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Master Thesis U.S.E

The Pricing of Carbon Transition Risk on European Union Sovereign Bond Yields

Gabriela Rachello Martinez
g.rachellomartinez@students.uu.nl (8953953)

Supervisor: Raphié Hayat[1]
Co-reader: Labrini Zarpala

A B S T R A C T

This research investigates whether climate transition risk is priced into the sovereign bond yields of European countries, utilizing carbon dioxide emissions per capita as a proxy for transition risk. Seven additional variables that potentially may impact government bonds are incorporated into the model. This study employs a fixed effects panel regression approach using yearly data for 21 European Union countries from 2006 to 2021. The analysis is conducted for the entire period as well as two sub-periods, allowing the examination before and after the implementation of the Paris Agreement 2015. The findings indicate that CO2 emissions per capita are not priced into the yields. Furthermore, the dataset presents highly significant time effects. Therefore, it can be implied that carbon risk is undervalued in financial markets, which entails financial concerns for carbon-intensive economies and investors. Thus, sovereign bonds from these countries should be considered riskier and with the possibility of experiencing an abrupt fall in their market value in the future. To mitigate the potential negative impact, investors should diversify their portfolios and invest in bonds from sustainable-driven governments.

JEL classifications

G11, G12, C33, E30, H63, Q54

Keywords

Carbon emissions • Transition risk • Sovereign bonds • Climate change

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[1] Acknowledgements can be found in section7.

1. Introduction

Climate change is a defining issue for our time. Different socioeconomic factors reflect the implications of the climate emergency the world is going through, representing a substantial aggregate risk to the global economy. When evaluating the financial health of a country, environmental indicators have been found to show earlier signs of warning before conventional economic indicators (Gervich, 2011; Hübel, 2022). Therefore, this research aims to examine whether carbon transition risk is priced into sovereign bond yields in European Union countries, providing valuable information for investors and guidance for policymakers.

Global warming awareness is increasing across many socioeconomic aspects (Huij et al., 2022). According to Standard & Poor's (2014), climate change should be considered a 'global mega-trend' for sovereign risk, as it influences the credit rating of a country through multiple dimensions, such as economic growth and public finance. Physical repercussions of climate change are evident to the environment and will intensify in the coming years (Woetzel et al., 2020). Persistent increase of temperatures, rise in sea levels and extreme climate phenomena are some of the main consequences of physical climate change, which has been the primary focus for empirical analysis over sovereign bonds (Ferrazzi et al., 2021).

Climate change is to a large extent a consequence of greenhouse gas emissions from fossil fuels, which is an essential input for industrial production (Giglio et al., 2020). However, climate transition risk has not been fully included when assessing sovereign debt instruments, but has recently gained interest by multiple economic agents, e.g. governments, business managers, retail and institutional investors. Transition risk reflects a country's process towards a carbon-neutral economy. It combines a variety of shocks from different agents, changes in investment preferences, regulatory policies, norms and technological innovation (Ferrazzi et al., 2021).

Political and economic elements are needed to tackle exposure to transition risk, including strong institutional and fiscal capacity, stability of the economy and technical ability to implement different climate-related measures (Gervich, 2011; Bretschger and Soretz, 2018). Through different programs and agreements, such as the Sustainable Development Goals (SDGs) established by the United Nations and the Paris Agreement of 2015, the vast majority of countries have considerably increased their effort to combat climate change (Hübel, 2022; Ehlers et al., 2022). Therefore, it is crucial to examine carbon transition risk from a financial economic perspective since it constitutes major risks associated with investors' risk preferences and optimal policy response to climate consequences (Giglio et al. 2020).

Decreasing greenhouse gas emissions is one step to mitigate the long run consequences. Nevertheless, the effects of decarbonization of the economy will not come immediately, which indicates that the trend of rising temperatures will last longer (Woetzel et al., 2020). Consequently, governments are implementing initiatives to reduce carbon emissions, boost investment in renewable energy and raise awareness about the impacts of global warming, in which more than 100 countries, that represent

50% of world's GDP, have already committed to achieving carbon neutrality (Bolton and Kacperczyk, 2021).

Empirical studies by Collender et al. (2022) and Boitan et al. (2022) associate higher sovereign borrowing costs and liquidity constraints to countries with poor management of carbon transition risk and low efforts to transition into greener economies. This diminishes their ability to carry out an adequate transition process and their ability to recover from a shock due to climate change. Similarly, Bingler (2022) suggests that lower yields on long-term sovereign bonds are related to high-rated nations with greater transition performance. On the other hand, countries with weaker institutions and fewer laws to decrease carbon emissions face higher borrowing costs and liquidity restrictions. Therefore, strong social and governance factors lead to lower sovereign yield spreads (Cappelle-Blancard et al., 2019), demonstrating the institutional strength of a country (Gervich, 2011).

Findings by Bernie et al. (2021), Cevik et al. (2022), and Battiston et al. (2019) are consistent with these results and demonstrate that both physical and transition risk have a major impact on sovereign bond spreads. It reflects whether a country is lagging behind in implementing climate policies to achieve a low-carbon economy. However, Bernie et al. (2021) include transition risk indexes as a robustness check for physical risk. They claim that the effect of transition risk is lower than physical risk and climate resilience, implying that carbon transition risk has not yet been completely priced into financial markets.

