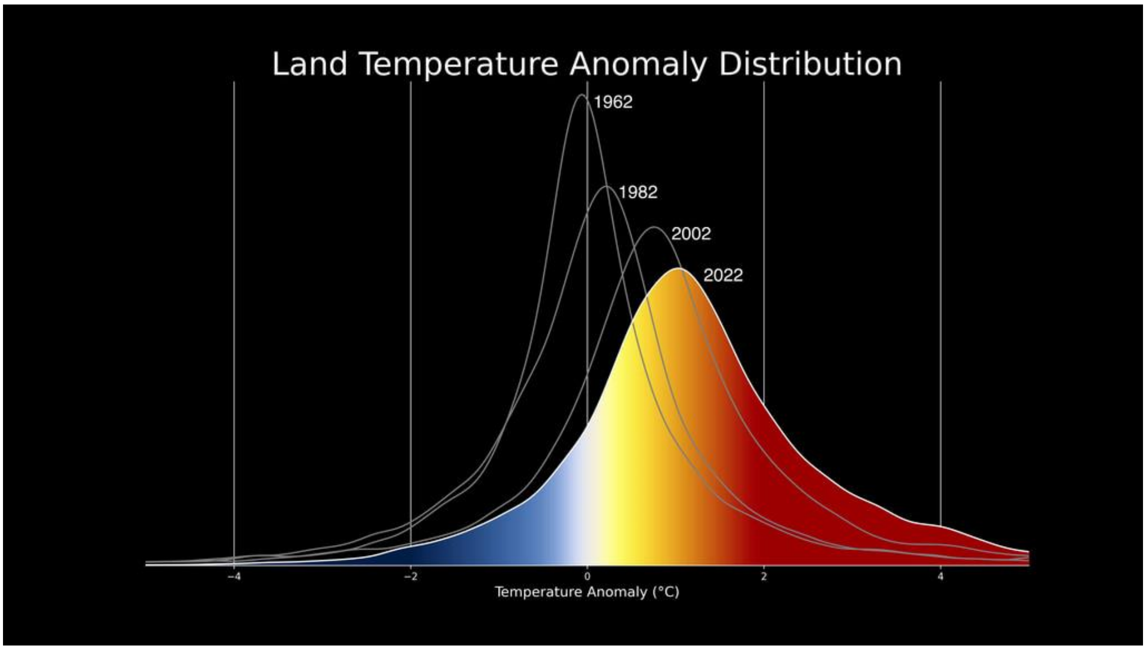
Other research shows that even when closing up the range of this analysis to the past decade, the situation has not shown any improvement and, on the contrary, carbon dioxide emissions from fossil fuels have even grown by more than 10% (Levin, 2019).

Furthermore, according to NOAA (National Oceanic and Atmospheric Administration), while the global average temperature in 2010 was 0.88°C higher than pre-industrial levels, in 2019 it was 1,1°C above these levels and the average global temperature in 2023 was the highest since the beginning of global records in 1850 (NOAA 2023 Annual Global Climate Record).

On top of that, extreme weather has become even more frequent and severe. Populations throughout the world are already dealing with the impacts of just 1°C of warming, with every additional fraction of a degree rise translating in more death and devastation, as also shown by Gasparrini et al. (2017).

Figure 1 below, provided by NASA's Scientific Visualization Studio, provides a clear picture of the change in distribution as well as temperature levels over the past 50 years.

Figure 1 - Shifting Distribution of Land Temperature Anomalies, 1962-2022



Source: NASA's Scientific Visualization Studio - https://svs.gsfc.nasa.gov/5065/

In short and to summarize the literature described above, climate change exists and can be defined as the result of human activities (such as the burning of fossil fuels) which generate increasing amounts of carbon emissions released into the atmosphere, with the end-result of enhancing what is known as the “Greenhouse Effect” (*What Is the Greenhouse Effect? - NASA Science*, n.d.).

It is important to note that such an effect does not represent a problem when it happens in a natural way. As a matter of fact, quite the opposite is true: it allows for life on Earth, as it is a phenomenon through which the heat radiated by the Sun is kept by the gases present in the atmosphere, hence slowing-down the cooling process of the planet (*What Is the Greenhouse Effect? - NASA Science*, n.d.).

The main issue of today’s situation is that this greenhouse effect is artificially-enhanced and, as a consequence, the heat gets “trapped” in the atmosphere for a much longer period of time than it should, with the end-result of overheating the surface of Earth and, finally, changing in an unnatural way the features of the planet, as shown by researchers working for institutions of high credibility, such as NASA (*What Is the Greenhouse Effect? - NASA Science*, n.d.).

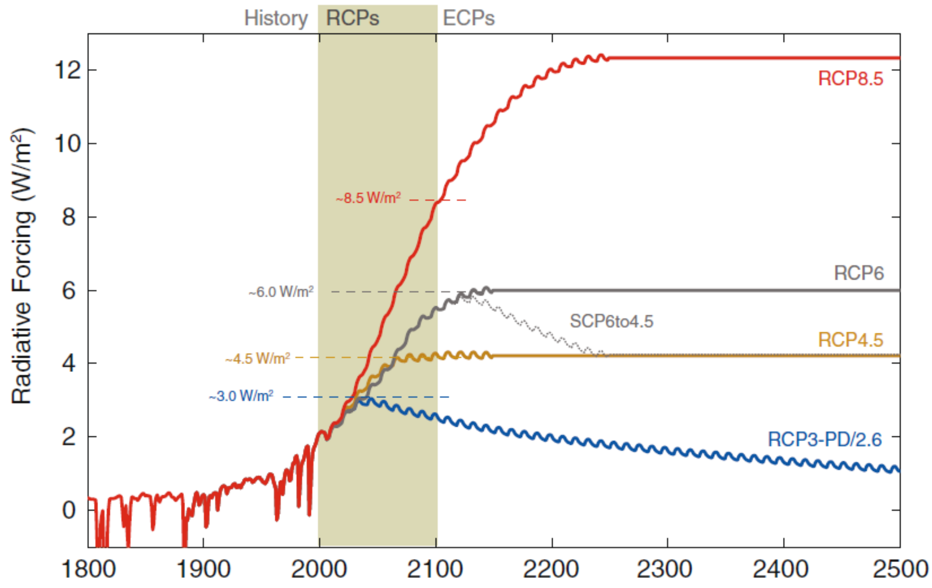
At this point, the question is to understand whether all of this can have impacts within societies, economies and, in turn, financial markets.

This is undoubtedly a very challenging aspect to study, given both its complexity and vastity. For this reason, a first good step is to have a better understanding of what future scenarios could unfold from a climate change perspective in order to have a clearer picture of what potential losses (and opportunities) might be derived by it and, in turn, to better understand the reasons behind the rise of a number of climate risks for market participants.

1.3. Future Developments of Climate Change and "Representative Concentration Pathways (RCPs)"

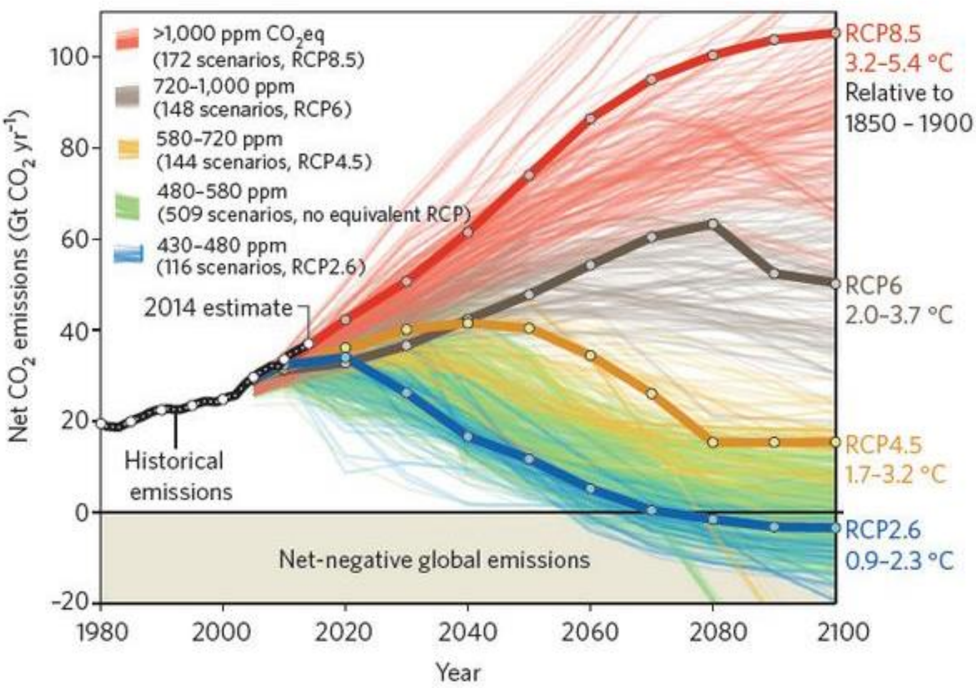
In order to analyze how climate change will develop with time, forecasts from a number of climate modelers can be used, as they allow for a credible assessment of its evolution, as well as plausible estimates concerning the impacts caused by it. Over the past decades, a number of researchers from all over the world have been investigating such issues, which altogether contributed to the creation of several common sets of scenarios. Two prominent specimens in this context are provided by the IS92 Scenarios (Leggett et al. 1992), as well as the more modernized scenarios incorporated in the Special Report on Emission Scenarios (SRES), by Nakicenovic et al. 2000. A big step ahead consisted of developing what today is known as "Representative Concentration Pathways", which is, as the term itself suggests, a set of four different pathways which provide forecasts of future temperatures and climate change developments as a whole. Their creation has been possible thanks to the contributions and collaborations of several emission inventory experts, terrestrial modelers, integrated assessment modelers and climate modelers (e.g., Meinshausen et al. 2011, Hurtt et al. 2011, Lamarque et al. 2011, Granier et al. 2011, Van Vuuren et al. 2011, Thomson et al. 2011, Riahi et al. 2011, Masui et al. 2011) and they have been developed with the aim to describe future possible radiative forcing levels within the year 2100 (also extensible up to the year 2300), which can be summarized in four "emission-scenarios", namely 8.5, 6, 4.5 and 2.6 W/m^2. Importantly, the literature contributing to the set-up of these scenarios has also been selected, among others, to realize one of the most worldwide-important reports which addresses climate change, that is to say the *Fifth Assessment Report (AR5)* from the IPCC. The reason for the success of this set of literature is that, when put together, it is regarded as representative of the total literature on this topic, as all the proposed results are compatible with the full range of scenarios available based on the current literature (from the more moderate to the most extreme outlines) and, in addition to it, the adopted methodology guarantees both the consistency and plausibility of such estimates (Van Vuuren et al. 2011). Below are two graphical representations of the results of the extensive literature described above.

Figure 2 - Total Radiative Forcing per RCP



Source: Van Vuuren et al. 2011

Figure 3 - RCPs scenarios with corresponding temperature levels and Net CO2 emissions



Source: Physics, 2015

To summarize the results provided in this section, it is possible to notice that there exists a direct and positive correlation between climate change and the levels of emissions which are produced by mankind, measured on a “radiative forcing”-level scale (Van Vuuren et al. 2011; Lee at al., 2021).

Therefore, and very importantly, the more emissions are released into the atmosphere, the more enhanced climate change is (Copernicus Climate Change Service, n.d.).

Focusing the attention on *Figure 3*, it appears clear that CO2 emissions are highly correlated with the RCP levels and, in turn, with climate change and that higher levels of emissions (namely, higher RCPs) correspond to higher temperatures, as also pointed out in Lee et al. (2021).

All of this information will become useful knowledge in order to better understand the dynamics behind the financial implications of climate change that will be discussed in the next section.

2. Literature Review

2.1. Financial Implications of Climate Change

In the previous chapters, it was explained what climate change is, as well as what the drivers for its future expected development are (i.e., carbon emissions, mainly).

At this point, the main issue is to understand whether such a phenomenon and its possible future developments translate into tangible financial risks, too.

An important contribution in this context is provided by Krueger et al. (2020). The authors argue that climate change and its associated risks will likely have large impacts on investors' portfolio companies. This is due to the dual nature of such risks, namely they can be either *Physical Risks*, or *Transition Risks* and most companies tend to be exposed to both of them.

The authors conclude that a vast number of firms face direct costs that are caused by climate change, such as those generated by extreme weather events or other physical phenomena which have been previously described. Hence, intuitively, a *physical risk* can be defined as the risk of undergoing physical damage to one's property or assets. For instance, the increased exposure of insurance companies when it comes to property and casualty losses, food producers' and farmers' higher risk of enduring sustained draughts in the future, or the increased exposure to flood-risks for firms operating near coastal areas (Krueger et al., 2020).

The flip side of the coin is represented by *Transition Risks*. Such can be defined as the risk of being more indirectly affected by climate change via changes in the regulatory environment which may be put in place in order to try tackling its development.

On top of that, Kureger et al. (2020) point out that there exist also technological risks involved with climate change, such as the possibility that some business models will be considered inadequate in a potentially greener world. Hence, companies which do not invest in innovation and other forward-looking green technologies might face adverse consequences (one example in this context is the rapid development of electric vehicles which could disarray the long-established combustion engine cars and their respective manufacturers).

Thus, one could conclude that *physical risks* and *transition risks* are two sides of the same coin called “climate change risk” and, although different in the drivers behind their materialization, they are both hugely and equally significant for the long-term sustainability of companies of any industry.

Therefore, independent of which scenario will unfold in the future in terms of climate change developments (as analyzed and discussed in chapter 1.3), it is fair to assert that each one of them will come along with different types and magnitudes of risks, potentially with enormous financial implications for firms operating in any part and industry of the world. The reason being that the two types of climate risks described (i.e., physical and transition) are to some extent one the trade-off of the other and, in the end, either way unavoidable (Krueger et al., 2020).

Going back to what was described in the previous chapter, it appears clear that physical risks are more likely to materialize at higher RCP levels (i.e., higher global temperature levels), as such circumstances are associated with the maximum manifestation of climate change and, hence, its (negative) physical consequences are also maximized and become more relevant.

On the other hand, the flip side of the coin is represented by the potential efforts of regulatory bodies to attempt to fight climate change by tackling it, as they will do so most likely by discouraging polluting behaviors of firms. As a consequence, this would likely result in enhanced carbon taxes or other similar penalties which would increase the portion of fixed costs of companies, hence reducing their expected future profitability (Dorsey-Palmateer and Niu, 2020).

Another aspect that ought to be taken into consideration and should not be underestimated is that the attention to ecology and sustainability of the younger generations has reached all-time-high records, with some literature in this regard showing that an increasing number of investors are willing to commit to such sustainability principles even beyond pecuniary motives (Riedl and Smeets, 2017; Hartzmark and Sussman, 2019). Therefore, a company disregarding climate change might also face losses of customers.

For all these reasons, a growing body of literature in finance has been developing with the aim to provide not only qualitative considerations, but also quantitative arguments in support of the importance of climate change and the risks, opportunities and implications that come with it.

To name a few examples, Bansal, Ochoa, and Kiku (2016) emphasize the importance of climate risk as a long-run risk factor. A number of studies also highlight the relevance of both pollution and carbon risk when it comes to stock returns (Bolton and Kacperczyk 2021; Hsu, Li, and Tsou 2022; Kruttli, Tran, and Watugala, 2023).

Similarly, Pankratz, Bauer, and Derwall (2023), Addoum, Ng, and Ortiz-Bobea (2020) also show that extreme temperatures can have negative shocks on firms' earnings.

Interestingly, Ginglinger and Moreau (2023) provide evidence about the leverage implications of climate risk, that is to say companies which are more exposed to climate risks tend to have a lower leverage, potentially as a result of the decreased demand of debt from companies, but also from a reduced willingness to lending from lending-institutions. This could also be in line with the find from Delis et al. (2019), who find out that after the Paris Agreement banks adopted a new approach of pricing carbon risks.

To end on a good note, there are also studies showing that adopting environmentally friendly practices and policies can result in lower downside portfolio risk (Hoepner et al., 2024; Gibson et al., 2020) and that incorporating climate aspects in investment decisions also contributes to the reduction in portfolio risk (Jagannathan, Ravikumar and Sammon, 2017).

2.2. Climate Risk Pricing in Financial Markets

Having understood that climate risks do indeed represent financial risks, too, a key question is whether they are reflected and priced in financial markets.

Although a fast-growing body of literature on this subject points out that financial markets have somehow begun to price such risks, many researchers believe that such pricing might be inadequate and uncapable of fully reflecting climate risks (Bolton et al., 2020, NGFS Technical Document, 2022, Carbone et al., 2021, OECD, 2021 and Campiglio et al., 2023), where uncertainty – partly caused by the lack of historical data – and imperfect information make such pricing even more complex (Eren et al. 2022, Hansen, 2022 and Barnett et al., 2020).

Such beliefs are further demonstrated by the results of a number of surveys in which it appears clear that, even according to industry professionals – such as academics, large institutions and asset managers – climate risks are very likely to be underestimated (Krueger et al., 2020; Stroebel and Wurgler, 2021).

When it comes to physical risks, there is evidence that they are priced in some markets. For example, it seems that investors are willing to pay a premium for corporate bonds which are more likely to do better when negative reports about climate change come out (Huynh and Xia, 2021) and that extreme weather events result in a deterioration of borrowing conditions in the Caribbean (Mallucci, 2022). Nonetheless, such indication of pricing is usually rather mixed and inadequately comprehensive to conclude that physical risks are rightly and fully priced across markets (Eren et al., 2022). In support of this conclusion, one study from Bernstein et al. (2019) shows that inundation risks are priced in the residential real estate market, while another study using a very similar methodology on a different sample shows the opposite (Murfin and Spiegel, 2020).

Similar to the case of physical risks, there is conflicting evidence about the effectiveness of the pricing of transition risks, too (Weder di Mauro, 2021).

For instance, Bolton and Kacperczyk (2021) find that stocks of companies which present a higher level of CO2 emissions earn higher returns, controlling for various return predictors, size, as well as book-to-market value. Such result was confirmed by the authors in a subsequent study carried out on a larger sample (Bolton and Kacperczyk, 2023).

On the other hand, Duan et al. (2021) find oppositive evidence and failed to confirm what is known as the *"carbon risk premium hypothesis"* on the corporate bond side, while Bats, Bua and Kapp (2024) find evidence of the existence of a transition risk in the Euro area corporate bond markets after Paris Agreement, although such estimates are mostly small and non-significant.

Furthermore, Hong, Li, and Xu (2019), as well as Cuculiza et al. (2023) provide evidence for clear climate risk mispricing in financial markets.

Therefore, all in all, it is fair to conclude that evidence about the pricing of climate risks is rather mixed and inconclusive. Nonetheless, the vast majority of researchers consider such climate-related risks inadequately priced within financial markets, with the end result of increasing the risk of sudden and severe price shocks, hence representing a potential threat to financial stability as a whole (Merten and Verhoeven, 2022).

One of the main problems seems to be the uncertainty implied by the nature itself of climate risks, which are not only implicitly hard to quantify in terms of financial impacts, but they are also hard to predict from a time-horizon standpoint (Ahairwe et al., 2022).

On top of that, according to Ahairwe et al. (2022), investments in climate adaptation are now considered to be too costly, but they might become financially attractive if they corresponded to a reduction in climate risk exposure which is not only qualitatively, but also (and especially) quantitatively measurable and priceable.

Another possible explanation for the phenomenon of climate risk mispricing could relate to the quality of information that market participants have at their disposal. As a matter of fact, investors who rely on ESG ratings to extract information about a certain company´s exposure to a number of risks, including climate risks, might be faced with the struggle of having different scores according to different score-providers (Avramov at al., 2022), making it difficult to truly comprehend the firm´s real ESG profile. Moreover, it seems that ESG rating providers attribute a higher weight to the current existence of corporate policies, rather than considering other forward-looking climate metrics (OECD, 2022).

Finally, recent findings suggest that ESG ratings and green innovation may not always fully align. For example, in the US, firms presenting lower ESG scores – which therefore resulted in these companies being interdicted from being part of most ESG funds – tend to be major green innovators (Cohen et al., 2020). All these misalignments could result in mispricing phenomena, as well as in the generation of inefficient capital allocations, given that ESG ratings have now become the dominant form of sustainable finance (OECD, 2022) and a vast number of institutions (mostly asset managers) base their investment decisions on such scores.

2.3. Climate Risk Pricing in Bond Markets

A number of studies find that investors tend to be sensitive to transition risks in fixed income markets. For example, Seltzer et al. (2022) document that the bonds of firms which are less likely to mitigate transition risks trade at a discount.

Similarly, it seems that companies presenting higher levels of CO2 emissions and lower E-Scores (Environmental scores) display greater credit risk, measured via the yield spreads of their bonds and the distance-to-default (Barth et al., 2022; Capasso et al., 2020).

Interestingly, according to Hsu et al. (2022), the uncertainty about environmental policies might justify the spreads in average returns between low- and high-emissions firms, also known as “pollution premium”.

Furthermore, there is evidence that after Paris Agreement transition risks are priced in syndicated loan markets (Ehlers et al., 2022) and that firms which are more exposed to such risks observed a deterioration of their credit ratings, especially in the US (Carbone et al., 2021).

Additionally, in the US, there is evidence that local exposure to heat stress correlates with higher yield spreads for bonds (Acharya et al., 2022) and in Europe investors demand higher returns (around 34 basis points) on bonds exposed to physical risk shocks, whereas transition risk premiums are much smaller and less - occasionally not at all - significant (Bats et al., 2024). The authors of this last study also find a non-linear relationship between exposure to transition risk and bond returns, where the two variables are initially negatively correlated, but they subsequently rebound and end-up with a potential reversal of this relationship, underlying the complexity of the relationship between bond returns and transition risks.

Similarly, other research shows that bonds with a higher climate change beta (i.e., a bond's covariance with a climate change index, which in turn reflects climate change risk) earn lower returns, although this value is rather small (Huynh and Xia, 2021). Other researchers have interpreted the results of this study as a potential sign that markets do not fully price-in climate risk, specifying that such a result is probably driven by the demand for hedging against physical risks, while the results for transition risk appear to be less evident (Bats et al., 2024).

Finally, a recent study carried out specifically on corporate bonds to explore whether carbon risk is priced in this market finds contrary results to the "carbon risk premium" hypothesis, therefore providing evidence that investors underreact and do not price carbon risk in the corporate bond market (Duan et al., 2021).

In conclusion, it is therefore fair to say that while on the one hand there is some evidence of climate risk pricing in fixed income markets, on the other hand the literature on this topic is still rather divided and occasionally even conflicting with each other.

3. Is Climate Risk a Priced Factor in Fixed-Income Markets? An Empirical Test in the US and European Corporate Bond Markets.

It appears clear that the lack of a universally accepted clear-cut answer requires further analysis in order to establish whether climate risk is reflected and priced in the important world of fixed-income markets.

A fair pricing in such markets is critical to market efficiency, given their massive size, as it would allow for a reduction both in wealth transfers between uninformed and sophisticated investors, as well as in the probability of extreme future price movements (Weikai Li– Singapore Management University, NGFS workshop).

Specifically, for the scope of this analysis, the focus will be on the materialization of a particular type of *transition risk*, namely the announcement of the enforcement of the Paris Agreement – which took place on December 12, 2015 – and its impacts in the US and European corporate bond markets.

In fact, during this conference, it was agreed by most governments throughout the world that addressing climate change by keeping the average temperature below 2°C above the pre-industrial levels was fundamental. This undoubtedly represents the realization of the climate risk defined as “transition risk”, as companies from most parts of the world were thereby officially demanded to change their business model and turn it into a greener one in order to comply with the new regulatory requirements, else they would be subject to strict penalties (as also discussed in Capasso et al., 2020).

Hence, one would expect that companies which are more exposed to such risks would be riskier than other firms due to a higher degree of difficulty in adapting to the new stringent regulation imposed by the Paris Agreement and that such adversity would also be reflected in their issued bonds.

There are many indicators that can be used as proxies of how “green” companies are. The most predominant one in the financial industry, as also highlighted in a notorious paper from the OECD (OECD, 2022), are the ESG ratings – Environmental, Social and Governance scores –.

In this analysis though, the E-pillar (Environmental score) will be also examined separately, as it provides a more detailed representation of a certain firm´s environmental performance, as it only focuses on companies’ resource use, emissions, and innovation (Refinitiv, 2022), hence reducing the potential noise generated by the S- and the G-pillars, which have nothing to do with the environmental profile of a company. In particular, the category “Emissions” includes emissions, waste, biodiversity and environmental management systems; the category “Innovation” refers to product innovation, green revenues, R&D and CAPEX; the category "Resource use”, finally, includes usage of water, energy, sustainable packaging and environmental supply chain (Refinitiv, 2022).

Thus, such a focus should also generate more reliable and meaningful results compared to only using a company´s ESG score as a whole.

Such a difference becomes more evident when looking at the definition of the E-Score of the financial data provider Refinitiv Eikon, reported below:

“The environmental pillar measures a company´s impact on living and non-living natural systems, including the air, land and water, as well as complete ecosystems. <u>It reflects how well a company uses best management practices to avoid environmental risks and capitalize on environmental opportunities in order to generate long-term shareholder value</u>”.

Hence, it is fair to assume that a company with a higher E-score should naturally be less exposed to climate risks and that, when it comes to the analysis of climate risks, such a score should represent a better proxy when compared to the broader ESG score.

Another proxy that ought to be taken into consideration is the level of greenhouse gas (GHG) emissions radiated into the atmosphere by the issuing companies. Clearly, as the

Paris Agreement aims at tackling climate change, one of the main channels that regulatory bodies have at their disposal in order to succeed in their mission is to reduce the level of GHG emissions, as already discussed chapter 1.

As a consequence, companies with higher levels of CO2 emissions should be more exposed and subject to financial sanctions or to drastic and costly changes in their business models in order to convert themselves into greener entities (as also supported in Krueger et al., 2020 and in Capasso et al., 2020).

Therefore, in order to contribute to the existing literature and to analyze this issue, three research questions will be examined:

1) Is climate risk reflected in the US and European corporate bond markets?

2) Should there be evidence of such a reflection, is it possible to link this to the companies´ ESG and Environmental scores in order to give climate risk a price?

3) Is it possible to price climate risk in the corporate bond market based on the issuing companies´ level of GHG emissions?

3.1. Data Collection

In order to answer the above questions, an extensive data collection has been carried out. Due to the impossibility of extrapolating corporate bond data in an automated manner, the collection has been entirely manual and executed on the platform Refinitiv Eikon, with the end-goal of analyzing the behavior of bonds issued by different companies with different environmental characteristics shortly before and after the Paris Agreement was implemented.

The companies (and, subsequently, their respective bonds) have been picked from the index *"iShares ESG Screened Global Corporate Bond index Fund"* because of its geographical and industrial diversity, but also because of the rather comprehensive availability of environmental data of its screened companies.

The companies have been ranked according to their Environmental Score (E-Score) for the year 2015. They were later on divided into quartiles and, subsequently, an equal number of companies for each quartile along the spectrum of the E-Score was taken. This provides a uniform ranking along the spectrum of the E-Scores among a diversified pool of industries.

For the US bond market, a total of 102 US-based companies from 43 different industries have been selected. This provides a power of .99 for a medium effect size of 0.5 and an alpha of 0.05 for the case of non-parametric testing.

The E-scores ranged from 0.00 to 97.4, with a mean of 57.149 and a standard deviation of 26.090.

For the European bond market, the data available was much scarcer than in the US. In the end, 41 companies from 22 different industries were selected. This provides a power of 0.92 for a medium effect size of 0.5 and an alpha of 0.05 for non-parametric testing.

The E-scores for the European-based companies ranged from 0.00 to 98.09, with a standard deviation of 26.678.

After selecting the companies, data from their respective outstanding bonds (as of 12th December 2015 – the date of the announcement of the Agreement) have been manually extracted.

For the US, data from 102 bonds were downloaded. The average maturity date was January 2046, with an average maturity of 36.373 years and a standard deviation of 18.378 years.

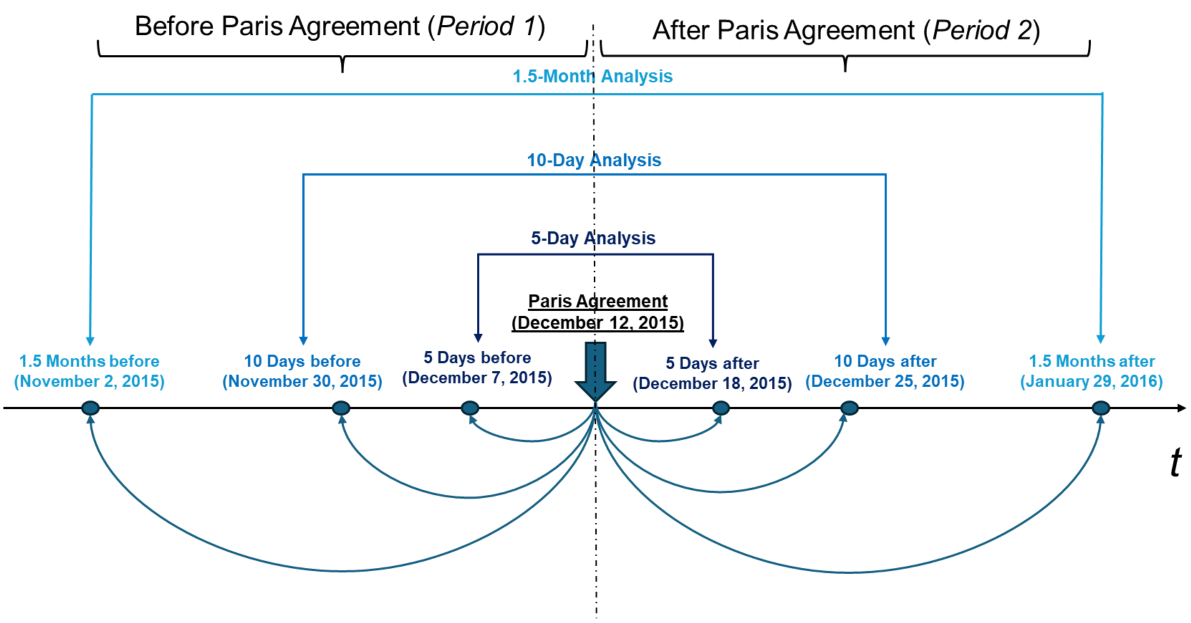
For Europe, data from 41 bonds were collected and the average maturity date was September 2036, with an average maturity of 25.366 years and standard deviation of 12.198 years.

3.2. Methodology

The whole analysis has been conducted comparing a number of bonds´ characteristics before and after the enforcement of Paris Agreement. This approach is consistent with previous research on climate change pricing in risky asset markets (Bats, Bua and Kapp, 2024) and partly follows the logics of Ramelli et al. (2018), who find evidence that investors are reactive when it comes to political events connected to firms' climate strategies.

In order to provide more granular information and to assess how efficiently (if at all) markets incorporate new information (i.e., the announcement of Paris Agreement), the analysis has been divided into three separated time windows, namely 1.5 months, 10 days and 5 days before versus after the announcement of the Agreement. The figure below graphically shows what has just been described.

Figure 4 - Analysis' Timeline and two-period separation



The first research question, namely whether climate risks are reflected in fixed-income markets, has been examined by analyzing changes in bonds under three dimensions.

The first one will be the analysis of the changes in *liquidity* of the individual companies´ outstanding bonds. In this case, liquidity will be measured using the bonds´ spreads bid-ask as proxy (consistent with Bats, Bua and Kapp (2024) and numerous Asset Pricing theories). The calculation for the spreads was the following:

$$Percentage\ Spread\ Bid\_Ask = \left(\frac{p(Ask)_i - p(Bid)_i}{p(Ask)_i}\right)$$

Where $p(Ask)_i$ is the daily ask-price and $p(Bid)_i$ is the daily bid-price.

This way, spreads are normalized, allowing for a better comparison, as differences in bond prices do not impact the result. Finally, in order to simplify the interpretation of numbers and results, such percentage spreads have been converted into basis points.

The second aspect considered will be the bonds´ actual *price change*, which in this case has been calculated as the difference of the average daily price change of the bonds compared to an initial fixed date over the two periods (i.e., before and after Paris Agreement). The formula used is the following:

$$Bid\_Price\ Change = \frac{\sum_{i=1}^{35}\left(\frac{p(bid)_i - p(bid)_{i=-1}}{p(bid)_{i=-1}}\right)}{35} - \frac{\sum_{i=-29}^{-1}\left(\frac{p(bid)_i - p(bid)_{i=-30}}{p(bid)_{i=-30}}\right)}{30}$$

And

$$Ask\_Price\ Change = \frac{\sum_{i=1}^{35}\left(\frac{p(ask)_i - p(ask)_{i=-1}}{p(ask)_{i=-1}}\right)}{35} - \frac{\sum_{i=-29}^{-1}\left(\frac{p(ask)_i - p(ask)_{i=-30}}{p(ask)_{i=-30}}\right)}{30}$$

Where $p(bid)_i$ and $p(ask)_i$ are the daily bid and ask prices of the bond, respectively; $p(bid)_{i=-1}$ and $p(ask)_{i=-1}$ are the bid and ask price as of 11th December 2015 and $p(bid)_{i=-30}$ and $p(ask)_{i=-30}$ are the bid and ask price as of 2nd November 2015.

Similar to the bid-ask spreads, also these percentage price changes have been converted into basis point for the analysis.

The third and last aspect that will be investigated is the changes in *volatility of returns*, measured as the standard deviation of prices before and after the announcement of the Agreement across the three different time windows selected and illustrated in *Figure 4* earlier.

To answer the question as to whether the materialization of the transition climate risk represented by the enforcement of the Paris Agreement is reflected in bond markets, t-tests will be performed in order to understand whether significant differences in these three dimensions before versus after the Paris Agreement exist.

When it comes to the second research question, i.e., whether significant changes after the enforcement of the Paris Agreement can be linked to the issuing companies´ ESG and E-Scores in order to price such a risk, both parametric and non-parametric correlation analyses have been performed. The reason behind this choice of also analyzing the ESG scores is that aggregated ESG scores have a stabilizing effect on banks' systemic risk measures, where such resiliency is mostly enhanced by the attention to long-term objectives, including customers and product responsibility (Gehrig et al. 2024). On this basis, ESG-scores might be useful indicators of a company's climate risk exposure in other industries as well, as higher ESG scores correspond to a higher attention to long-term goals. The E-scores, on the other hand, should reflect how well a company's business model is resilient to environmental risks and can capitalize on environmental opportunities.

Finally, to answer the third and last research question, namely whether it is possible to give a price to climate risk in the corporate bond market based on the issuing companies' emission levels, more correlation analyses and regressions between the significant bond price changes after the announcement of the Agreement and the levels of GHG emissions of the issuing firms will be performed. The reason behind the choice of this analysis is that the reduction of carbon emissions is one of the main goals of the Agreement and, therefore, regulatory bodies are likely to sanction more strictly companies with a higher carbon intensity.