In contrast to previous studies, the findings of this research suggest that CO2 emissions are not fully incorporated into government rates, thus bonds might be mispriced. It is important to note that the sample presents a highly significant time trend. These results raise financial concerns for both carbon-intensive economies and investors. High CO2 emitting countries with insufficient efforts to offset greenhouse gas emissions may be perceived as riskier, which leads to higher costs of debt and higher probability of having a significant drop in the prices in the future. The lack of understanding among investors regarding the long-term consequences of carbon-intensive practices leaves them exposed to potential financial losses. Incorporating CO2 emissions into bond pricing would trigger a full reassessment of the financial stability of economies heavily reliant on carbon-intensive industries. To mitigate the potential negative repercussions, investors are advised to diversify their investments, conducting climate risk assessments, and engaging with sustainable companies and governments. Taking these measures can help investors navigate the uncertainties associated with the eventual pricing of carbon transition risk, minimizing the impact of a potential drop of their investments. Furthermore, the results of the analysis reveal that physical climate risk is not reflected on sovereign yields either. This indicates that investors and financial markets are not pricing the financial consequences associated with both types of climate-related risks.

When assessing climate change, carbon transition risk on sovereign bonds has received less attention, as academic literature has focused mostly on physical risk (Kling et al.,2018; Cevik and Jalles, 2022; Volz et al.,2020; Bernie et al.,2021). Even though transition risk is as relevant as physical risk, given that it reflects how committed governments are with the reduction of carbon emissions to achieve a more sustainable economic future, such an assessment has not been studied in depth.

Therefore, this research contributes to a small but growing literature by the following. First, fills the lack of research on the pricing of climate transition variables on government bond yields, with an emphasis on European Union countries. Thus, the study generates new research findings with an extended period of time for the analysis. Second, conclude from a financial point of view if transition risk affects governments' borrowing costs and determine if strategies implemented by the Paris agreement 2015 might be considered a turning point on the pricing of this risk. Finally, since government bond markets are key to the financial system, as they can act as safe haven assets in crisis events, a benchmark for other securities, and as a liquidity source for governments and banking institutions; this study provides a valuable insight for investors and policymakers on how vulnerable bonds are with regard to global warming consequences in terms of climate policy and net zero emissions.

Investors, particularly environment-aware people, might obtain further information on the efforts each country is making in order to decarbonize the economy. Hence, they are able to make better-informed decisions, while promoting the development of more sustainable and resilient investment practices. Investors' expectations play an important role when assessing climate change risks. There's been a progressive shift of people's investment choices which are highly motivated to support companies, countries or ideas that implement ESG factors into their strategy.

On the other hand, policymakers may obtain a broader outlook on how carbon risk affects their public budget due to the cost of financing, likewise, their ability to fund regulations to achieve a low-carbon transition. Understanding better how managing transition risk effectively has a positive financial effect on borrowing costs, incentivizes them to further implement climate regulations. The ability of a country to handle climate change events is a key determinant on how companies handle it as well. Thus, factors regarding climate change should always be included from now on as a component of risk assessment and the cost of government debt.

To empirically validate the relationship between carbon risk and government bond yields, a fixed effects panel model is used, in which the main explanatory variable is carbon dioxide emissions per capita on a country level, as proxy for transition risk, the 13th goal of SDF. Physical risk, as a secondary independent variable, will be measured through the exposition component of the World Risk Index extracted from the Bündnis Entwicklung Hilft Institute. Additionally, six macroeconomic, fiscal and governance factors are introduced in the model as control variables to mitigate endogeneity issues. The timeframe of this study is from 2006 to 2021 for 21 European Union countries.

The remainder of this paper is structured as follows. Section 2 covers relevant literature review related to transition risk and other determinants of sovereign bond yields. In addition, the theoretical framework used for this research is established. Section 3 outlines the sample setup, data collection, and variable descriptions. Section 4 introduces the methodology used to develop the empirical analysis.

Section 5 presents the results. Finally, section 6 displays the conclusion and discussion regarding the results obtained and section 7 presents the acknowledgments.

2. Literature review and Theoretical Framework

Climate change refers to a slow gradual alteration of the prevailing climatic patterns (Weber, 2010). Human activity for economic purposes is the principal cause of climate change. Burning fossil fuels such as coal, oil, and gas are activities that contribute the most to carbon dioxide emissions (CO2) and methane. These two greenhouse gasses account for over 75% of the total emissions[2]. To understand the effects of climate change on asset prices, it is fundamental to note that there are multiple climate hazards that may be priced in the financial markets but do not materialize simultaneously (Giglio et al., 2020). The main two categories are transition risk and physical risk; each has a main component, mitigation and adaptation, respectively (Ferrazzi et al., 2021).

Transition risk refers to the effects of energy transformation and policies which aim to promote greener economies by mitigating the impact of climate change through regulations (Cevik and Jalles, 2022). Treaties as the Paris agreement of 2015, established long-term goals to achieve low-carbon economies, requiring modifications in the energy system (Giglio et al., 2020). One of the main targets is to reduce greenhouse gas emissions per country to limit rising global temperatures.

On the other hand, physical risk reflects the direct effect of climate change on infrastructure assets and productivity, which are visible and irreversible. It is caused by extreme weather phenomena such as tsunamis, hurricanes, droughts, and wildfires (Ferrazzi et al., 2021). The potential capacity of adaptation and the ability to cope with the consequences of climate change is an essential factor when evaluating a nation's risk profile. Both types of risk are related in the long term; however, the impact of each depends on country-specific conditions (Kling et al.,2018). One might present greater geography risk while another may have weaker institutional systems to conduct regulations against global warming.