The data for this third analysis has also been collected through Refinitiv, manually extracting the GHG data from the ESG-Statement section of each issuing firm, whenever available.

Refinitiv provides the following definitions for the various emission scopes:

- *Scope 1 Emissions* (CO2 Equivalent Emissions, Direct): Direct CO2 and CO2 equivalents emissions in tons. Direct emissions from sources that are owned or controlled by the company.

- *Scope 2 Emissions* (CO2 Equivalent Emissions, Indirect): Indirect CO2 and CO2 equivalents emissions in tons. Indirect emissions from consumption of purchased electricity, heat or steam which occur at the facility where electricity, steam or heat is generated.

- *Scope 3 Emissions* (CO2 Equivalent Emissions, Indirect): Total CO2 and CO2 Scope Three equivalent emissions in tons. Scope 3 includes emissions from contractor-owned vehicles, employee business travel (by rail or air), waste disposal, outsources activities – emissions from product use by customers, emissions from the production of purchases materials, emissions from electricity purchases for resale.

Whenever not available, Refinitiv provides estimates for the sum of Scope 1 and Scope 2 emissions - in tons - (later reported as *Scopes 1+2* during the analysis) via the use of four different CO2 estimation methods (Reported, CO2 Model, Energy Model and Median Model). As these are all internal models, further details about their calculation methods are not available.

4. Is Climate Risk reflected in the US Corporate Bond Market? Empirical Tests

4.1. Liquidity changes – Results

As already mentioned in the methodology section, the utilized proxy for a bond's liquidity is its percentage spread bid-ask (converted into basis points).

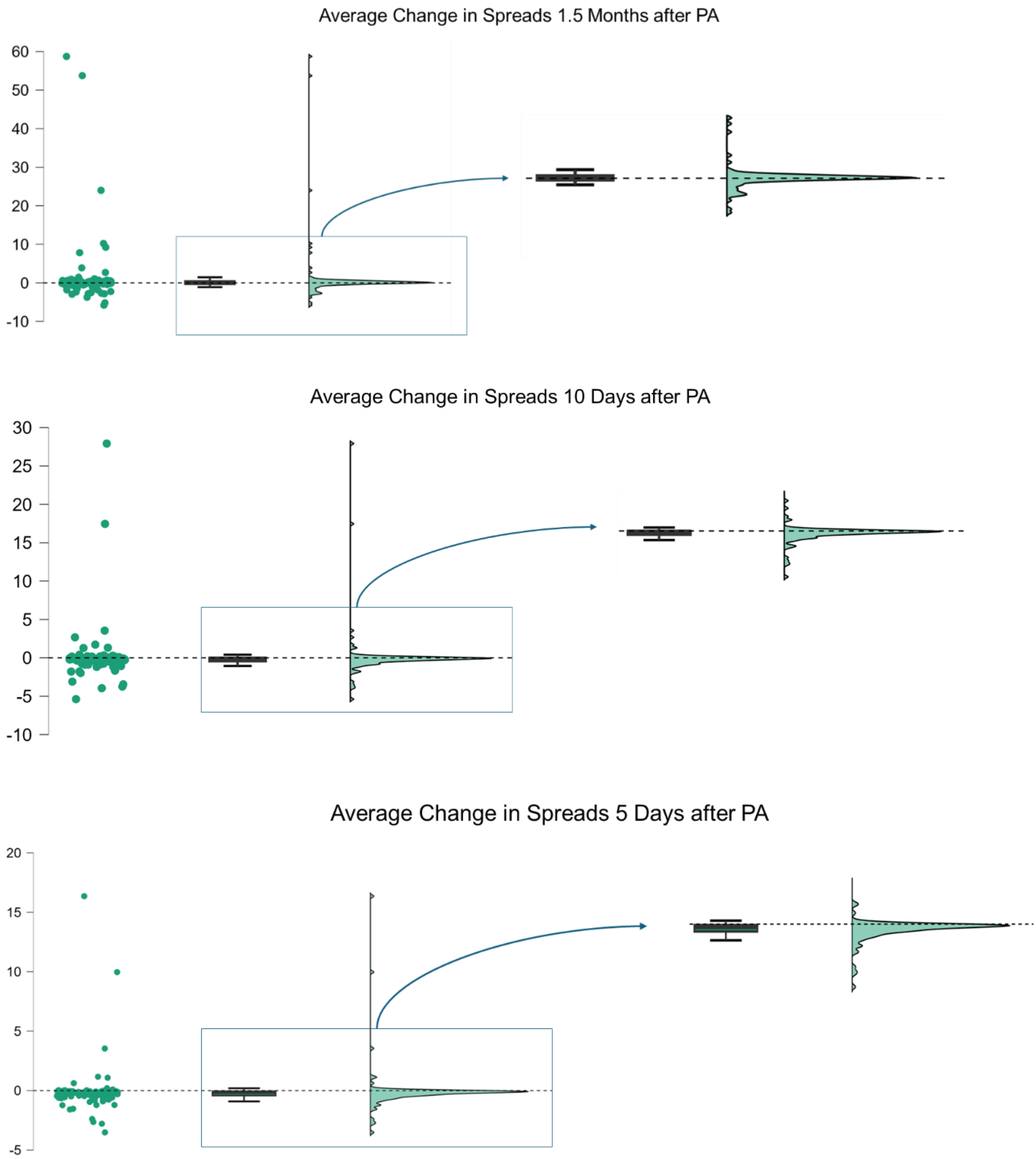
As the results of the normality test (Shapiro-Wilk) are significant all over the three time windows analyzed (p***<.001), the classic parametric Student tests will be accompanied by their non-parametric counterparties, namely the Wilcoxon tests, for completeness.

The test hypothesis is that spreads before the announcement of the Agreement were larger than after such announcement. The assumption behind the choice of this alternative hypothesis is that spreads (liquidity) after the announcement of Paris Agreement might decrease (increase) as a result of an increased market participation in fixed-income markets compared to other more risky ones (like the stock market), as bonds might be perceived as safer instruments.

The outputs of the Student tests show no significant changes in spreads within the 1.5-months, 10-days and 5-days time frames (p=0.948, p=0.614 and p=0.408, respectively), while the Wilcoxon test detects a small significant change in the 5-day and 10-day comparisons (p***<.001), suggesting that the announcement of Paris Agreement potentially reduced bid-ask spreads and, hence, increased liquidity.

Below are three raincloud plots that graphically illustrate the average changes in spreads after the implementation of the Agreement (in basis points).

Figure 5 - Average Changes in Bid-Ask Spreads after Paris Agreement's Announcement (US)



4.2. Bid-Price Changes – Results

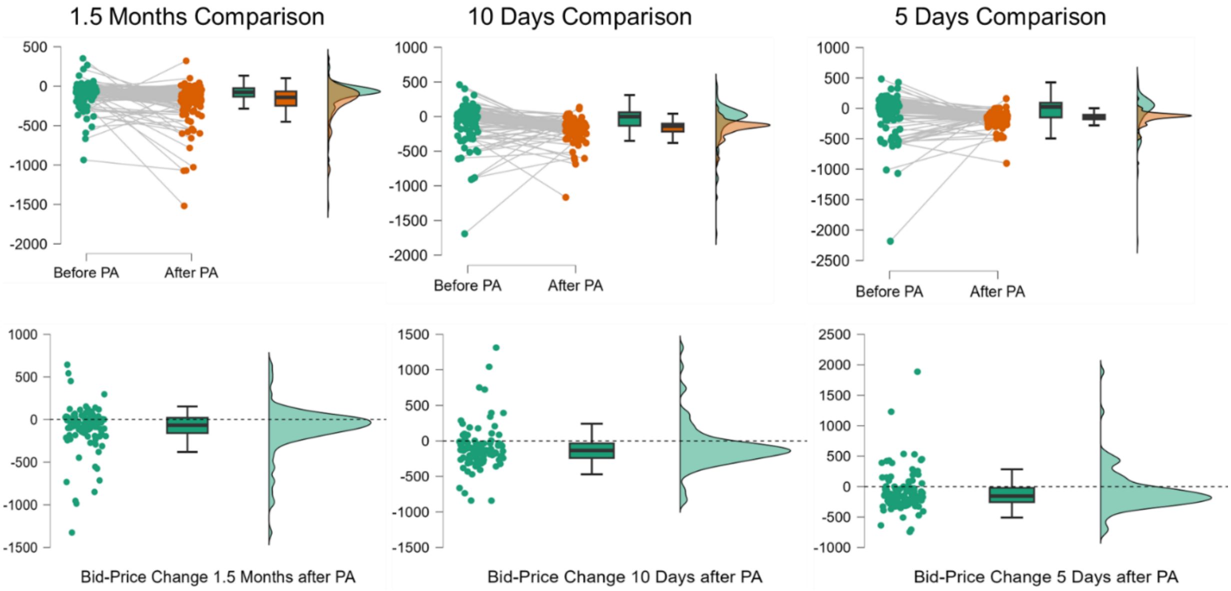
Similar to the case of spreads, the significant results of the Shapiro-Wilk tests (*p****<.001) indicate that the data is not normally distributed. Hence, Wilcoxon tests will be performed together with the Student tests. For all tests, the alternative hypothesis is that the average bond prices after the Paris Agreement decreased (or, at least, dropped by a larger factor, where they were already decreasing) compared to the days and weeks before its announcement.

The reason for this assumption is that following the Paris Agreement, as previously discussed, most companies might face financial issues due to the need of meeting new and more stringent regulatory requirements, which translates in either a costly change of the firm's business model or, should a company ignore such requirements, in severe costs derived by financial penalties and fines (see for example discussions in Capasso et al., 2020 and Krueger et al., 2020).

This time, the outputs of the Student and the Wilcoxon tests are the same both in terms of direction and significance. In fact, within the 1.5-month, 10-day and 5-day comparisons, bond prices significantly declined after the announcement of the Paris Agreement (all *p****<0.001 and *p***=.008 for the 5-day change).

Looking at the descriptives of such changes, specifically, it can be observed that within the 1.5 months window the average change after the implementation of the Paris Agreement was of -105.03 bp, over the 10-day period -101.84 bp and in the 5-day period -81.464 bp. Such change appears also evident when looking at *Figure 6* below, which graphically shows via raincloud plots how bond prices moved after the enforcement of the Agreement.

Figure 6 - Bid-Price Changes before versus after announcement of Paris Agreement (US)



One possible reason for such a pronounced decrease in prices could be attributed to an increased perceived probability of default of the issuing companies.

In fact, coherent with asset pricing theories, one could think of the price of the bond (hence, its value) as a reflection of its probability of default. Such a view is also supported by recent literature. For example, Battiston and Monasterolo (2020) provide the following simple model for the valuation of corporate bonds:

$$v_j(T) = \begin{cases} R_j = (1 - LGD_j) & \text{if issuer } j \text{ defaults (with prob. } q_j) \\ 1 & \text{else (with prob. } 1 - q_j) \end{cases}$$

Where v_j is the bond's value at maturity time T, R_j is the recovery rate (meaning the percentage of notional that can be recovered in case of default) and LGD_j is the Loss-Given-Default, namely the percentage loss upon default.

Such equation can be rewritten as:

$$\mathbb{E}[v_j] = R_j * q_j + (1 - q_j)$$

After distributing the terms and factoring out q_j, the equation becomes:

$$\mathbb{E}[v_j] = 1 - q_j(1 - R_j)$$

Where $1 - R_j$, as described earlier, is nothing but the LGD of the bond. Hence:

$$\mathbb{E}[v_j] = 1 - q_j * LGD_j$$

Finally, a general bond's price can be calculated as the bond's expected value discounted by the risk-free rate:

$$p_j = \mathbb{E}[v_j] * e^{-rf*t}$$

Hence, this model provides a rather simple, yet effective way of describing how an increased (perceived) probability of default can cause bond prices to decline, as such probability directly affects the bond's expected value. A more in-depth discussion will follow in paragraph 4.4 at the end of this chapter.

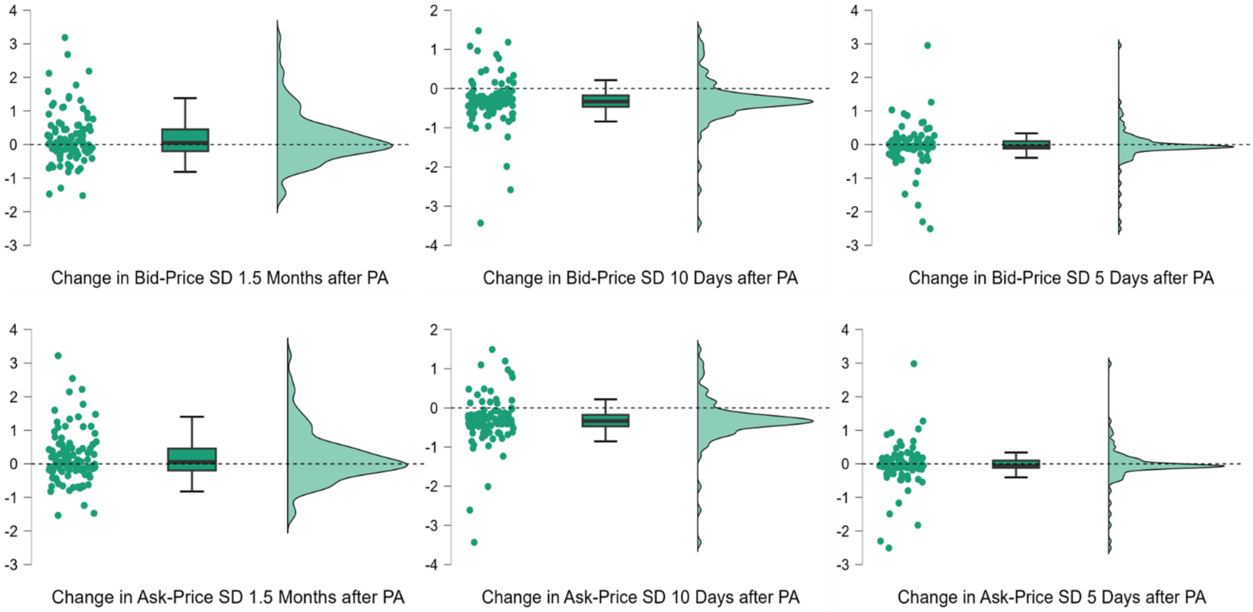
4.3. Volatility Changes – Results

Again, the results of the Shapiro-Wilk tests for normality are all significant, hence both Student and Wilcoxon paired-samples t-tests have been performed in order to understand whether there exist differences between the bid- and ask-prices' standard deviations before versus after the announcement of the Paris Agreement.

The alternative hypothesis in this case is that bond volatilities after the Paris Agreement decrease, as the degree of uncertainty that might have surrounded markets before its implementation should have then been reduced.

The results show no significant changes in price volatilities in the 1.5-month window (Student p=0.993, Wilcoxon p=0.963), while these have significantly decreased (p***<.001) in the 10-day comparison window. Concerning the 5-day window, only Wilcoxon shows a significant decrease (p**=.026), whereas Student's p=0.174. Below is a graphical representation of the results.

Figure 7 - Changes in Price's Standard Deviation after Paris Agreement (US)



4.4. Reflections of the Paris Agreement in the US Corporate Bond Market – Discussion of Results

To summarize the results presented in this chapter, when it comes to liquidity, the outputs of the Student tests show no significant changes in spreads within the 1.5-month, 10-day and 5-day time frames, while the Wilcoxon test detects a small significant change in the 5-day and 10-day comparisons. It is therefore hard to say with confidence whether the announcement of the Agreement created tangible impacts from a liquidity perspective.

On the other hand, from a price standpoint, the combination of the method of bond valuation and the significant results of the tested hypothesis is potentially coherent with the idea that transition risks are reflected in bond markets, as market participants factor in that, after the Paris Agreement, companies would need to reorganize themselves in order to meet the new greener regulatory requirements imposed and that such a process comes at a high cost. Furthermore, some firms might face structural problems in converting themselves as required and, thus, the issuers' ability to generate future cash flows which are large enough to pay back all their debt obligations may be seen as more uncertain, especially in this context of long-term bonds.

Lastly, concerning the bond price volatilities, one could conclude that with high probability there were no real implications in the 1.5-month window, but in the shorter-term (i.e., 5-day and, especially 10-day comparisons) the Paris Agreement might have generated more stability and hence reduced bond price volatilities. Another possible interpretation can be given when simultaneously looking at the results of the spreads bid-ask tests. In fact, such spreads significantly decreased in the 5- and 10-day windows after the Agreement was announced (i.e., the bond market liquidity increased). Hence, the fact that price volatilities decreased within the same time spans could be read together, meaning that narrower spreads (higher liquidity) may have caused prices to move less in order to execute trades, thus potentially contributing to the overall reduction in price volatility in the market. A similar view is also shared by previous literature examining the interactions between market liquidity and volatility (Brunnermeier et al., 2009; Nguyen et al., 2020).

5. Is Climate Risk a Priced Factor in the US Fixed-Income Market?

To summarize the results of the previous analysis, according to the Wilcoxon test spreads bid-ask have significantly decreased (i.e., market liquidity increased) within the 5- and 10-day windows after the announcement of the Paris Agreement. Prices have significantly decreased within all the three time frames. Finally, standard deviation of prices (i.e., volatility) significantly decreased in the 10-day window and, according to the Wilcoxon test, also in the 5-day frame.

Having found such significant changes, which are plausibly generated by the enforcement of the Agreement, the next question is to understand whether they can be explained (and, therefore, priced) based on a number of the issuing firms' characteristics.

For the analysis, three main potential indicators of a company's green-profile and, in turn, potential exposure to climate risks will be examined, namely the ESG score, the E-Score and the level of GHG (greenhouse gas) emissions.

The original idea was to perform single linear regressions in order to detect eventual interrelationships between the significant changes discussed above and these firms' characteristics. For this reason, to make sure that the statistical requirements were met, a number of assumptions have been checked, namely linearity (via a residuals-vs-dependent plot), outliers (via a residuals-vs-predicted plot), homoscedasticity (via a scatter plot of residuals), independence of observations (via a Durbin-Watson test) and normality of data (via a Quantile-Quantile plot). While most assumptions were met, the assumptions of homoscedasticity and normal distribution of data seem violated. Hence, the data appears to be heteroscedastic and not normally distributed.

Given this issue, an alternative would have been to perform the analyses through Generalized Linear Models (GLM) or, using a similar approach to the analysis carried out earlier, to use non-parametric versions of the standard single regressions and Pearson’s correlation.

A number of issues arose from the potential use of GLMs. Specifically, a logistic regression was not feasible due to a non-binomial distribution of data. Both Poisson and negative binomial regressions are not applicable due to the violation of the requirement of only-discrete distributions and the fact that the dependent variable does not only assume positive values. Finally, a Gamma-distribution cannot be applied because of the presence of negative values in the dependent variable.

All things considered, it was opted for correlation analyses consisting of determining Pearson’s coefficients, as well as their non-parametric counterparts, namely Spearman’s rho and Kendall’s tau-b. These last two should help provide even more robust results, as they are unaffected by the violations of the normality and variance assumptions.

5.1. Correlation between liquidity changes and E- and ESG-Scores

According to the Wilcoxon tests, spreads bid-ask significantly decreased in the first 5 and 10 days after the implementation of the Paris Agreement. Hence, a correlation analysis between such changes and the issuing companies’ E- and ESG-Scores was performed.

The alternative hypothesis in this case is that there exists a negative correlation between the E- and ESG-Scores and the changes in bid-ask spreads, meaning that higher scores should be associated with smaller bid-ask spreads. This is based on the assumption that bonds traded by companies with a greener profile enjoy a higher degree of liquidity compared to those issued by firms with lower scores, as market participants might increase their demand for assets which are a better hedge against climate risk (see for example results of the study from Huynh and Xia, 2021 and the subsequent interpretation and discussion provided by Bats et al., 2024).

The results show no significant correlation between the spreads bid-ask changes and the ESG Scores. On the other hand, more interesting results appear when it comes to the

Environmental Score (E-Score). Specifically, while Pearson's correlation still detects no significant relationship between such score and the changes in bid-ask spreads, its non-parametric counterpart – Spearman's rho correlation - shows a weak significance between bid-ask spread changes and the E-Scores in the 10-day window (p^*=.039 with effect size Fisher's z = -0.178) and an even stronger significance in the 5-day window (p^{**}=.008 with effect size Fisher's z = -0.242).

Given these results, it is fair to assume that the reduction in spreads bid-ask in the US bond market following the Paris Agreement does not depend on the companies' ESG Score, as all tests show no significant results. Similarly, it is hard to establish whether there is enough evidence to conclude that the same changes in spreads bid-ask can be predicted by the companies' green profile by using their E-Scores as proxy, as conflicting results show up depending on whether a parametric or a non-parametric test is used. It appears therefore evident that further research in this context is needed.

Arguably, one of the most interesting results of this correlation analysis is that the E-Scores and the ESG scores cannot be used interchangeably, as they provide different estimates when it comes to testing. This should be taken into account by both small investors and institutional investors, given the widespread development of ESG-Funds and the little-to-none existence of E-Funds.

5.2. Correlation between Volatility changes and E- and ESG-Scores

Previous results showed that, on average, price standard deviations significantly decreased in the 10-day window after the announcement of the Paris Agreement. Hence, correlation analyses between such changes and the E-, ESG-Scores have been performed.

The alternative hypothesis is that there exists a negative correlation between the changes in price's volatilities and the E-, ESG-Scores, based on the idea that the bonds issued by companies which are considered to be greener (i.e., with a higher E- or ESG-Scores) should have a lower price-volatility compared to those issued by "brown" firms, as such firms should be less exposed to the negative implications of the transition risk represented by the enforcement of the Paris Agreement, hence translating in a higher instability on their issued bonds as well.

The results straightforwardly show no significant relationship between the changes in volatility neither with the E-Scores nor with the ESG-Scores. Therefore, it is fair to conclude that the reduction in price volatilities (measured via the prices' standard deviation) in the US bond market following the Paris Agreement does not depend on the issuing companies' E- and ESG Scores.

5.3 Correlation between Price changes and E- and ESG-Scores

From the previous analysis, it appeared evident that bond prices after the announcement of the Paris Agreement significantly decreased within all three time frames analyzed. In order to understand whether such changes can be predicted by the issuing companies´ E- and ESG-scores, correlation analyses between such scores and the price changes have been computed.

The alternative hypothesis is that there exists a positive correlation between the E- and the ESG-Score of the issuing companies and their respective bond's price change, based on the idea that companies which are assigned a greener profile should be less exposed to the negative impacts of the Paris Agreement, as they should be less exposed to climate risks (including the transition risk represented by implementation of the Agreement), hence their probability of default – and, in turn, the one of their bonds – should be lower, meaning that their issued bonds should have a lower price drop compared to the ones issued by companies with lower scores.

Similar to the case of prices´ standard deviation, the results of the performed correlation analyses are all non-significant, suggesting that the null hypothesis cannot be rejected, indicating that bonds´ price changes following the announcement of the Paris Agreement cannot be meaningfully predicted by the issuing companies´ E- and ESG-scores.

In addition, industry-controlled correlations have also been performed for the sectors which had the largest number of observations within the selected sample (*Oil, Gas & Consumable Fuels* (n=8); *Capital Markets* (n=7); *Chemicals* (n=7), *Insurance* (n=6), *Healthcare Providers* (n=5); *Machinery* (n=5); and *Metals and Mining* (n=5)). The reason for this supplementary analysis is that ESG- and E-scores are formulated and assigned on an industry basis, hence this further analysis might have provided more robust results which account and control for differences between different industries.

The results, though, were identical to the non-controlled ones, as they all turned out to be not significant.

5.4. E- and ESG-Scores Correlation Analyses – Discussion of Results

In conclusion, it seems that it is not possible to predict (hence, in a sense, price and hedge) the materialization of the climate risk represented by the implementation of the Paris Agreement in the US bond market based on the issuing companies´ E- and ESG-Scores, as all significant changes in bonds´ characteristics following the Agreement are not meaningfully correlated with such scores. This result is in line with the existing literature in this topic (as summarized in Eren et al., 2022) and there might be a number of reasons why the E- and ESG-scores fail to be helpful when it comes to asset pricing in the bond market (as already summarized in chapter 2). For instance, investors who desire to extract information from ESG ratings encounter a considerable amount of uncertainty about a company´s actual ESG profile, as the scores assigned to a same firm often vary depending on the rating agency (Avramov et al., 2022). Furthermore, it seems that ESG rating providers give more importance to already-existing corporate policies rather than forward-looking climate metrics, including GHG reductions (OECD, 2022). Finally, there is evidence that ESG ratings may not reflect the firms´ true climate innovation potential. Cohen et al. (2020), for example, find that in the US a number of firms which are assigned low ESG scores (and are therefore ruled out when it comes to the universe of ESG-fund investing) in reality significantly contribute to green innovation.

One last attempt to understand whether climate risks (in this case, transition risks) are priced in the US fixed-income market is to examine whether the (negative) price changes following the enforcement of the Paris Agreement can be predicted by the issuing firms´ level of greenhouse gas emissions, as such are arguably the main target of policy makers for the reasons illustrated in the first two chapters of this work.

5.4. Correlation between Price changes and greenhouse gas (GHG) emissions – US

As previously discussed in Chapter 2, extensive literature has investigated whether the firms´ levels of GHG emissions have some implications for asset pricing dynamics, but the results are rather mixed and, often-times, conflicting with each other (see for example the contrasting findings provided by Duan et al., 2021 compared to Bolton and Kacperczyk, 2022 or the ones from Bernstein et al., 2019 when compared to Murfin and Spiegel, 2020).

For this reason, a comprehensive analysis of the levels of GHG emissions of the issuing firms and the reflection on their issued bonds has been performed.

Specifically, regressions between the bonds´ price changes and all three scopes of emissions have been computed.

As already mentioned in the methodology section (paragraph 3.2), the data has been collected through Refinitiv, manually extracting the GHG data from the ESG-Statement section of each issuing firm, whenever available.

Refinitiv provides the following definitions for the various emission scopes:

- *Scope 1 Emissions* (CO2 Equivalent Emissions, Direct): Direct emissions from sources that are owned or controlled by the company (measured in tons).

- *Scope 2 Emissions* (CO2 Equivalent Emissions, Indirect): Indirect emissions from consumption of purchased electricity, heat or steam which occur at the facility where electricity, steam or heat is generated (measured in tons).

- *Scope 3 Emissions* (CO2 Equivalent Emissions, Indirect): Emissions from contractor-owned vehicles, employee business travel (by rail or air), waste disposal, outsources activities – emissions from product use by customers, emissions from the production of purchases materials, emissions from electricity purchases for resale (in tons).

Correlation analyses between the price changes and the different levels of emissions have been carried out. The alternative hypothesis is that the levels of GHG emissions released by the individual firms are negatively correlated with the price changes of their issued bonds, as the main goal of the Paris Agreement is to reduce carbon emissions and, hence, companies with higher levels should be more exposed to such climate risks, which would likely consist of facing potentially severe financial penalties or having to re-adjust entire business models in order to become greener and comply to the new regulations, therefore being more exposed to large transformation costs for such a transition.

For scope 1 emissions, the sample consisted of 68 observations. For scope 2 emissions, n=65; for scope 3 emissions, n=48. For the sum of Scope 1 and 2 emissions, the number of observations was n=100 and, finally, for the total levels of emissions (i.e., Scopes 1 + 2 + 3), n=48.

As the Shapiro-Wilk tests still indicate that the data is not normally distributed, parametric Pearson´s correlations have been accompanied by their non-parametric counterparts, namely Spearman´s rho and Kendall´s Tau B.

While the results were all non-significant for the non-parametric tests, Pearson´s correlation detected significant negative correlations between the price changes over the 1.5 month-window following the Paris Agreement and most scopes of emissions.

Specifically, the correlation between the 1.5-month price changes and the Scope 1 GHG emissions came significant with $p^*=.023$ and $r = -.243$; with Scope 3, $p^{**}=.003$ with $r = -.397$; with Scopes 1+2, $p^*=.043$ with $r = -.203$, and with Scopes 1+2+3, $p^{**}= .003$ with $r = -.424$. On the other hand, the correlation with Scope 2 emissions was non-significant in this context ($p=.445$ with $r = -.018$).

This is an important result, as according to Pearson´s outputs it is possible to reject the null hypothesis and, hence, one can conclude that the climate risk represented by the Paris Agreement was a priced factor in the 2015 US fixed-income market of corporate bonds. In order to give an actual price-value to this factor, a regression on the most significant relationship with the highest size effect has been performed.

Therefore, a single regression has been carried out, where the dependent variable is the 1.5-month price change of bonds after the Paris Agreement and the independent variable is the total level of emissions (i.e., scopes 1+2+3) of the respective issuing firms. Below is reported the summary of the model.

Figure 8 - 1.5-Month Bid-Price Change and GHG Emissions Regression (US)

Model Summary - Average Change in Bid-Price 1.5 Months after Event in bps

Model	**R**	**R^2**	**Adjusted R^2**	**RMSE**
H_0	0.000	0.000	0.000	221.611
H_1	0.424	0.180	0.162	202.880

ANOVA

Model		**Sum of Squares**	**df**	**Mean Square**	**F**	**p**
H_1	Regression	414860.622	1	414860.622	10.079	0.003
	Residual	$1.893\times10^{+6}$	46	41160.409		
	Total	$2.308\times10^{+6}$	47			

Coefficients

Model		**Unst.**	**St. Error**	**Standardized**	**t**	**p**
H_0	(Intercept)	-136.943	31.987		-4.281	< .001
H_1	**(Intercept)**	**-97.236**	31.842		-3.054	0.004
	Scope 1+2+3 CO2 Emissions (in tons)	**-1.116×10^{-6}**	3.514×10^{-7}	-0.424	-3.175	0.003

Hence, this output can be summarized within a single equation as follows:

$$\mathbf{1.5}\ \boldsymbol{Month\ Price\ Change\ (in\ bps)} = \mathbf{-97.236 - 1.116 \times 10^{-6}} \times \boldsymbol{Total\ GHG\ Emissions\ (in\ tons)}$$

This would mean that, following the announcement of the implementation of the Paris Agreement, there is a non-diversifiable price loss on corporate bonds of 97.236 basis points, as this does not depend on the issuing firms´ total level of GHG emissions and that each 896,057.35 (calculated as $\frac{1}{1.116\times10^{-6}}$) tons of GHG emissions released by the issuing companies correspond to a 1-basis-point price loss on their issued bonds.

This result, which to some extent would provide evidence that this climate risk was priced in the US fixed-income market, goes in the same direction as the one found by Bats, Bua and Kapp (2024), who find evidence of the existence of a transition risk premium in the Euro area of corporate bond markets after the Paris Agreement (although such estimates are mostly small and non-significant). Similarly, looking at the stock market, the result is similar to the one of Bolton and Kacperczyk (2022), who find that stocks of companies which present a higher level of CO2 emissions earn higher returns, controlling for various return predictors, size, as well as book-to-market value.

As a last note, interestingly, the results of the correlation for the 5- and 10-day windows turn out to be insignificant, hence only the 1.5-month price changes seem to incorporate this pricing effect. This might be evidence that the market took a longer time to incorporate this new information into bond pricing, therefore representing a potential lag in how markets incorporate these risks, which would contrast with the efficient market hypothesis.

6. Is Climate Risk reflected in the European Corporate Bond Market? Empirical Tests

The same analysis that was carried out for the US corporate bond market has been replicated for the European corporate bond market, using an identical methodology.

6.1. Liquidity Changes - Results

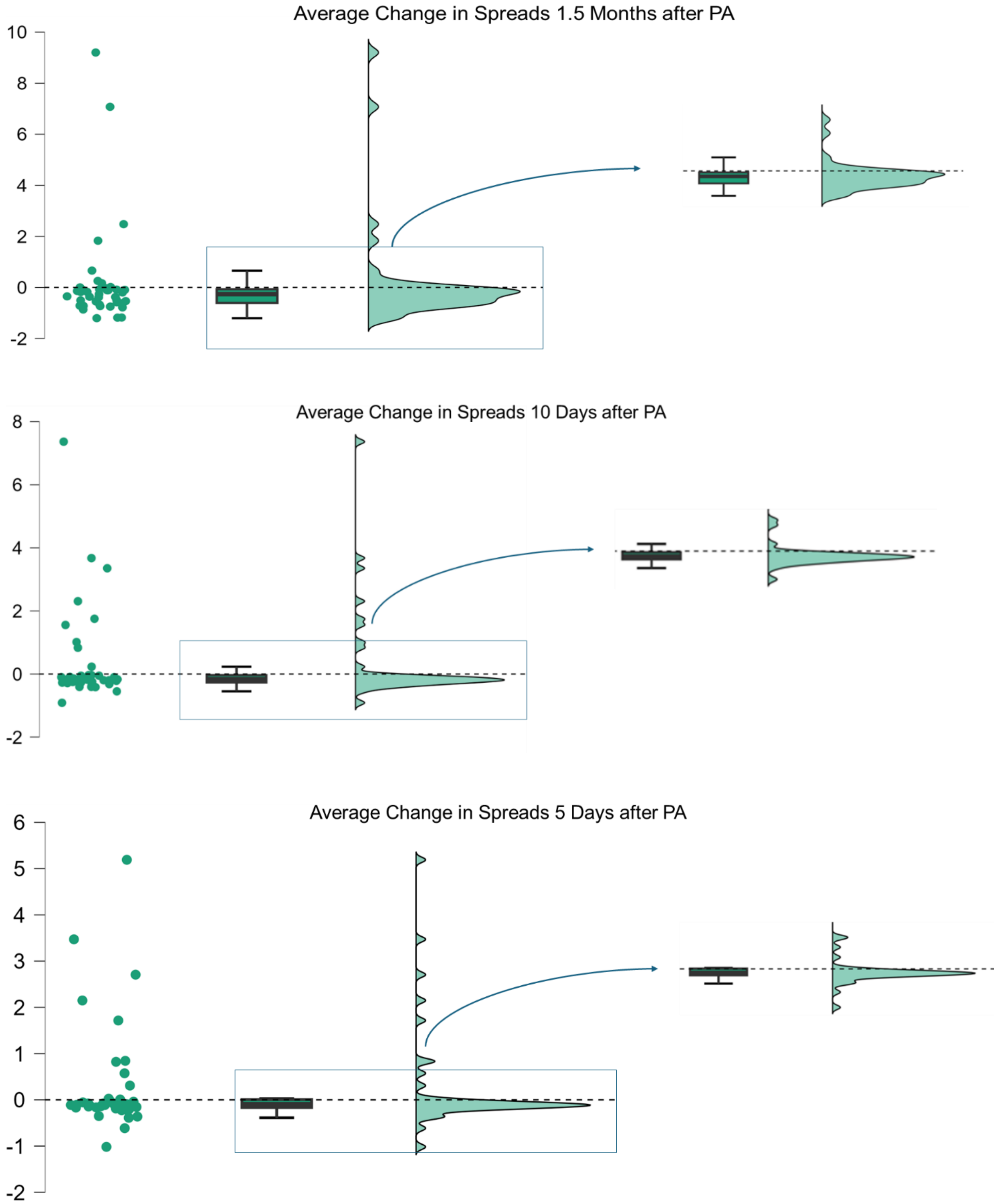
Liquidity, like for the US case, was measured using the percentage spreads bid-ask as a proxy (converted into basis points). Again, the results of the Shapiro-Wilk test for normality showed that the data are not normally distributed ($p^{***}<.001$), hence the standard Student tests have been accompanied by the non-parametric Wilcoxon tests.