2.1. Carbon Dioxide Emissions - Transition risk

Greenhouse gasses are the primary contributor to climate change, especially carbon dioxide (CO2) (Pazienza, 2019; Garmann, 2014). CO2 emissions have been a primary factor when analyzing economic growth and energy consumption (Sebri and Ben-Salha, 2014, Cowan et al., 2014). According to Sadorsky (2013), environmental transition theory states that urbanization and industrialization is linked to high energy consumption, which leads to pollution and carbon dioxide emissions. It has been proven that an acceleration of CO2 emissions speeds up climate change, which produces quicker effects on the economy (Nordhaus, 1977, 1991, 1992). To successfully achieve low-carbon transition, financial

[2] Causes and Effects of Climate Change, United Nations (2022). Retrieved from: Causes and Effects of Climate Change | United Nations

regulation and the execution of policies related to transition risks aligned with the sustainable targets of a country, can facilitate the transition to greener economies (Dunz et al., 2021; Muhammad and Long, 2021).

Existing literature demonstrates that countries with lower carbon emissions present lower borrowing costs. Collender et al. (2022) find this result by using three indicators as proxies for transition risk: carbon dioxide emissions, natural resources rents, and renewable energy consumption. Through a one-way fixed effects model, they find a positive significant relation with government bond spreads and yields of advanced and developing countries. They state that a rise in carbon dioxide emissions and natural resources rents imply greater reliance on fossil fuels and a more challenging transition to a low-carbon economy. Therefore, countries which prioritize achieving a zero emissions economy are rewarded with lower cost of debt.

Bingler (2022) investigates climate performance and three different dimensions of climate risk, transition, physical, and innovation aspects. The study was done over 29 countries from 2008 to 2021 through a fixed effects panel regression. She uses a variety of indexes for physical risk and transition risk. Her results indicate that effects of physical and transition risks vary depending on the credit rating of a country and the maturity of the debt. High-rated countries with greater transition performance are associated with lower long-term sovereign bonds yields. Conversely, concerning physical risk exposure, financial markets associate higher bond yields with lower-rated countries (for long-term maturities). Both effects are more significant after the Paris Agreement 2015, in line with Kölbel (2022) results, who point out that these factors will acquire greater weight on the valuation of securities as the situation deteriorates.

Therefore, regions with great ESG performance and well established strategies to tackle climate risk offer lower rates that investors are willing to buy, since it is aligned with their environmental values (Cifro et al., 2017; Capelle-Blancard et al.; 2019 Boitan et al.,2022). On the contrary, nations with weaker institutions and few regulations to reduce carbon emissions experience greater borrowing costs and liquidity constraints (Bingler, 2022).

In line with these results, findings of Bernie et al. (2021), Cevik et al. (2022) and Battiston et al. (2019) show that both transition risk and physical risk present significant effects on sovereign bond yields. However, Bernie et al. (2021) apply an assessment of transition risk as robustness check for physical risk. They use the FTSE Russell index as a proxy for transition risk. The outcome suggests that on average climate vulnerability, referring to physical risk, is far more significant for sovereign borrowing costs than climate risk resilience and transition risk. Hence, they confirm the general concern that this type of risk has not yet completely priced into financial markets. In line with economic intuition, they imply that economies that present higher risk premiums are the ones with greater degree of exposure to climate change, requiring more resilient investment. Therefore, I propose the following hypothesis:

__Hypothesis 1:__ A higher level of yearly dioxide carbon emission per capita, on a country level, is associated with higher sovereign bond yields.

2.2. Physical climate risk

Climate Finance has received more attention over sovereign bond yields in the past years. Particularly, physical risk has been evaluated in empirical analysis more widely than transition risk. Kling et al. (2018) is one of the pioneers in researching climate vulnerability over sovereign bonds. Through a panel OLS model, using indices from the Notre Dame Global Adaptation Initiative and controlling for different macroeconomic factors, they demonstrate that countries with greater exposure to physical risk are associated on average with 1.17 percent higher cost of debt.

Painter (2020) investigates the effects of physical risk on municipal bonds. His findings show that counties with higher physical climate risk are associated with larger fees and higher issuing yields. The effect is evident on long-term municipal bonds, particularly for municipalities with lower credit ratings. However, it is absent in short-term maturities. This outcome implies that the market values climate change risk in relation to credit quality. Likewise, Goldsmith-Pinkham et al. (2022) analyze how municipal bond yields are exposed to sea level rise. Their results evidence the importance of climate change risk as a key driver for long-term municipal bond prices. Thus, public debt backed by tax revenues from regions with higher physical climate risk, is expected to present significantly higher yields (Giglio et al., 2020).

Similarly, an assessment made by Böhm (2021), suggests that rising temperatures increase the cost of sovereign borrowing and negatively affect sovereign creditworthiness of emerging economies. Countries with higher levels of vulnerability are associated with higher government bond yields, less capacity to deal with climate disaster and deficient implementation of regulations against global warming (Boitan et al., 2022; Bingler, 2022).

This research tests physical climate risk parallel with transition risk, a different approach than previous papers in the literature who use physical risk as the main explanatory variable, and occasionally use transition risk for robustness checks of the model. The World Risk Index by Bündnis Entwicklung Hilft Institute is used as measurement for this explanatory variable. With this context, the first sub-hypothesis I test is the following:

__Sub-hypothesis 1:__ A higher level of physical climate risk leads to higher government bonds yields, since countries with larger exposure to extreme climate events are riskier.

2.3. Control variables and Robustness checks

2.3.1. Macroeconomic, fiscal and governance factors

Following the studies of Bernie et al.(2021), Collender et al. (2022), and Bingler (2022), six country-level macroeconomic determinants of sovereign bond yields are incorporated in the model:

Gross Domestic Product Growth, Gross Domestic Product per capita, Inflation, Current account balance relative to GDP, Institutional quality, Central government debt to GDP, and Fiscal deficit as percentage of GDP. Each variable will be described further in Section 3.