The alternative hypothesis is that the spreads before the announcement of the Agreement were larger than after its implementation, based again on the idea that, after the shock caused by the Agreement, market participation in fixed-income markets increases, as these markets might be considered as less risky than others, such as the stock market.

Similar to the US case, Student tests detect no significant changes in spreads after the Paris Agreement was enforced. On the other hand, the Wilcoxon test shows a significant decrease in the 1.5-month window ($p^{**} = .002$ with an effect size of 0.503).

Compared to the US, which showed a significant decrease in spreads in the 5- and 10-day windows, these results might be evidence that in the European market it might have taken a longer time for agents to incorporate this new information, with a consequential delayed effect of the Paris Agreement on bonds´ liquidity.

Figure 9 - Average Changes in Bid-Ask Spreads after Paris Agreement's Announcement (Europe)



6.2. Bid-Price Change - Results

Like for the US analysis, the alternative hypothesis is that the average bond prices after the Paris Agreement decreased (or dropped by a larger factor, where they were already decreasing) compared to before its announcement.

The results are very close to the ones for the US, as both Student and Wilcoxon tests show a highly significant drop in prices among all three time windows ($p^{***}<.001$ for all tests with a rather strong effect size ranging from 0.62 to 0.75, where Student´s effect size is given by Cohen´s *d* and Wilcoxon's by the matched rank biserial correlation).

Moreover, looking at the descriptives, it can be noted that such a drop consists of approximately 155.32 bp in the 1.5-month window (in the US it was 105.03 bp), 170.41 bp in the 10-day frame (versus 101.84 bp in the US) and 149.852 bp within the 5-day time window (versus 81.464 bp for the US case).

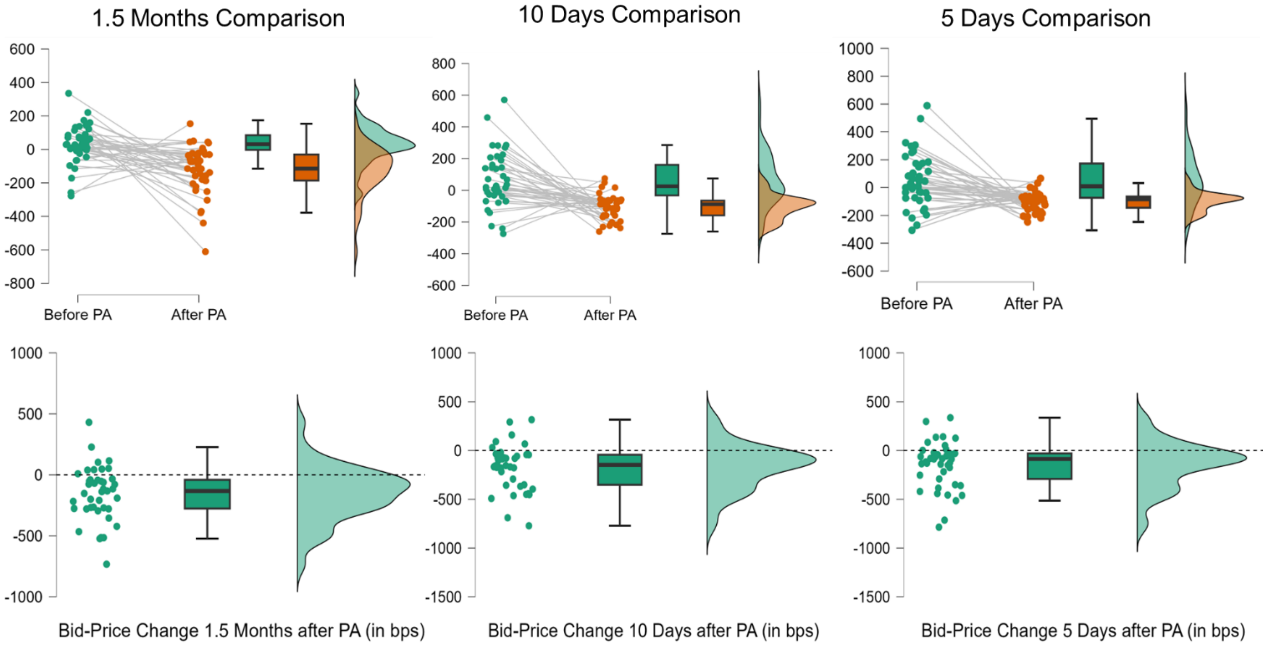
This is an interesting result when compared to the situation in the US market, suggesting that, on average, bonds issued by European companies have suffered more from the announcement of the Agreement in comparison to the US-based ones, as the negative delta in price loss for such European bonds was 50.29 bp in the 1.5-month period, 68.57 bp in the 10-day period and, finally, 68.388 bp in the 5-day period compared to the US price drops.

This would mean that, when it comes to the realization of a climate risk (a transition risk, specifically), European corporate bonds are more exposed to price-risk compared to US corporate bonds. This might have important implications in terms of asset management and risk management.

One possible interpretation of such conclusion is that, as the EU has always been traditionally stricter when it comes to environmental policies and regulations (Brunnée, 2008; Vogler and Bretherton, 2006), market participants might have feared a more aggressive implementation of the Agreement in the Old Continent compared to its application in the US, potentially resulting in additional costs for European companies compared to their transatlantic peers.

As a consequence, this might have generated a feeling of higher uncertainty for investors who, according to the model from Battiston and Monasterolo (2020) illustrated in the previous chapter, might have attributed a higher probability of default to European-based companies, hence resulting in more pronounced bonds´ price losses compared to the US-based ones.

Figure 10 - Bid-Price Changes before versus after announcement of Paris Agreement (Europe)



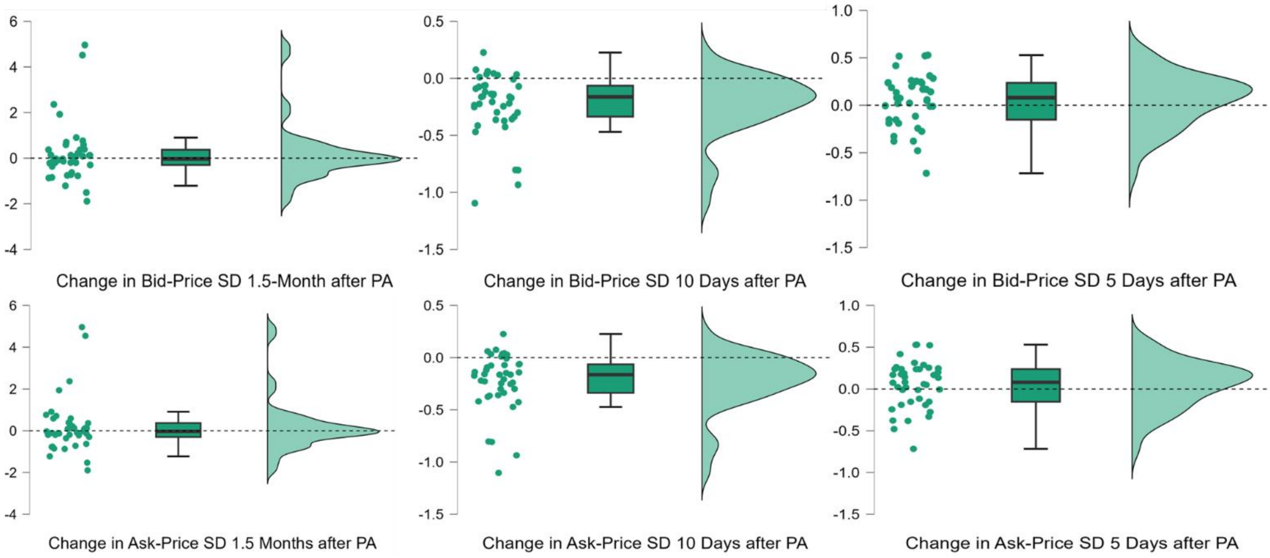
6.3. Volatility Changes - Results

Following the US analysis, the alternative hypothesis is that the volatility of bond prices - measured as the bid-price´s standard deviation - after the announcement of the Agreement decreased, as its implementation might have reduced the degree of uncertainty that might have surrounded the market in the days and weeks before the enforcement.

Both the Student and the Wilcoxon tests show a decline in price volatilities in the 10-day period (Pearson $p^{***}<.001$, d= -0.830 and Wilcoxon $p^{***}<.001$ with an effect size given by the matched rank biserial correlation of -0.851).

In particular, the mean standard deviation before the event was 0.781, while afterwards it was reduced to 0.552, hence representing a considerable average decrease of approximately 29.38% in volatility and, hence, in fluctuation of European bond prices. This result is aligned with the one in the US, where the price volatilities of bonds after the announcement of the Agreement significantly decreased in the 10-day window by an average of around 28.36%

Figure 11 - Changes in Price's Standard Deviation after Paris Agreement (Europe)



6.4. Reflections of the Paris Agreement in the European Corporate Bond Market – Discussion of Results

Bringing it all together, it is possible to conclude that with high probability the Paris Agreement did not leave tangible impacts when it comes to liquidity, neither for the US nor for the European corporate bond markets. Concerning the price implications, on the other hand, there is strong evidence (supported by the highly significant statistics with rather high effect sizes for both the parametric and the non-parametric tests) that the Paris Agreement generated a shift in bond prices, positioning them at a new lower price-equilibrium, as they drastically decreased for both US- and Europe-based companies, although European bonds seem to have suffered additional price losses compared to the US ones. This might be due to the fear of stricter regulations and implementation policies that the EU has traditionally imposed when it comes to climate change topics, hence market participants might have perceived European bonds to be riskier than the ones issued by US-based companies.

Similar consequences for the two continents can be derived in the context of price volatilities. In fact, both for US- and Europe-based companies, bond prices´ standard deviations significantly decreased after the announcement of the Agreement, therefore suggesting that its official implementation might have created a higher degree of certainty compared to the days and weeks leading up to it (for US bonds, the decrease was of approximately 28.36%, while for European bonds such decline consisted of around 29.32% in the 10-day window of comparison).

The combination of the more severe reductions in prices and price volatilities for Europe-based bonds might be a signal that market participants react more severely to European-based companies when the occurrence of a climate risk of 'transition risk' type takes place, and this might be due to the belief that European companies are considered to be more highly impacted by their regulations in comparison to US-based firms.

7. Is Climate Risk a Priced Factor in the European Corporate Bond Market?

7.1. Correlation between liquidity changes and E- and ESG-Scores

According to the Wilcoxon test, spreads bid-ask (liquidity) significantly decreased (increased) in the 1.5-month window. Therefore, a number of tests have been conducted to understand whether such changes can be correlated with the issuing companies' E- and ESG-score. The alternative hypothesis, as in the US analysis, is that changes in spreads bid-ask and issuing companies' E-, ESG-scores are negatively correlated with each other.

The results, similar to the ones obtained for the US analysis, show no significant correlation between the ESG scores and the 1.5-month changes in spreads bid-ask. Furthermore, the correlation between such spreads changes also turns out to be statistically non-significant with regard to the issuing companies' E-scores.

A first conclusion that can be drawn is that the ESG scores of the issuing firms do not seem able to predict changes in their respective bonds' liquidity (spreads bid-ask) when a transition risk like the implementation of the Paris Agreement materializes. Similarly, the E-score seems to have no predicting power as well in the European bond market, whereas for the US more research is needed, as estimates vary based on whether a parametric or a non-parametric test is used.

7.2. Correlation between volatility changes and E- and ESG-Scores

The previous analysis showed that bond prices' standard deviations in the European market significantly decreased in the 10-day window after the announcement of the Paris Agreement. The alternative hypothesis is that such changes should be negatively correlated with the issuing firms' E- or ESG-scores, as companies which are "greener" on paper might be more stable compared to "brown" firms when a climate risk of transition type verifies, and such a stability may also be reflected into the price of their issued bonds.

The test outputs nonetheless straightforwardly show that such changes in price volatilities cannot be explained neither by the E-scores nor by the ESG-scores. This result, which is identical to the one found during the US analysis, might be evidence that changes in bond price volatilities cannot be explained by how green the issuing company's profile is, if this is measured by its E- or ESG-score.

7.3. Correlation between Price changes and E- and ESG-Scores

Previous results showed that, after the Paris Agreement, bond prices in the European market significantly decreased in all three time periods analyzed. Therefore, a number of tests trying to correlate such changes to the issuing companies' E- and ESG-scores have been conducted, where the alternative hypothesis, as in the US case, is that there exists a positive correlation between such price changes and the companies' scores, meaning that companies with higher environmental and ESG scores should be less exposed and, in turn, their issued bonds should suffer less from a price loss compared to those issued by companies whose scores are lower.

Identically to the US results, the null hypothesis cannot be rejected in any of the correlation analyses, meaning that bonds´ price changes following the Paris Agreement cannot be meaningfully predicted by neither their issuing companies´ E- nor by their ESG-score.

Due to the scarcity of data for the European market, which made it impossible to extract more than one sub-sample of industries with enough observations to make a statistical analysis reliable, only one industry-correlated correlation was feasible, namely the one within the banking sector ($n=7$). The results nonetheless show no significant relationships as well, following the same outcomes observed for the US industry-controlled correlations, which also turned all out to be non-significant.

7.4. E- and ESG-Scores Correlation Analyses – Discussion of Results

In conclusion, the combination of the results obtained for the European market with the ones captured during the US analysis suggests that climate risks consisting of transition risks (like the announcement of the Paris Agreement) seem not to be priced in the fixed-income markets of corporate bonds when using the E- and the ESG-scores of the respective issuing companies as predictive factors.

A last attempt has been made by using the issuing companies' respective GHG emission levels, which follows the previous logic explained in the course of the US analysis.

7.5. Correlation between Price changes and greenhouse gas (GHG) emissions – Europe

This analysis follows the exact logic and approach already explained for the US case. Therefore, the alternative hypothesis is that the level of GHG emissions released by the issuing firms is negatively correlated with the price changes of their outstanding bonds.

This time, for *Scope 1* as well as for *Scope 2* emissions, the total number of observations was 34; for *Scope 3*, n=30; for *Scopes 1+2*, n=39 and, finally, for the sum of *Scopes 1, 2,* and *3* (i.e., the total level of GHG emissions of a company), n=30.

Similar to the US analysis, the results of the Shapiro-Wilk tests suggest that the data does not follow a normal distribution. Hence, the classic Pearson's correlations have been accompanied by their non-parametric correspondents, namely Spearman's rho and Kendall's Tau-b.

In terms of statistics, the results go in the same direction as in the US, with the non-parametric tests not being able to detect any significant relationship between the levels of GHG emissions and the price changes, whereas Pearson's correlation turns out to be significant in some cases.

Specifically, *Scope 1* emissions are significantly negatively correlated with the price changes of the bonds within all 3 time-windows examined (1.5-month p*=.039 with r = -.307; 10-day p*=.017 with r = -.364; 5-day p*=0.018 with r = -.360).

On the other hand, showing stronger results, *Scopes 1+2* emissions are even more highly significantly correlated with the price changes (1.5-month p*=.038 with r = -.287; 10-day p**=.009 with r = -.375; 5-day p**=*.010* with r = -.372).

Scope 2, Scope 3 and *Scopes 1+2+3* correlations with the price changes all turned out to be non-significant.

This is an interesting result in many ways. First, it emphasizes that market participants within the European market seem to have been more efficient in pricing the materialization of this climate risk via firm-specific characteristics (in this case, the GHG emissions of the issuing companies) than in the US, as first evidence of a correlation between the price changes and the GHG emissions in the US only appears in the 1.5-month window, while for the European market such evidence already showed up in the 5- and 10-day period. Secondly, it highlights an important predictive similarity of the level of GHG emissions within the two continents. Namely, both for the European and for the US bond market, the level of *Scope* 1 emissions of the issuing firms could be used to somewhat predict the price change on their issued bonds. Moreover, *Scope 2* emissions do not provide any additional information when taken alone (possibly due to their rather small effect size). On the other hand, an interesting divergence appears clear when confronting the results of the two continents. Namely, in the US, *Scope 3* emissions seem to have a rather distinguished predictive power for price changes, while for the European market such a scope of emission does not seem to provide any information neither when taken alone nor in combination with the other scopes of emission (i.e., *Scope 1* and *Scope 2*).

In analogy with the US results, Pearson's outputs would suggest that the null hypothesis can be rejected, indicating that the climate risk (specifically, a transition risk in this case) represented by the implementation of the Paris Agreement is a priced factor in the European bond market as well.

For this reason, a single regression has been performed on the relationship with the highest significance and the highest effect size (measured by Pearson's *r*). Hence, the level of *Scopes 1+2* emissions has been set as the independent variable, while the 10-day price change of bonds is the dependent variable. Below is the output.