According to economic literature, different macroeconomic and fiscal fundamentals of the economy explain a substantial part of the variation on government bond yields, particularly public debt, foreign reserves, current account balance, and inflation (Edwards, 1984; Hilscher and Nosbusch, 2010). However, research made by Diaz Weigel and Gemmill (2006) suggests that macroeconomic variables account for a small portion of the premium from government bonds, weighing more regional and global variables. Bernie et al. (2021) find that weak macroeconomic fundamentals, such as decreasing GDP growth, GDP per capita and current account balance are associated with higher government bonds yields, indicating slow economic development and growth. Similarly, Beirne and Fratzscher (2013) through research over advanced and emerging countries, argue that the main driver for sovereign bond yields are weak economic fundamentals.

2.3.2. Robustness check

To enhance the robustness of the study, three variations of the model will be included: sovereign bond spreads, as an alternative dependent variable, the current carbon tax environment as an extra explanatory variable, and two additional regressions for the sub-periods before (2006-2014) and after (2015-2021) the signature of the Paris agreement 2015. First, following the methodology of Collender et al. 2022, Bingler (2022), Boitan et al. (2022), government bond spreads are used as a complementary variable. It is relevant to test the spread because it specifically captures the risk premium of bonds relative to a benchmark, whereas the yield reflects the overall cost of borrowing for governments. Hence, investigating the effect of the explanatory variables over the spreads allows for a more comprehensive assessment of the study.

Secondly, no research was found that explores the effect of carbon tax on sovereign bond yields when studying the effect of climate transition risk. Therefore, the inclusion of this variable adds value to the existing academic work. This policy instrument was designed to incentivize a reduction of CO2 emissions. Thus, this policy can play a crucial role influencing the transition to carbon neutrality. Through the carbon tax variable it's possible to assess how effective is the implementation of this policy in terms of economic and financial impact on government rates. This variation of the model can provide insights on how significant carbon taxes have helped in mitigating climate change. Furthermore, it can shed light to what extent carbon taxes affect carbon emissions and, as a result, which effect they have on government bond rates. This understanding is key for policymakers and stakeholders seeking effective climate change mitigation strategies.

Finally, by dividing the sample into two sub-periods, I assess if the Paris agreement 2015 has a significant impact over government bond yields. Kölbel et al. (2022) explored the influence of the Paris agreement signed in 2015. They found a stronger impact of transition climate risk after the Paris Agreement 2015, concluding that transition risk is associated with higher credit spreads. This treaty was a turning point that reflected a change in the market, since climate change started to be more priced in financial assets, in terms of yield and risk (Ilhan et al. 2019). I therefore propose the second testable sub-hypothesis:

> ***Sub-hypothesis 2:*** *The effect of carbon-risk is more significant on sovereign bond yields after the Paris Agreement 2015 due to a greater joint compromise from countries to achieve carbon neutrality to mitigate global warming effects.*

3. Data collection and description

3.1. Sample

The sample for this research consists of 21 European Union countries observed for 16 years, from 2006 to 2021. The selection of these years is based on data availability, as the majority of 10-year bond data became accessible starting from 2006. Five countries were removed from the sample as they did not have data available for the entire sample period; Greece was removed as it is considered an outlier due to the financial crisis they had, which can distort the results (Bingler, 2022); details of the country-selection can be found in Appendix A. Even though climate risk can be seen as a localized concern for some businesses, sectors or regions, the scope of the research is through a national perspective, which is more appropriate for further analysis.

3.2. Dependent variable

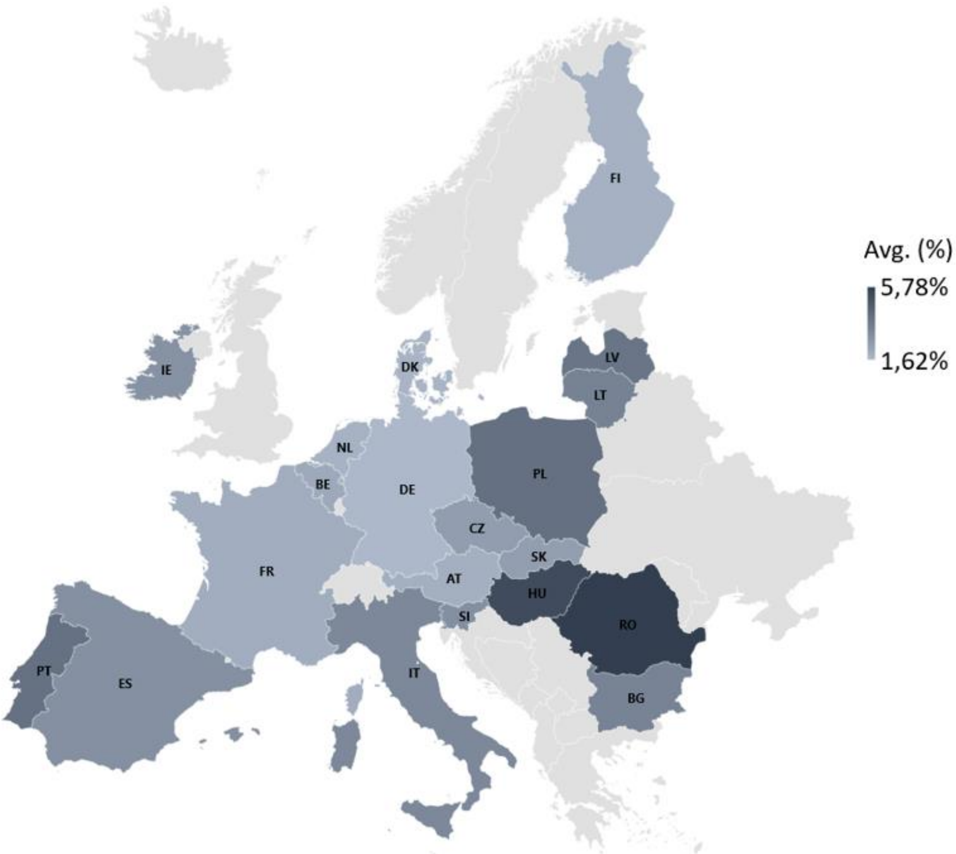
Sovereign benchmark bond yields with a maturity of 10 years $\left(Y_{i,t}\right)$ are obtained from FactSet with a daily frequency. However, since the independent variables are at an annual frequency, annual yields are used for the analysis. To transform the variable, the average of the daily yield was computed for each year. Figure 1 presents the 10-year government bond average yields from 2006 to 2021. From the map, great differences in the yield among countries are visible. The average yield ranges from 1.62% to 5.78%. This high dispersion can be explained by macroeconomic differences between regions, such as stronger economic growth, creditworthiness, lower debt levels, political stability, among others.

3.2. Independent variables

Carbon dioxide emissions per capita ($CO2_{i,t}$) is used as a proxy to measure climate transition risk, the main independent variable of interest. Data for this explanatory variable is collected from Our World in Data, sourced from the Global Carbon Project. The average citizen's contribution to CO2 is determined by dividing each country's total emissions by its population. The measurement takes into account the burning of fossil fuels for energy and cement production.

Physical climate risk ($Phy_{i,t}$) is measured through the World Risk Index extracted from the Bündnis Entwicklung Hilft Institute. The index is composed of two subdivisions, exposition and vulnerability. Exposition considers extreme weather events such as earthquakes, tsunamis, coastal floodings, riverine floods, droughts and rising sea level. On the other hand, the vulnerability component includes socioeconomic factors with regard to susceptibility, lack of coping and adaptive capacities. For the purposes of this investigation, only the exposition component is taken as a proxy for physical climate risk.

Figure 1. Average Government bond yields per country from 2006 to 2021



3.3. Control variables

Similar to Bernie et al. (2021), Collender et al. (2022), Bingler, (2022), and Cevik and Jalles, 2022, the following annual macroeconomic indicators are incorporated to enhance the robustness of the regression analysis: Gross Domestic Product Growth ($GDPgrowth_{i,t}$), Gross Domestic Product Per capita ($GDPcapita_{i,t}$), Inflation ($Inflation_{i,t}$), Current account balance relative to GDP ($Balance_{i,t}$), and Institutional quality ($Ins.Quality_{i,t}$) are extracted from The World Bank dataset. Central government debt to GDP ($Debt_{i,t}$) is obtained from the International Monetary Fund (IMF) and Fiscal deficit as percentage of GDP ($Deficit_{i,t}$) from the Organization for Economic Cooperation and Development (OECD). Credit ratings were removed as explanatory variable from the model due to issues finding the data.

GDP growth measures the annual percentage change in productivity of each country at market prices based on constant local currency. GDP per capita measures the growth of monetary value of all goods and services produced in a country over its total population based on constant local currency. Both measures reflect the economic health of a country and its financial capacity to repay its debt.

Inflation measured by the Consumer Price Index, reflects the annual percentage price change related to household spending. Current balance account as a percentage of GDP represents the sum of net exports of goods and services, net primary income, and net secondary income (World Bank, 2022). Central Government Debt as percentage of GDP indicates governments' gross fixed-term obligations relative to GDP, including domestic and foreign liabilities, securities and loans. Fiscal deficit as percentage of GDP reflects the balance of income and expenditure of a government (World Bank, 2022; OECD, 2021; Collender et al., 2022). Institutional Quality is computed as the average of the six governance indicators from The World Bank, measured as z-scores ranging from -2.5 to 2.5. It includes the estimate of government effectiveness, control of corruption, political stability and absence of violence/terrorism, regulatory quality, rule of law, and voice and accountability[3] (World Bank, 2022).

3.4. Robustness check tests

To enhance the robustness of the estimation, sovereign bond spreads are used as an alternative dependent variable. The variables are computed as the difference between the 10-year bond yield of each specific country and the yield of the benchmark bond country, Germany, with a comparable maturity (Hilscher et al., 2010; Capelle-Blancard et al., 2019). In this study, the 10-year German Bund is used as the 'benchmark rate' following the methodology of Bingler (2022). The aim is to test the relevance of the explanatory variables using both yields and spreads.

CO2 emissions covered by a carbon tax as a share of the country's CO2 emissions are extracted from Our World in Data. Carbon taxes directly influence the cost of emitting greenhouse gasses and incentivize CO2 emissions reduction. Carbon tax environment ($Carbontax_{i,t}$) changes greatly in each country, hence, including it as a variable in the model accounts for government policies which internalize the costs of carbon emissions and how it affects their bond rates. Higher carbon taxes might reflect a stronger commitment to achieve carbon-zero economies, which might result in a positive perception for investors and consequently lower sovereign bond yields.

The Paris Agreement 2015 is incorporated to analyze if there is a distinction on the significance of the variables post-agreement. Two regressions will be run, one before the signature of the agreement (2006-2014) and one after (2015-2021). The sub-period after the signature includes a more aware financial sector which priced in more climate-related risks, the recommendation from the Task Force on Climate-related Financial Disclosures (TCFD) to financial actors to take into account climate risk into their investment decisions and the special report done by the Intergovernmental Panel on Climate Change (IPCC) stating the severe consequences of climate change on all countries and economies worldwide.