Figure 12 - 10-Day Bid-Price Change and GHG Emissions Regression (Europe)

Model Summary - Average Change in Bid-Price 10 Days after Event in bps

Model	R	R^2	Adjusted R^2	RMSE
H_0	0.000	0.000	0.000	230.006
H_1	0.375	0.141	0.117	216.095

ANOVA

Model		Sum of Squares	df	Mean Square	F	p
H_1	Regression	282511.589	1	282511.589	6.050	0.019
	Residual	$1.728\times10^{+6}$	37	46697.014		
	Total	$2.010\times10^{+6}$	38			

Coefficients

Model		Unstandardized	Standard Error	Standardized	t	p
H_0	(Intercept)	-164.471	36.830		-4.466	< .001
H_1	**(Intercept)**	**-136.537**	36.419		-3.749	< .001
	Total Scope 1 + 2 Emissions (in tons)	**-3.211×10^{-6}**	1.305×10^{-6}	-0.375	-2.460	0.019

This model can be therefore summarized in the following equation:

$$\mathbf{10\_}\boldsymbol{Day\ Price\ Change}\ (\boldsymbol{in\ bps}) = \mathbf{-136.537 - 3.211} \times \mathbf{10^{-6}} \times \boldsymbol{GHG\ Emissions}\ (\boldsymbol{Scopes}\ \mathbf{1+2})$$

Such equation suggests that in the European corporate bond market, following the announcement of the enforcement of the Paris Agreement, a non-diversifiable bond price loss of 136.537 basis points takes place, and then each additional 311,411.86 ca (calculated as $\frac{1}{3.211\times10^{-6}}$) tons of *Scopes 1+2* GHG emissions released by the respective issuing companies result in an additional 1-basis-point loss on the price of their issued bonds.

This result is consistent with other outcomes and consideration already observed in this extensive analysis when comparing the two continents. In fact, the same model to calculate the price change in the US showed a non-diversifiable price loss of 97.236 (hence, 39.3 basis points less than in Europe).

Concerning the additional 1-basis-point price loss which depends on the level of GHG emissions, the comparison between the two continents is not particularly agile, as two different levels of GHG emissions have been examined to price the climate risk analyzed, depending on their respective statistical significance and effect size (*Scopes 1+2* for Europe and *Scopes 1+2+3* in the US).

8. Discussion and Conclusions

Climate change and the risks associated with it represent a financial challenge in both their shapes: physical risk and transition risk.

The transition risk analyzed in this context, namely the announcement of the imminent enforcement of the Paris Agreement seems to have generated a number of effects in both the US and the European fixed-income market of corporate bonds.

From a liquidity standpoint, the Agreement seems to have resulted in a slight decline in spreads bid-ask which, although statistically significant when adopting non-parametric tests, is likely to have produced no tangible impacts for trading, given that most observations are still very centered around the mean of zero. The parametric Student tests performed on the same sample, for instance, show no significant changes in spreads before versus after the event.

A more evident impact can be observed when analyzing the variation in the price volatilities of bonds (measured via their respective prices' standard deviations) after the announcement of the Agreement. In the US, bond volatilities significantly decreased within the 10-day window, with an average decrease of approximately 28.34%. A very similar result is obtained for the Europe-based bonds, with an average decline in their price's volatilities in the 10-day period subsequent the Agreement of approximately 29.38%. Hence, it is possible to conclude that the Paris Agreement generated an enhanced price stability within the corporate bond market of the two continents. This might be due to a reduction in uncertainty granted by more regulatory clarity about the trajectory of future policies.

The most striking result was probably the reflection of the announcement of the Agreement on the bonds' prices. The test results straightforwardly show a sharp decline within all three time periods analyzed adjacent to its announcement. In fact, bond prices in the US market declined by an average of 105.03 bp in the 1.5-month window, 101.84 bp in the 10-day period and 81.464 bp in the 5-day comparison. These drops are even more pronounced for bonds issued by European-based companies, where such price slums consisted of 155.32 bp, 170.41 bp and 149.852 bp, respectively.

One could therefore conclude that the Agreement generated a shock in the prices of corporate bonds for both continents, likely moving them to a new lower equilibrium.

One possible interpretation can be provided by the model for corporate bonds valuation provided by Battiston and Monasterolo (2020), according to which a drop in the price of bonds can be attributed to an increase in its probability of default. This appears a reasonable interpretation, as the Agreement would require massive business model transformations for most companies in order to adapt to the new greener regulation, which might not be feasible for every company and, nonetheless, it would come at a high cost, thereby prospectively adding new lumps of fixed costs for companies against variable and uncertain revenues, which might result in decreased profitability margins, but also in general cash-flow instabilities which would hence negatively affect solvency and, hence, the issued bonds' prices.

Furthermore, these results would suggest that European bonds are assigned a higher probability of default when compared to the US ones, given that their prices declined by a larger factor in all the three time-windows analyzed. This is also plausible, as Europe has always been traditionally more sensible to climate-related topics than the US (Brunnée, 2008; Vogler and Bretherton, 2006). Therefore, market participants might have believed that European regulatory bodies and policy makers might implement the Agreement more stringently than the respective US authorities, which would then justify the difference in the observed relative price drops. These results might have important implications for asset managers who hold large quantities of corporate bonds in their portfolios.

When it comes to the ESG and the Environmental scores of the issuing companies, the main conclusion is that these are not good factors at predicting the significant price changes discussed above, as higher scores are not positively correlated with the respective issued bonds' price changes (neither with their liquidity nor volatility changes). This might be the first sign of climate risk mispricing, as the ESG- and, especially, the E-scores should reflect a company's exposure to such risks. Hence, higher scores should, in theory, correspond to lower bond price declines when it comes to the materialization of a climate risk.

One possible interpretation in this context is that climate risks (in this case, transition risks) are mispriced in this market. Alternatively, one could also argue that these scores are not fully reliable and, hence, do not truly represent the company's green profile, as also argued by Avramov et al. (2022) and Cohen et al. (2020).

Lastly, concerning the correlation analyses of the GHG emissions of the issuing firms and their issued bonds' price changes, a number of conclusions can be drawn. Firstly, while for most statistical tests during the course of this work the parametric tests (either Student or Pearson) reported the same results as their non-parametric counterparts (i.e., Wilcoxon, Spearman's rho and Kendall's Tau B), for these GHG emission analyses only the parametric Pearson's correlations report a statistically significant negative interaction between the level of greenhouse gas emissions of the issuing firms and the price of their issued bonds. The non-parametric correlation analyses, on the other hand, do not detect any significant correlation.

Pearson shows a significant relationship indicating a potential linear association between the two variables. Specifically, for the US bond market, each additional 896,057.35 tons of total GHG emissions (i.e., *Scopes 1+2+3*) generate an additional 1-basis-point price decrease on the issued bonds, while for European bonds such a price drop is generated with each additional 311,411.86 tons of GHG emissions of *Scopes 1+2*.

Should this be the case, this could be evidence that climate risk is indeed a priced factor in the fixed-income market of corporate bonds. This result would go in the same direction as the one provided by Bolton and Kacperczyk (2022), who find that stocks of companies which present a higher level of CO_2 emissions earn higher returns.

However, the non-normal distribution of the data should not be underestimated. Spearman's rho and Kendall's Tau-b correlations, due to their non-parametric nature, might be more robust under such conditions and they were not able to find any significant monotonic relationship between the GHG emission levels and the bonds' price changes, potentially suggesting that outliers or the non-linear patterns might influence the correlation. This last consideration, on the other hand, would find the approval of the study from Duan et al. (2021), who examine the same issue in the context of corporate bond markets and fail to confirm what is known as the "carbon risk premium hypothesis".

All in all, putting everything together, the overall results of this analysis come probably the closest to the ones provided by the recent study of Bats, Bua and Kapp (2024), who find evidence of the existence of a transition risk premium in the corporate bond market of the Euro area after the Paris Agreement, although such estimates are mostly small and non-significant. Therefore, caution should be exercised when interpreting the results of Pearson's tests.

In conclusion and to summarize all the above-mentioned results, the climate risk of transition type (i.e., the announcement of the enforcement of the Paris Agreement, in this case) is reflected in the fixed-income market of corporate bonds both in the US and in Europe, as after its implementation bond prices as well as their volatilities significantly decreased, where the price decline was more pronounced for European bonds. Such significant changes following the Agreement cannot be predicted in seemingly any way via the use of the issuing companies' ESG- and E-Scores. Finally, when trying to correlate such price changes with the level of GHG emissions of the issuing firms, caution is needed in interpreting the results, given the tedious nature of the data of the analyzed sample. One the one hand, Pearson provides the foundation to consider this climate risk a priced factor, while on the other hand its non-parametric counterparts are not able to find such a significant relationship. Therefore, more research would be needed in order to overcome this data limitation present within the studied sample, as this would thereby likely provide more precise insights as to whether and to what extent climate risk is a priced factor in fixed-income markets.

9. Limitations

As discussed in the conclusions, the major issue encountered was the tedious nature of the analyzed data, which was mostly non-normally distributed, making it necessary to incorporate non-parametric testing together with the classic parametric ones in order to ensure a comprehensive analysis. Although almost always reporting same results in terms of significance of estimates, a few divergences appeared for some specific tests, making these few results and their subsequent interpretations rather laborious and, at times, contingent on subjective judgment, which required the use of scatter plots and rainbow-cloud graphs in order to provide more reliable readings.

Similarly, another major issued faced was the data collection process, which required a manual hand-picking of all the raw financial information of the bonds and their respective issuing firms' characteristics and environmental information, which then had to be re-elaborated in multiple spreadsheets in order to be adjusted and prepared for the subsequent statistical analyses, all of which hindered and drastically slowed-down the data-collection process.

Lastly, the data availability when it comes to corporate bonds' financial information and firms' sustainable data was rather scarce (especially for the European bonds), resulting in a rather small sample size, which made it impossible to control for a number of characteristics, including issuer's credit rating and bond's credit rating.

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11. Appendix

US ANALYSIS OUTPUTS

Spreads Bid-Ask Change:

Test of Normality (Shapiro-Wilk)

			W	p
Average Bid-Ask Spread 1.5 Months before (in bps)	-	Average Bid-Ask Spread 1.5 Months after (in bps)	0.308	< .001
Average Bid-Ask Spread 10 days before (in bps)	-	Average Bid-Ask Spread 10 days after (in bps)	0.339	< .001
Average Bid-Ask Spread 5 days before (in bps)	-	Average Bid-Ask Spread 5 days after (in bps)	0.365	< .001

Note. Significant results suggest a deviation from normality.

Paired Samples T-Test

Measure 1		Measure 2	Test	Statistic	z	df	p
Average Bid-Ask Spread 1.5 Months before (in bps)	-	Average Bid-Ask Spread 1.5 Months after (in bps)	Student	-1.640		101	0.948
			Wilcoxon	2351.000	-0.920		0.822
Average Bid-Ask Spread 10 days before (in bps)	-	Average Bid-Ask Spread 10 days after (in bps)	Student	-0.291		101	0.614
			Wilcoxon	3967.000	4.475		< .001
Average Bid-Ask Spread 5 days before (in bps)	-	Average Bid-Ask Spread 5 days after (in bps)	Student	0.234		101	0.408
			Wilcoxon	4547.000	6.411		< .001

Note. For all tests, the alternative hypothesis specifies that Measure 1 is greater than Measure 2. For example, Average Bid-Ask Spread 1.5 Months before (in bps) is greater than Average Bid-Ask Spread 1.5 Months after (in bps).

Bid Price change:

Test of Normality (Shapiro-Wilk)

			W	p
AVERAGE % Bid-Price change compared to first-period price (1.5 months before event) in bps	-	AVERAGE % Bid-Price change compared to first-period price (1.5 months after event) in bps	0.811	< .001
AVERAGE % Bid-Price change compared to first-period price (10 days before event) in bps	-	AVERAGE % Bid-Price change compared to first-period price (10 days after event) in bps	0.836	< .001
AVERAGE % Bid-Price change compared to first-period price (5 days before event) in bps	-	AVERAGE % Bid-Price change compared to first-period price (5 days after event) in bps	0.788	< .001

Note. Significant results suggest a deviation from normality.

Paired Samples T-Test

Measure 1		Measure 2	Test	Statistic	z	df	p	Effect Size	SE Effect Size
AVERAGE % Bid-Price change compared to first-period price (1.5 months before event) in bps	-	AVERAGE % Bid-Price change compared to first-period price (1.5 months after event) in bps	Student	3.894		101	< .001	0.386	0.126
			Wilcoxon	4012.000	4.625		< .001	0.528	0.114
AVERAGE % Bid-Price change compared to first-period price (10 days before event) in bps	-	AVERAGE % Bid-Price change compared to first-period price (10 days after event) in bps	Student	3.384		101	< .001	0.335	0.130
			Wilcoxon	4140.000	5.052		< .001	0.576	0.114
AVERAGE % Bid-Price change compared to first-period price (5 days before event) in bps	-	AVERAGE % Bid-Price change compared to first-period price (5 days after event) in bps	Student	2.428		101	0.008	0.240	0.126
			Wilcoxon	3796.000	4.135		< .001	0.474	0.114

Note. For all tests, the alternative hypothesis specifies that Measure 1 is greater than Measure 2. For example, AVERAGE % Bid-Price change compared to first-period price (1.5 months before event) is greater than AVERAGE % Bid-Price change compared to first-period price (1.5 months after event).

Note. For the Student t-test, effect size is given by Cohen's *d* . For the Wilcoxon test, effect size is given by the matched rank biserial correlation.

Descriptives

	N	Mean	SD	SE	Coeff. of var.
AVERAGE % Bid-Price change compared to first-period price (1.5 months before event) in bps	102	-103.59	167.288	16.564	-1.615
AVERAGE % Bid-Price change compared to first-period price (1.5 months after event) in bps	102	-208.62	260.983	25.841	-1.251
AVERAGE % Bid-Price change compared to first-period price (10 days before event) in bps	102	-78.44	286.037	28.322	-3.646
AVERAGE % Bid-Price change compared to first-period price (10 days after event) in bps	102	-180.28	170.391	16.871	-0.945
AVERAGE % Bid-Price change compared to first-period price (5 days before event) in bps	102	-78.945	342.151	33.878	-4.334
AVERAGE % Bid-Price change compared to first-period price (5 days after event) in bps	102	-160.40	125.371	12.414	-0.782

Price Standard Deviation Changes

Paired Samples T-Test

Measure 1		Measure 2	Test	Statistic	z	df	p	Effect Size	SE Effect Size
Bid-Price Standard Deviation 1.5 Months before	-	Bid-Price Standard Deviation 1.5 Months after	Student	-2.499		101	0.993	-0.247	0.094
			Wilcoxon	2091.000	-1.788		0.963	-0.204	0.114
Ask-Price Standard Deviation 1.5 Months before	-	Ask-Price Standard Deviation 1.5 Months after	Student	-2.511		101	0.993	-0.249	0.093
			Wilcoxon	2087.000	-1.801		0.964	-0.205	0.114
Bid-Price Standard Deviation 10 Days before	-	Bid-Price Standard Deviation 10 Days after	Student	5.257		101	< .001	0.521	0.109
			Wilcoxon	4367.000	5.810		< .001	0.663	0.114
Ask-Price Standard Deviation 10 Days before	-	Ask-Price Standard Deviation 10 Days after	Student	5.276		101	< .001	0.522	0.109
			Wilcoxon	4373.000	5.830		< .001	0.665	0.114
Bid-Price Standard Deviation 5 Days before	-	Bid-Price Standard Deviation 5 Days after	Student	0.943		101	0.174	0.093	0.114
			Wilcoxon	3211.000	1.951		0.026	0.223	0.114
Ask-Price Standard Deviation 5 Days before	-	Ask-Price Standard Deviation 5 Days after	Student	0.943		101	0.174	0.093	0.114
			Wilcoxon	3209.000	1.944		0.026	0.222	0.114

Note. For all tests, the alternative hypothesis specifies that Measure 1 is greater than Measure 2. For example, Bid-Price Standard Deviation 1.5 Months before is greater than Bid-Price Standard Deviation 1.5 Months after.

Correlation between Bid-Ask Spread changes and E-, ESG-Scores

Correlation Table

Variable		Average Change in Bid-Ask Spread 5 Days before vs after in bps	ESG Score (FY2015)
1. Average Change in Bid-Ask Spread 5 Days after event in bps	Pearson's r	—	
	p-value	—	
	Effect size (Fisher's z)	—	
	SE Effect size	—	
	Spearman's rho	—	
	p-value	—	
	Effect size (Fisher's z)	—	
	SE Effect size	—	
	Kendall's Tau B	—	
	p-value	—	
	Effect size (Fisher's z)	—	
	SE Effect size	—	
2. ESG Score (FY2015)	Pearson's r	-0.048	—
	p-value	0.318	—
	Effect size (Fisher's z)	-0.048	—
	SE Effect size	0.101	—
	Spearman's rho	-0.160	—
	p-value	0.054	—
	Effect size (Fisher's z)	-0.161	—
	SE Effect size	0.101	—
	Kendall's Tau B	-0.106	—
	p-value	0.058	—
	Effect size (Fisher's z)	-0.106	—
	SE Effect size	0.066	—

Note. All tests one-tailed, for negative correlation.

* p < .05, ** p < .01, *** p < .001, one-tailed

Correlation Table

Variable		Average Change in Bid-Ask Spread 10 days after event in bps	ESG Score (FY2015)
1. Average Change in Bid-Ask Spread 10 days after event in bps	Pearson's r	—	
	p-value	—	
	Effect size (Fisher's z)	—	
	SE Effect size	—	
	Spearman's rho	—	
	p-value	—	
	Effect size (Fisher's z)	—	
	SE Effect size	—	
	Kendall's Tau B	—	
	p-value	—	
	Effect size (Fisher's z)	—	
	SE Effect size	—	
2. ESG Score (FY2015)	Pearson's r	-0.038	—
	p-value	0.353	—
	Effect size (Fisher's z)	-0.038	—
	SE Effect size	0.101	—
	Spearman's rho	-0.117	—
	p-value	0.121	—
	Effect size (Fisher's z)	-0.118	—
	SE Effect size	0.101	—
	Kendall's Tau B	-0.076	—
	p-value	0.128	—
	Effect size (Fisher's z)	-0.076	—
	SE Effect size	0.067	—

Note. All tests one-tailed, for negative correlation.

* p < .05, ** p < .01, *** p < .001, one-tailed

Correlation Table

Variable		Average Change in Bid-Ask Spread 5 Days after Event in bps		Environmental Pillar Score (FY2015)
1. Average Change in Bid-Ask Spread 5 Days after event in bps	Pearson's r	—		
	p-value	—		
	Effect size (Fisher's z)	—		
	SE Effect size	—		
	Spearman's rho	—		
	p-value	—		
	Effect size (Fisher's z)	—		
	SE Effect size	—		
	Kendall's Tau B	—		
	p-value	—		
	Effect size (Fisher's z)	—		
	SE Effect size	—		
2. Environmental Pillar Score (FY2015)	Pearson's r	-0.100		—
	p-value	0.159		—
	Effect size (Fisher's z)	-0.100		—
	SE Effect size	0.101		—
	Spearman's rho	-0.237	**	—
	p-value	0.008		—
	Effect size (Fisher's z)	-0.242		—
	SE Effect size	0.102		—
	Kendall's Tau B	-0.155	*	—
	p-value	0.011		—
	Effect size (Fisher's z)	-0.156		—
	SE Effect size	0.065		—

Note. All tests one-tailed, for negative correlation.

* p < .05, ** p < .01, *** p < .001, one-tailed

Correlation Table

Variable		Average Change in Bid-Ask Spread 10 days after event in bps	Environmental Pillar Score (FY2015)
1. Average Change in Bid-Ask Spread 10 days after event in bps	Pearson's r	—	
	p-value	—	
	Effect size (Fisher's z)	—	
	SE Effect size	—	
	Spearman's rho	—	
	p-value	—	
	Effect size (Fisher's z)	—	
	SE Effect size	—	
	Kendall's Tau B	—	
	p-value	—	
	Effect size (Fisher's z)	—	
	SE Effect size	—	
2. Environmental Pillar Score (FY2015)	Pearson's r	-0.080	—
	p-value	0.211	—
	Effect size (Fisher's z)	-0.081	—
	SE Effect size	0.101	—
	Spearman's rho	-0.176 *	—
	p-value	0.039	—
	Effect size (Fisher's z)	-0.178	—
	SE Effect size	0.101	—
	Kendall's Tau B	-0.113 *	—
	p-value	0.047	—
	Effect size (Fisher's z)	-0.113	—
	SE Effect size	0.066	—

Note. All tests one-tailed, for negative correlation.

* p < .05, ** p < .01, *** p < .001, one-tailed

Correlation between Prices’ Standard Deviation changes and E-, ESG-Scores

Correlation Table

Variable		**Change in Bid-Price Standard Deviation 10 Days after event**	**ESG Score (FY2015)**
1. Change in Bid-Price Standard Deviation 10 Days after event	Pearson's r	—	
	p-value	—	
	Effect size (Fisher's z)	—	
	SE Effect size	—	
	Spearman's rho	—	
	p-value	—	
	Effect size (Fisher's z)	—	
	SE Effect size	—	
	Kendall's Tau B	—	
	p-value	—	
	Effect size (Fisher's z)	—	
	SE Effect size	—	
2. ESG Score (FY2015)	Pearson's r	0.034	—
	p-value	0.633	—
	Effect size (Fisher's z)	0.034	—
	SE Effect size	0.101	—
	Spearman's rho	0.135	—
	p-value	0.912	—
	Effect size (Fisher's z)	0.136	—
	SE Effect size	0.101	—
	Kendall's Tau B	0.101	—
	p-value	0.933	—
	Effect size (Fisher's z)	0.101	—
	SE Effect size	0.066	—

Note. All tests one-tailed, for negative correlation.

* p < .05, ** p < .01, *** p < .001, one-tailed

Correlation Table

Variable		Change in Bid-Price Standard Deviation 10 Days after event	Environmental Pillar Score (FY2015)
1. Change in Bid-Price Standard Deviation 10 Days after event	Pearson's r	—	
	p-value	—	
	Effect size (Fisher's z)	—	
	SE Effect size	—	
	Spearman's rho	—	
	p-value	—	
	Effect size (Fisher's z)	—	
	SE Effect size	—	
	Kendall's Tau B	—	
	p-value	—	
	Effect size (Fisher's z)	—	
	SE Effect size	—	
2. Environmental Pillar Score (FY2015)	Pearson's r	-0.003	—
	p-value	0.489	—
	Effect size (Fisher's z)	-0.003	—
	SE Effect size	0.101	—
	Spearman's rho	0.088	—
	p-value	0.809	—
	Effect size (Fisher's z)	0.088	—
	SE Effect size	0.101	—
	Kendall's Tau B	0.063	—
	p-value	0.826	—
	Effect size (Fisher's z)	0.063	—
	SE Effect size	0.067	—

Note. All tests one-tailed, for negative correlation.

* p < .05, ** p < .01, *** p < .001, one-tailed

Correlation between Prices changes and E-, ESG-Scores

Correlation Table

Variable		**Average daily Change in Bid-Price compared to first-period-price in bps (1.5-Month-basis)**	**Environmental Pillar Score (FY2015)**
1. Average daily Change in Bid-Price compared to first-period-price in bps (1.5-Month-basis)	Pearson's r	—	
	p-value	—	
	Effect size (Fisher's z)	—	
	SE Effect size	—	
	Spearman's rho	—	
	p-value	—	
	Effect size (Fisher's z)	—	
	SE Effect size	—	
	Kendall's Tau B	—	
	p-value	—	
	Effect size (Fisher's z)	—	
	SE Effect size	—	
2. Environmental Pillar Score (FY2015)	Pearson's r	-0.168	—
	p-value	0.955	—
	Effect size (Fisher's z)	-0.170	—
	SE Effect size	0.101	—
	Spearman's rho	-0.192	—
	p-value	0.974	—
	Effect size (Fisher's z)	-0.195	—
	SE Effect size	0.102	—
	Kendall's Tau B	-0.136	—
	p-value	0.979	—
	Effect size (Fisher's z)	-0.137	—
	SE Effect size	0.066	—

Note. All tests one-tailed, for positive correlation.

* p < .05, ** p < .01, *** p < .001, one-tailed

Correlation Table

Variable		Average daily Change in Bid-Price compared to first-period-price in bps (1.5-Month-basis)	ESG Score (FY2015)
1. Average daily Change in Bid-Price compared to first-period-price in bps (1.5-Month-basis)	Pearson's r	—	
	p-value	—	
	Effect size (Fisher's z)	—	
	SE Effect size	—	
	Spearman's rho	—	
	p-value	—	
	Effect size (Fisher's z)	—	
	SE Effect size	—	
	Kendall's Tau B	—	
	p-value	—	
	Effect size (Fisher's z)	—	
	SE Effect size	—	
2. ESG Score (FY2015)	Pearson's r	-0.183	—
	p-value	0.967	—
	Effect size (Fisher's z)	-0.185	—
	SE Effect size	0.101	—
	Spearman's rho	-0.177	—
	p-value	0.962	—
	Effect size (Fisher's z)	-0.179	—
	SE Effect size	0.101	—
	Kendall's Tau B	-0.119	—
	p-value	0.962	—
	Effect size (Fisher's z)	-0.120	—
	SE Effect size	0.066	—

Note. All tests one-tailed, for positive correlation.

* p < .05, ** p < .01, *** p < .001, one-tailed

Correlation Table

Variable		Average daily Change in Bid-Price compared to first-period-price in bps (10-Day-basis)	Environmental Pillar Score (FY2015)
1. Average daily Change in Bid-Price compared to first-period-price in bps (10-Day-basis)	Pearson's r	—	
	p-value	—	
	Effect size (Fisher's z)	—	
	SE Effect size	—	
	Spearman's rho	—	
	p-value	—	
	Effect size (Fisher's z)	—	
	SE Effect size	—	
	Kendall's Tau B	—	
	p-value	—	
	Effect size (Fisher's z)	—	
	SE Effect size	—	
2. Environmental Pillar Score (FY2015)	Pearson's r	-0.158	—
	p-value	0.944	—
	Effect size (Fisher's z)	-0.159	—
	SE Effect size	0.101	—
	Spearman's rho	-0.205	—
	p-value	0.980	—
	Effect size (Fisher's z)	-0.208	—
	SE Effect size	0.102	—
	Kendall's Tau B	-0.141	—
	p-value	0.982	—
	Effect size (Fisher's z)	-0.142	—
	SE Effect size	0.066	—

Note. All tests one-tailed, for positive correlation.

* $p < .05$, ** $p < .01$, *** $p < .001$, one-tailed

Correlation Table

Variable		**Average daily Change in Bid-Price compared to first-period-price in bps (10-Day-basis)**	**ESG Score (FY2015)**
1. Average daily Change in Bid-Price compared to first-period-price in bps (10-Day-basis)	Pearson's r	—	
	p-value	—	
	Effect size (Fisher's z)	—	
	SE Effect size	—	
	Spearman's rho	—	
	p-value	—	
	Effect size (Fisher's z)	—	
	SE Effect size	—	
	Kendall's Tau B	—	
	p-value	—	
	Effect size (Fisher's z)	—	
	SE Effect size	—	
2. ESG Score (FY2015)	Pearson's r	-0.159	—
	p-value	0.945	—
	Effect size (Fisher's z)	-0.160	—
	SE Effect size	0.101	—
	Spearman's rho	-0.164	—
	p-value	0.950	—
	Effect size (Fisher's z)	-0.165	—
	SE Effect size	0.101	—
	Kendall's Tau B	-0.114	—
	p-value	0.956	—
	Effect size (Fisher's z)	-0.115	—
	SE Effect size	0.066	—

Note. All tests one-tailed, for positive correlation.

* p < .05, ** p < .01, *** p < .001, one-tailed

Correlation Table

Variable		Average daily Change in Bid-Price compared to first-period-price in bps (5-Day-basis)	Environmental Pillar Score (FY2015)
1. Average daily Change in Bid-Price compared to first-period-price in bps (5-Day-basis)	Pearson's r	—	
	p-value	—	
	Effect size (Fisher's z)	—	
	SE Effect size	—	
	Spearman's rho	—	
	p-value	—	
	Effect size (Fisher's z)	—	
	SE Effect size	—	
	Kendall's Tau B	—	
	p-value	—	
	Effect size (Fisher's z)	—	
	SE Effect size	—	
2. Environmental Pillar Score (FY2015)	Pearson's r	-0.108	—
	p-value	0.861	—
	Effect size (Fisher's z)	-0.109	—
	SE Effect size	0.101	—
	Spearman's rho	-0.158	—
	p-value	0.944	—
	Effect size (Fisher's z)	-0.160	—
	SE Effect size	0.101	—
	Kendall's Tau B	-0.111	—
	p-value	0.952	—
	Effect size (Fisher's z)	-0.112	—
	SE Effect size	0.066	—

Note. All tests one-tailed, for positive correlation.

* p < .05, ** p < .01, *** p < .001, one-tailed

GHG Emissions – Correlations

Correlation Table

			Pearson		Spearman		Kendall	
			r	p	rho	p	tau B	p
Scope 1 CO2 Emissions (in tons)	-	Average Change in Bid-Price 5 Days after Event in bps	0.106	0.805	0.175	0.923	0.115	0.918
Scope 1 CO2 Emissions (in tons)	-	Average Change in Bid-Price 10 Days after Event in bps	-0.038	0.379	-0.012	0.463	-0.009	0.456
Scope 1 CO2 Emissions (in tons)	-	Average Change in Bid-Price 1.5 Months after Event in bps	-0.243 *	0.023	-0.084	0.249	-0.053	0.261

Note. All tests one-tailed, for negative correlation.

* p < .05, ** p < .01, *** p < .001, one-tailed

Correlation Table

			Pearson		Spearman		Kendall	
			r	p	rho	p	tau B	p
Scope 2 CO2 Emissions (in tons)	-	Average Change in Bid-Price 5 Days after Event in bps	0.092	0.766	0.038	0.618	0.028	0.629
Scope 2 CO2 Emissions (in tons)	-	Average Change in Bid-Price 10 Days after Event in bps	0.091	0.763	0.038	0.619	0.021	0.598
Scope 2 CO2 Emissions (in tons)	-	Average Change in Bid-Price 1.5 Months after Event in bps	-0.018	0.445	-0.060	0.317	-0.044	0.301

Note. All tests one-tailed, for negative correlation.

* p < .05, ** p < .01, *** p < .001, one-tailed

Correlation Table

			Pearson			Spearman		Kendall	
			r		p	rho	p	tau B	p
Scope 3 CO2 Emissions (in tons)	-	Average Change in Bid-Price 5 Days after Event in bps	0.157		0.857	0.152	0.849	0.096	0.833
Scope 3 CO2 Emissions (in tons)	-	Average Change in Bid-Price 10 Days after Event in bps	0.026		0.569	-0.024	0.434	-0.018	0.433
Scope 3 CO2 Emissions (in tons)	-	Average Change in Bid-Price 1.5 Months after Event in bps	-0.397	**	0.003	-0.218	0.068	-0.142	0.079

Note. All tests one-tailed, for negative correlation.
* p < .05, ** p < .01, *** p < .001, one-tailed

Correlation Table

			Pearson		Spearman		Kendall	
			r	p	rho	p	tau B	p
Total Scope 1 + 2 Emissions (in tons)	-	Average Change in Bid-Price 5 Days after Event in bps	0.151	0.133	0.124	0.218	0.086	0.205
Total Scope 1 + 2 Emissions (in tons)	-	Average Change in Bid-Price 10 Days after Event in bps	0.023	0.821	-0.002	0.981	8.082×10^{-4}	0.990
Total Scope 1 + 2 Emissions (in tons)	-	Average Change in Bid-Price 1.5 Months after Event in bps	-0.203 *	0.043	-0.157	0.118	-0.106	0.119

* p < .05, ** p < .01, *** p < .001

Correlation Table

			Pearson			Spearman		Kendall	
			r		p	rho	p	tau B	p
Total Scopes 1 + 2 + 3 CO2 Emissions (in tons)	-	Average Change in Bid-Price 5 Days after Event in bps	0.169		0.251	0.254	0.081	0.176	0.080
Total Scopes 1 + 2 + 3 CO2 Emissions (in tons)	-	Average Change in Bid-Price 10 Days after Event in bps	0.031		0.837	0.065	0.659	0.043	0.678
Total Scopes 1 + 2 + 3 CO2 Emissions (in tons)	-	Average Change in Bid-Price 1.5 Months after Event in bps	-0.424	**	0.003	-0.164	0.263	-0.124	0.218

* p < .05, ** p < .01, *** p < .001

EU TESTS

<u>Spreads Bid-Ask Change</u>

Paired Samples T-Test

Measure 1		Measure 2	Test	Statistic	z	df	p	Effect Size	SE Effect Size
Average Bid-Ask Spread 1.5 Months before in bps	-	Average Bid-Ask Spread 1.5 Months after in bps	Student	-0.522		40	0.698	-0.082	0.005
			Wilcoxon	647.000	2.805		0.002	0.503	0.177
Average Bid-Ask Spread 10 days before in bps	-	Average Bid-Ask Spread 10 days after in bps	Student	-1.506		40	0.930	-0.235	0.003
			Wilcoxon	543.000	1.458		0.074	0.261	0.177
Average Bid-Ask Spread 5 Days before in bps	-	Average Bid-Ask Spread 5 Days after in bps	Student	-1.606		40	0.942	-0.251	0.002
			Wilcoxon	534.000	1.341		0.092	0.240	0.177

Note. For all tests, the alternative hypothesis specifies that Measure 1 is greater than Measure 2. For example, Average Bid-Ask Spread 1.5 Months before in bps is greater than Average Bid-Ask Spread 1.5 Months after in bps.

Note. For the Student t-test, effect size is given by Cohen's *d* . For the Wilcoxon test, effect size is given by the matched rank biserial correlation.

Bid Price Change

Paired Samples T-Test

Measure 1	Measure 2	Test	Statistic	z	df	p	Effect Size	SE Effect Size
Average % Bid-Price Change compared to first-period-price 1.5 Months before in bps	- Average % Bid-Price Change compared to first-period-price 1.5 Months after in bps	Student	4.493		40	< .001	0.702	0.296
		Wilcoxon	741.000	4.024		< .001	0.721	0.177
Average % Bid-Price Change compared to first-period-price 10 Days before in bps	- Average % Bid-Price Change compared to first-period-price 10 Days after in bps	Student	4.736		40	< .001	0.740	0.315
		Wilcoxon	755.000	4.205		< .001	0.754	0.177
Average % Bid-Price Change compared to first-period-price 5 Days before in bps	- Average % Bid-Price Change compared to first-period-price 5 Days after in bps	Student	3.990		40	< .001	0.623	0.307
		Wilcoxon	714.000	3.674		< .001	0.659	0.177

Note. For all tests, the alternative hypothesis specifies that Measure 1 is greater than Measure 2. For example, Average % Bid-Price Change compared to first-period-price 1.5 Months before in bps is greater than Average % Bid-Price Change compared to first-period-price 1.5 Months after in bps.

Note. For the Student t-test, effect size is given by Cohen's *d* . For the Wilcoxon test, effect size is given by the matched rank biserial correlation.