3.5. Descriptive statistics

Table 1 presents the descriptive statistics for sovereign bond yields and the macroeconomic variables for all countries in terms of mean, standard deviation, minimum and maximum. The number

[3] Further explanation of each Institutional quality indicator can be found in Appendix B.

of observations show a balanced panel. There are 336 observations for each variable, a total of 21 countries and 16 years. The average yield for government bonds of European countries over the last 16 years has been 2.96%. This implies that, on average from 2006 to 2021, investors received 2.96% of yield from holding 10-year bonds of EU nations. Additionally, the spread mean is 1.40% indicating that, relative to German bunds, other countries paid investors on average a risk premium of 1.40%, during this timeframe. GDP growth and GDP per capita present an average of 1.90% and 1.80%, respectively. This provides insights of the sample's economic conditions. In the context of Europe, these values suggest a moderate level of economic development. However, it is noteworthy that there are significant variations in the variables among individual countries. Moving on to inflation, despite fluctuations observed over the years, the average CPI of EU countries from 2006 to 2021 is 2.03%. This level aligns closely with the European Central Bank's (ECB) inflation target of 2% in the long-run, indicating a level of price stability in the region.

The variable debt as a percentage of GDP has an average of 57.22%. This level is within the fiscal reference values set by the Maastricht treaty, which requires EU members to maintain their government debt below 60% (Deutsche Bundesbank, 2018). However, the variable presents a high standard deviation of 28.96, indicating a relatively high level of variability in debt ratios across the selected countries. This suggests differences in fiscal policies, economic performance, distinct levels of government spending, revenues sources and financial stability among countries. Additionally, the Maastricht criteria requires governments to limit their budget deficits to 3% of GDP. Observing the results, the fiscal balance average is -2.86, which can be interpreted as an average deficit of 2.86% of GDP, which is also below the threshold of the criteria. Therefore, the descriptive statistics provide an accurate overview of EU members' macroeconomic fundamentals.

Table 1. Descriptive statistics

Variable	Obs	Mean	Std. Dev.	Min	Max
Yield	336	2.961	2.220	-0.472	11.832
Spread	320	1.405	1.558	-0.139	8.595
CO2 per capita	336	7.013	2.213	3.425	12.983
Physical risk	336	1.741	2.306	0.100	8.820
GDP Growth	336	1.901	3.930	-14.839	24.370
GDP per capita	336	1.792	4.021	-13.888	23.201
Inflation	336	2.032	2.056	-4.478	15.402
Current acc. balance	336	0.191	5.400	-25.74	14.324
Institutional quality	336	1.050	0.490	0.084	1.883
Debt to GDP	336	57.263	28.967	6.467	150.849
Fiscal balance	336	-2.869	3.613	-32.119	5.108

Table 1 shows the descriptive statistics for all variables between 2006 to 2021

Figure 2 illustrates the performance of government bond yields since 2006 to 2021. Over the past years, there is evidence that government bond rates have had a declining trend; some countries have even gone negative in the last three years. Regarding the period of time studied in this research, in the mid-2000s, most countries had sovereign yields ranging from 4% to 6%. In more recent years, European Union yields range from 2% to 0%. There are some outliers of higher yields between 2008 to 2013 specifically in countries such as Romania and Bulgaria, which are developing countries, and advanced countries such as Lithuania, Hungary, and Portugal. The steady decline trend of European union long-term government yields are a consequence of many factors including decreasing policy rate by the European Central Bank (ECB), low inflation rates, downward pressure on inflation expectations, accommodative monetary policy to boost economic growth (particularly after the pandemic of Coronavirus), investor sentiment, among others (World Bank, 2015).

Figure 2. Sovereign Bond Yields of 21 European Union countries

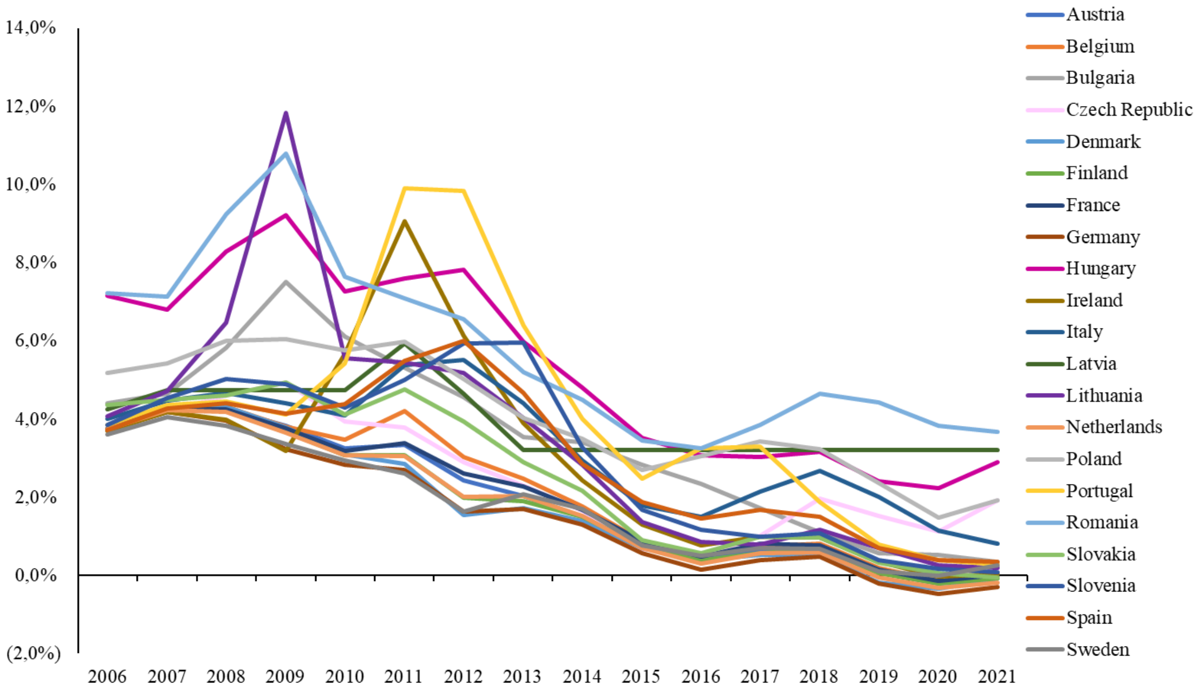


Figure 2 displays the sovereign bond yields for 21 European Union countries from 2006 to 2021 on a yearly frequency. On the left axis, yields are in percentage form and on the right axis are the corresponding country legend.

Furthermore, the aging population is considered to be a major driver for the prolonged decline of sovereign bond yields. Demographic aging is an issue in which the number of older people increases, while the proportion of working-age people in the EU is decreasing. This trend is driven by historically low birth rates, rising life expectancy, and in some circumstances, migratory patterns (inflows of retired people) (Eurostat, 2020). Pinho and Barradas (2021), argue that an aging population can lead to slower economic growth. Lower marginal productivity of capital reduces the investment demand through a decrease in the labor force. This slower economic growth can result in reduced inflationary pressures, which contributes to the downward trend in bond yields. Moreover, they state that elderly people tend to prioritize capital preservation, therefore, they seek safe-haven assets, increasing the demand for government bonds. Similarly, Ichiue and Shimizu (2012) reach the conclusion that a decrease in the working-age population ratio, as a proxy for a higher level of population aging, favors a decline in interest rates.

The Spearman correlation and the VIF (Variable inflation factor) approach were used to assess the set of independent variables for multicollinearity. Overall, the correlation matrix in table 2 shows low coefficients between the independent variables, ensuring that the estimations will not be biased by high multicollinearity. The climate-related risks, transition and physical risk, present a low negative correlation. This implies that they are complementary indicators of a country's vulnerability to climate change and each adds value to the analysis. The only variables that present almost perfect multicollinearity are GDP growth and GDP per capita, with a coefficient of 0.98. This positive correlation indicates that as GDP growth increases, GDP per capita tends to be higher.

Table 2. Correlation Matrix

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
(1) CO2 per capita	1.000								
(2) Physical risk	-0.074	1.000							
(3) GDP growth	0.051	-0.154	1.000						
(4) GDP per capita	-0.030	-0.176	0.984	1.000					
(5) Inflation	-0.051	-0.155	0.168	0.208	1.000				
(6) Current acc. Bal.	0.181	-0.004	-0.184	-0.227	-0.534	1.000			
(7) Inst. quality	0.450	-0.141	-0.067	-0.170	-0.281	0.509	1.000		
(8) Debt to GDP	-0.095	0.610	-0.180	-0.204	-0.331	0.145	0.004	1.000	
(9) Fiscal balance	0.175	-0.196	0.370	0.336	0.066	0.174	0.222	-0.338	1.000

Table 2 displays the Spearman correlation coefficients based on the pooled sample

To confirm the suspicion of high correlation between the variables mentioned above, the VIF test was applied. A VIF value above 5 indicates the presence of high multicollinearity. Table 3 shows the results of the test including all variables. GDP per capita presents the highest VIF of 58.66, followed by GDP growth with a value of 57.48, confirming the presence of multicollinearity. Thus, in order to account for this issue, GDP per capita is removed from the model. The VIF test excluding GDP per capita (Table 4) reflects low levels of correlation in all variables, including GDP growth, which now after dropping GDP per capita, has the lowest VIF value. The decision to remove GDP per capita was based first on its high VIF value; indicating potential issues of multicollinearity and unreliable estimates. Instead, GDP growth was chosen as it provides a broader understanding of economic growth across countries, accounting for variations in population sizes. GDP growth captures a wider outlook of economic performance, reflecting the rate at which an economy is expanding over time. The remaining independent variables exhibit a low degree of correlation, making them suitable for the subsequent panel analysis.

Table 3. VIF test

Variable	VIF
GDP per capita	58.66
GDP growth	57.48
Institutional quality	2.21
Debt to GDP	1.97
Current acc. Balance	1.89
Physical risk	1.75
Inflation	1.58
Fiscal balance	1.48
CO2 emissions	1.40
Mean VIF	14.27

Table 4. VIF test

Variable	VIF
Debt to GDP	1.96
Current acc. Balance	1.87
Institutional quality	1.72
Physical risk	1.69
Inflation	1.56
Fiscal balance	1.47
CO2 emissions	1.29
GDP growth	1.27
Mean VIF	1.60

Table 3 displays the results for the VIF test including all independent variables. Table 4 shows the findings of the VIF test excluding GDP per capita.

4. Methodology

To determine whether climate transition risk affects sovereign bond yields, a panel data model is used. This estimation approach allows the cross-sectional and time-series assessment of the impact of various climate risk proxies and multiple country-specific macroeconomic and fiscal indicators. The selected group of control variables are included to address the issue of endogeneity related to omitted variables and simultaneity. Hence, it is preferable to add variables to avoid endogeneity problems in the empirical analysis (Barros et al., 2020).