Descriptives

	N	Mean	SD	SE	Coeff. of variation
Average % Bid-Price Change compared to first-period-price 1.5 Months before in bps	41	30.363	114.150	17.827	3.760
Average % Bid-Price Change compared to first-period-price 1.5 Months after in bps	41	-124.957	146.187	22.831	-1.170
Average % Bid-Price Change compared to first-period-price 10 Days before in bps	41	65.256	174.857	27.308	2.680
Average % Bid-Price Change compared to first-period-price 10 Days after in bps	41	-105.154	78.346	12.236	-0.745
Average % Bid-Price Change compared to first-period-price 5 Days before in bps	41	50.340	192.676	30.091	3.827
Average % Bid-Price Change compared to first-period-price 5 Days after in bps	41	-99.512	68.041	10.626	-0.684

Bid-Price Volatility Change

One Sample T-Test

	Test	Statistic	df	p	Effect Size	SE Effect Size
Change in Bid-Price Standard Deviation 1.5 Months after event	Student	0.969	40	0.831	0.151	0.157
	Wilcoxon	429.000		0.495	-0.003	0.177
Change in Ask-Price Standard Deviation 1.5 Months after event	Student	0.965	40	0.830	0.151	0.157
	Wilcoxon	429.000		0.495	-0.003	0.177
Change in Bid-Price Standard Deviation 10 Days after event	Student	-5.312	40	< .001	-0.830	0.181
	Wilcoxon	64.000		< .001	-0.851	0.177
Change in Ask-Price Standard Deviation 10 Days after event	Student	-5.319	40	< .001	-0.831	0.181
	Wilcoxon	62.000		< .001	-0.856	0.177
Change in Bid-Price Standard Deviation 5 Days after event	Student	1.196	40	0.881	0.187	0.158
	Wilcoxon	543.000		0.928	0.261	0.177
Change in Ask-Price Standard Deviation 5 Days after event	Student	1.200	40	0.881	0.187	0.158
	Wilcoxon	543.000		0.928	0.261	0.177

Note. For the Student t-test, effect size is given by Cohen's *d* . For the Wilcoxon test, effect size is given by the matched rank biserial correlation.

Note. For the Student t-test, the alternative hypothesis specifies that the mean is less than 0. For the Wilcoxon test, the alternative hypothesis specifies that the median is less than 0.

Descriptives

	N	Mean	SD	SE	Coefficient of variation
Bid-Price Standard Deviation 10 Days before	41	0.781	0.314	0.049	0.402
Bid-Price Standard Deviation 10 Days after	41	0.552	0.218	0.034	0.394
Ask-Price Standard Deviation 10 Days before	41	0.785	0.316	0.049	0.403
Ask-Price Standard Deviation 10 Days after	41	0.555	0.220	0.034	0.396

Correlation E, ESG-Scores with Spreads Bid-Ask Changes

Correlation Table

Variable		**ESG Score (FY2015)**	**Average Change in Bid-Ask Spread 1.5 Months after event in bps**
1. ESG Score (FY2015)	Pearson's r	—	
	p-value	—	
	Effect size (Fisher's z)	—	
	SE Effect size	—	
	Spearman's rho	—	
	p-value	—	
	Effect size (Fisher's z)	—	
	SE Effect size	—	
	Kendall's Tau B	—	
	p-value	—	
	Effect size (Fisher's z)	—	
	SE Effect size	—	
2. Average Change in Bid-Ask Spread 1.5 Months after event in bps	Pearson's r	0.010	—
	p-value	0.524	—
	Effect size (Fisher's z)	0.010	—
	SE Effect size	0.162	—
	Spearman's rho	0.065	—
	p-value	0.657	—
	Effect size (Fisher's z)	0.065	—
	SE Effect size	0.161	—
	Kendall's Tau B	0.049	—
	p-value	0.676	—
	Effect size (Fisher's z)	0.049	—
	SE Effect size	0.108	—

Note. All tests one-tailed, for negative correlation.

* $p < .05$, ** $p < .01$, *** $p < .001$, one-tailed

Correlation Table

Variable		Environmental Pillar Score (FY2015)	Average Change in Bid-Price Change 1.5 Months after event in bps
1. Environmental Pillar Score (FY2015)	Pearson's r	—	
	p-value	—	
	Effect size (Fisher's z)	—	
	SE Effect size	—	
	Spearman's rho	—	
	p-value	—	
	Effect size (Fisher's z)	—	
	SE Effect size	—	
	Kendall's Tau B	—	
	p-value	—	
	Effect size (Fisher's z)	—	
	SE Effect size	—	
2. Average Change in Bid-Price Change 1.5 Months after event in bps	Pearson's r	-0.018	—
	p-value	0.455	—
	Effect size (Fisher's z)	-0.018	—
	SE Effect size	0.162	—
	Spearman's rho	-0.011	—
	p-value	0.473	—
	Effect size (Fisher's z)	-0.011	—
	SE Effect size	0.160	—
	Kendall's Tau B	-0.013	—
	p-value	0.451	—
	Effect size (Fisher's z)	-0.013	—
	SE Effect size	0.109	—

Note. All tests one-tailed, for negative correlation.

* p < .05, ** p < .01, *** p < .001, one-tailed

Correlation between E-,ESG-Scores and Price Volatility Changes

Correlation Table

Variable		**Environmental Pillar Score (FY2015)**	**Change in Bid-Price Standard Deviation 10 Days after event**
1. Environmental Pillar Score (FY2015)	Pearson's r	—	
	p-value	—	
	Effect size (Fisher's z)	—	
	SE Effect size	—	
	Spearman's rho	—	
	p-value	—	
	Effect size (Fisher's z)	—	
	SE Effect size	—	
	Kendall's Tau B	—	
	p-value	—	
	Effect size (Fisher's z)	—	
	SE Effect size	—	
2. Change in Bid-Price Standard Deviation 10 Days after event	Pearson's r	-0.089	—
	p-value	0.291	—
	Effect size (Fisher's z)	-0.089	—
	SE Effect size	0.162	—
	Spearman's rho	-0.088	—
	p-value	0.293	—
	Effect size (Fisher's z)	-0.088	—
	SE Effect size	0.161	—
	Kendall's Tau B	-0.070	—
	p-value	0.261	—
	Effect size (Fisher's z)	-0.070	—
	SE Effect size	0.108	—

Note. All tests one-tailed, for negative correlation.

* p < .05, ** p < .01, *** p < .001, one-tailed

Correlation Table

Variable		ESG Score (FY2015)	Change in Bid-Price Standard Deviation 10 Days after event
1. ESG Score (FY2015)	Pearson's r	—	
	p-value	—	
	Effect size (Fisher's z)	—	
	SE Effect size	—	
	Spearman's rho	—	
	p-value	—	
	Effect size (Fisher's z)	—	
	SE Effect size	—	
	Kendall's Tau B	—	
	p-value	—	
	Effect size (Fisher's z)	—	
	SE Effect size	—	
2. Change in Bid-Price Standard Deviation 10 Days after event	Pearson's r	-0.030	—
	p-value	0.425	—
	Effect size (Fisher's z)	-0.030	—
	SE Effect size	0.162	—
	Spearman's rho	-0.041	—
	p-value	0.398	—
	Effect size (Fisher's z)	-0.041	—
	SE Effect size	0.161	—
	Kendall's Tau B	-0.012	—
	p-value	0.460	—
	Effect size (Fisher's z)	-0.012	—
	SE Effect size	0.109	—

Note. All tests one-tailed, for negative correlation.

* $p < .05$, ** $p < .01$, *** $p < .001$, one-tailed

Correlation between price changes and E-, ESG scores

Correlation Table

Variable		Environmental Pillar Score (FY2015)	Average Change in Bid-Price Change 1.5 Months after event in bps
1. Environmental Pillar Score (FY2015)	Pearson's r	—	
	p-value	—	
	Effect size (Fisher's z)	—	
	SE Effect size	—	
	Spearman's rho	—	
	p-value	—	
	Effect size (Fisher's z)	—	
	SE Effect size	—	
	Kendall's Tau B	—	
	p-value	—	
	Effect size (Fisher's z)	—	
	SE Effect size	—	
2. Average Change in Bid-Price Change 1.5 Months after event in bps	Pearson's r	-0.018	—
	p-value	0.545	—
	Effect size (Fisher's z)	-0.018	—
	SE Effect size	0.162	—
	Spearman's rho	-0.011	—
	p-value	0.527	—
	Effect size (Fisher's z)	-0.011	—
	SE Effect size	0.160	—
	Kendall's Tau B	-0.013	—
	p-value	0.549	—
	Effect size (Fisher's z)	-0.013	—
	SE Effect size	0.109	—

Note. All tests one-tailed, for positive correlation.

* p < .05, ** p < .01, *** p < .001, one-tailed

Correlation Table

Variable		ESG Score (FY2015)	Average Change in Bid-Price Change 1.5 Months after event in bps
1. ESG Score (FY2015)	Pearson's r	—	
	p-value	—	
	Effect size (Fisher's z)	—	
	SE Effect size	—	
	Spearman's rho	—	
	p-value	—	
	Effect size (Fisher's z)	—	
	SE Effect size	—	
	Kendall's Tau B	—	
	p-value	—	
	Effect size (Fisher's z)	—	
	SE Effect size	—	
2. Average Change in Bid-Price Change 1.5 Months after event in bps	Pearson's r	0.060	—
	p-value	0.355	—
	Effect size (Fisher's z)	0.060	—
	SE Effect size	0.162	—
	Spearman's rho	0.049	—
	p-value	0.381	—
	Effect size (Fisher's z)	0.049	—
	SE Effect size	0.161	—
	Kendall's Tau B	0.034	—
	p-value	0.382	—
	Effect size (Fisher's z)	0.034	—
	SE Effect size	0.108	—

Note. All tests one-tailed, for positive correlation.

* p < .05, ** p < .01, *** p < .001, one-tailed

Correlation Table

Variable		Environmental Pillar Score (FY2015)	Average Change in Bid-Price 10 Days after event in bps
1. Environmental Pillar Score (FY2015)	Pearson's r	—	
	p-value	—	
	Effect size (Fisher's z)	—	
	SE Effect size	—	
	Spearman's rho	—	
	p-value	—	
	Effect size (Fisher's z)	—	
	SE Effect size	—	
	Kendall's Tau B	—	
	p-value	—	
	Effect size (Fisher's z)	—	
	SE Effect size	—	
2. Average Change in Bid-Price 10 Days after event in bps	Pearson's r	-0.063	—
	p-value	0.653	—
	Effect size (Fisher's z)	-0.063	—
	SE Effect size	0.162	—
	Spearman's rho	0.035	—
	p-value	0.414	—
	Effect size (Fisher's z)	0.035	—
	SE Effect size	0.161	—
	Kendall's Tau B	0.004	—
	p-value	0.487	—
	Effect size (Fisher's z)	0.004	—
	SE Effect size	0.109	—

Note. All tests one-tailed, for positive correlation.

* p < .05, ** p < .01, *** p < .001, one-tailed

Correlation Table

Variable		ESG Score (FY2015)	Average Change in Bid-Price 10 Days after event in bps
1. ESG Score (FY2015)	Pearson's r	—	
	p-value	—	
	Effect size (Fisher's z)	—	
	SE Effect size	—	
	Spearman's rho	—	
	p-value	—	
	Effect size (Fisher's z)	—	
	SE Effect size	—	
	Kendall's Tau B	—	
	p-value	—	
	Effect size (Fisher's z)	—	
	SE Effect size	—	
2. Average Change in Bid-Price 10 Days after event in bps	Pearson's r	0.007	—
	p-value	0.482	—
	Effect size (Fisher's z)	0.007	—
	SE Effect size	0.162	—
	Spearman's rho	0.135	—
	p-value	0.199	—
	Effect size (Fisher's z)	0.136	—
	SE Effect size	0.162	—
	Kendall's Tau B	0.080	—
	p-value	0.234	—
	Effect size (Fisher's z)	0.081	—
	SE Effect size	0.108	—

Note. All tests one-tailed, for positive correlation.

* p < .05, ** p < .01, *** p < .001, one-tailed

Correlation Table

Variable		Environmental Pillar Score (FY2015)	Average Change in Bid-Price 5 Days after event in bps
1. Environmental Pillar Score (FY2015)	Pearson's r	—	
	p-value	—	
	Effect size (Fisher's z)	—	
	SE Effect size	—	
	Spearman's rho	—	
	p-value	—	
	Effect size (Fisher's z)	—	
	SE Effect size	—	
	Kendall's Tau B	—	
	p-value	—	
	Effect size (Fisher's z)	—	
	SE Effect size	—	
2. Average Change in Bid-Price 5 Days after event in bps	Pearson's r	-0.047	—
	p-value	0.615	—
	Effect size (Fisher's z)	-0.047	—
	SE Effect size	0.162	—
	Spearman's rho	0.013	—
	p-value	0.467	—
	Effect size (Fisher's z)	0.013	—
	SE Effect size	0.160	—
	Kendall's Tau B	0.001	—
	p-value	0.496	—
	Effect size (Fisher's z)	0.001	—
	SE Effect size	0.109	—

Note. All tests one-tailed, for positive correlation.

* p < .05, ** p < .01, *** p < .001, one-tailed

Correlation Table

Variable		ESG Score (FY2015)	Average Change in Bid-Price 5 Days after event in bps
1. ESG Score (FY2015)	Pearson's r	—	
	p-value	—	
	Effect size (Fisher's z)	—	
	SE Effect size	—	
	Spearman's rho	—	
	p-value	—	
	Effect size (Fisher's z)	—	
	SE Effect size	—	
	Kendall's Tau B	—	
	p-value	—	
	Effect size (Fisher's z)	—	
	SE Effect size	—	
2. Average Change in Bid-Price 5 Days after event in bps	Pearson's r	0.017	—
	p-value	0.458	—
	Effect size (Fisher's z)	0.017	—
	SE Effect size	0.162	—
	Spearman's rho	0.134	—
	p-value	0.202	—
	Effect size (Fisher's z)	0.134	—
	SE Effect size	0.162	—
	Kendall's Tau B	0.088	—
	p-value	0.214	—
	Effect size (Fisher's z)	0.088	—
	SE Effect size	0.108	—

Note. All tests one-tailed, for positive correlation.

* p < .05, ** p < .01, *** p < .001, one-tailed

Correlations GHG Emissions – Price Changes

Correlation Table

		Pearson			Spearman		Kendall	
		r		p	rho	p	tau B	p
Scope 1 CO2 Emissions (in tons)	- Average Change in Bid-Price 1.5 Months after Event in bps	-0.307	*	0.039	-0.200	0.127	-0.137	0.131
Scope 1 CO2 Emissions (in tons)	- Average Change in Bid-Price 10 Days after Event in bps	-0.364	*	0.017	-0.007	0.486	-0.002	0.500
Scope 1 CO2 Emissions (in tons)	- Average Change in Bid-Price 5 Days after Event in bps	-0.360	*	0.018	-0.014	0.470	-0.005	0.488

Note. All tests one-tailed, for negative correlation.
* p < .05, ** p < .01, *** p < .001, one-tailed

Correlation Table

		Pearson		Spearman		Kendall	
		r	p	rho	p	tau B	p
Scope 2 CO2 Emissions (in tons)	- Average Change in Bid-Price 1.5 Months after event in bps	-0.187	0.144	-0.054	0.380	-0.041	0.373
Scope 2 CO2 Emissions (in tons)	- Average Change in Bid-Price 10 Days after event in bps	-0.237	0.088	-0.036	0.419	0.009	0.535
Scope 2 CO2 Emissions (in tons)	- Average Change in Bid-Price5 Days after event in bps	-0.235	0.091	-0.051	0.388	-0.023	0.430

Note. All tests one-tailed, for negative correlation.
* p < .05, ** p < .01, *** p < .001, one-tailed

Correlation Table

		Pearson		Spearman		Kendall	
		r	p	rho	p	tau B	p
Scope 3 CO2 Emissions (in tons)	- Average Change in Bid-Price 1.5 Months after Event in bps	-0.209	0.134	-0.191	0.156	-0.126	0.169
Scope 3 CO2 Emissions (in tons)	- Average Change in Bid-Price 10 Days after Event in bps	0.035	0.574	-0.030	0.438	-0.034	0.402
Scope 3 CO2 Emissions (in tons)	- Average Change in Bid-Price 5 Days after Event in bps	0.089	0.681	-0.018	0.463	-0.025	0.430

Note. All tests one-tailed, for negative correlation.
* p < .05, ** p < .01, *** p < .001, one-tailed

Correlation Table

	Pearson		Spearman		Kendall	
	r	p	rho	p	tau B	p
Total Scope 1 + 2 Emissions (in tons) - Average Change in Bid-Price 1.5 Months after Event in bps	-0.287 *	0.038	-0.129	0.216	-0.096	0.200
Total Scope 1 + 2 Emissions (in tons) - Average Change in Bid-Price 10 Days after Event in bps	-0.375 **	0.009	0.046	0.610	0.045	0.659
Total Scope 1 + 2 Emissions (in tons) - Average Change in Bid-Price 5 Days after Event in bps	-0.372 **	0.010	0.030	0.573	0.031	0.613

Note. All tests one-tailed, for negative correlation.

* p < .05, ** p < .01, *** p < .001, one-tailed

Correlation Table

	Pearson		Spearman		Kendall	
	r	p	rho	p	tau B	p
Total Scope 1 + 2 + 3 CO2 Emissions (in tons) - Average Change in Bid-Price 1.5 Months after Event in bps	-0.270	0.075	-0.208	0.134	-0.131	0.160
Total Scope 1 + 2 + 3 CO2 Emissions (in tons) - Average Change in Bid-Price 10 Days after Event in bps	-0.059	0.378	0.003	0.507	0.011	0.542
Total Scope 1 + 2 + 3 CO2 Emissions (in tons) - Average Change in Bid-Price 5 Days after Event in bps	-0.009	0.480	-0.010	0.478	-0.007	0.486

Note. All tests one-tailed, for negative correlation.

* p < .05, ** p < .01, *** p < .001, one-tailed

12. Table of Figures