For this research it is essential to account for the individual effects of each country, otherwise it can lead to biased coefficients. This can be controlled by removing the effect of time-invariant characteristics, referring to the variation between countries. Fixed effects and random effects panel models were tested. In order to determine the empirical relevance of both tests mentioned above, I applied the Hausman test to assess for non-correlation between the unobserved effect and the regressors (Hausman, 1978). The comparison of both estimators goes under the null hypothesis that the preferred model is random effects. After running the Hausman test, the panel estimation that fits better the specifications of the model is fixed effects, rejecting the null hypothesis. The results from the test can be found in Appendix C. All econometric estimations in this study are done through the fixed effects regression model.

To test the presence of additional issues related to panel data, such as autocorrelation and heteroskedasticity, the Breusch Godfrey and Breusch Pagan were applied over the sample. All of the models showed the presence of both issues. Therefore, the regressions were corrected with a country cluster for autocorrelation and heteroskedasticity. In addition, an F-test was applied for each variable to identify the need of lags on the explanatory variables in order to address the simultaneity issue between the dependent and independent variables (Afonso et al., 2015; Capelle-Blancard et al. 2019; Volz et al., 2020). All explanatory variables, excluding GDP growth, include a one-period lag.

Two variations of the model were tested for the main results. The first model includes a lag for some explanatory variables (equation 1), following Boitan et al. (2022) and Bernie et al. (2021) methodology. Introducing lags mitigates potential endogeneity issues, which could lead to biased coefficients. It adds a temporal separation between the dependent and independent variables. Furthermore, since the data for the climate risk variables and macroeconomics fundamentals is available yearly, the information for a given year becomes available the following year. Hence, accounting for time lags align the release of the data for the independent variables with the corresponding sovereign bond yields. This modification reflects the market dynamics regarding macroeconomic fundamentals and climate-related risks.

Equation (1) specifies the panel regression model with sovereign bond yields and lagged independent variables:

$$
\begin{aligned}
Y_{i,t} = \alpha + \gamma_1 CO2_{i,t}\gamma_1 + \gamma_2 l.CO2_{i,t} + \gamma_3\, Phy_{i,t} + \gamma_4\, l.Phy_{i,t} + \beta_1\, GDPgrowth_{i,t} + \beta_2\, Inflation_{i,t} \\
+ \beta_3\, l.Inflation_{i,t} + \beta_4\, Debt_{i,t} + \beta_5\, l.Debt_{i,t} + \beta_6\, Deficit_{i,t} + \beta_7\, l.Deficit_{i,t} \\
+ \beta_8\, Balance_{i,t} + \beta_9\, l.Balance_{i,t} + \beta_{10}\, Ins.Quality_{i,t} + \beta_{11}\, l.Ins.Quality_{i,t} + \varepsilon_{i,t}
\end{aligned}
$$

with α as intercept, i the country, t the year, $Y_{i,t}$ the dependent variable sovereign bond yields, and $\varepsilon_{i,t}$ the error term which is assumed to be identically and independently distributed (i.i.d) with mean equal to zero, constant variance and no association between error terms across time.

The second model includes a time trend (equation 2). As seen in the descriptive statistics, sovereign bond yields present a declining trend since 2006. Overall, sovereign bond markets are going through a long-term structural change. Despite adding numerous control variables, there might be other systematic changes in sovereign bond rates that are not accounted for in the model. Therefore, a time trend controls for common factors that might be influencing yields across countries and time periods. To test the significance of time effects, the regression is run including a yearly time effect alongside the independent variables. Then, through the t-statistic and p-value determine the level of statistical significance which indicates if it is needed or not.

Equation (2) specifies the panel regression model with sovereign bond yields, lagged independent variables and a time trend:

$$Y_{i,t} = \alpha + \gamma_1 CO2_{i,t}\gamma_1 + \gamma_2 l.CO2_{i,t} + \gamma_3\, Phy_{i,t} + \gamma_4\, l.Phy_{i,t} + \beta_1\, GDPgrowth_{i,t} + \beta_2\, Inflation_{i,t} + \beta_3\, l.Inflation_{i,t} + \beta_4\, Debt_{i,t} + \beta_5\, l.Debt_{i,t} + \beta_6\, Deficit_{i,t} + \beta_7\, l.Deficit_{i,t} + \beta_8\, Balance_{i,t} + \beta_9\, l.Balance_{i,t} + \beta_{10}\, Ins.Quality_{i,t} + \beta_{11}\, l.Ins.Quality_{i,t} + \beta_{12}\, Time_t + \varepsilon_{i,t}$$

Similar to Collender (2022), and Cevik and Jalles (2022) the model is assessed via several sensitivity analyses. The robustness checks include an alternative dependent variable: the spread of sovereign bonds (equation 3), an extra explanatory variable: carbon tax environment (equation 4), and the analysis of two sub-periods to assess the relevance of the Paris agreement of 2015. The sensitivity analyses used to assess the models' robustness were done following the same tests mentioned above. Hence, all models were corrected via country cluster, all independent variables present one lag(excluding GDP growth) and each model accounts for a time trend.

Equation (3) determines the model for robustness check using sovereign bond spreads:

$$YS_{i,t} = \alpha + \gamma_1 CO2_{i,t}\gamma_1 + \gamma_2 l.CO2_{i,t} + \gamma_3\, Phy_{i,t} + \gamma_4\, l.Phy_{i,t} + \beta_1\, GDPgrowth_{i,t} + \beta_2\, Inflation_{i,t} + \beta_3\, l.Inflation_{i,t} + \beta_4\, Debt_{i,t} + \beta_5\, l.Debt_{i,t} + \beta_6\, Deficit_{i,t} + \beta_7\, l.Deficit_{i,t} + \beta_8\, Balance_{i,t} + \beta_9\, l.Balance_{i,t} + \beta_{10}\, Ins.Quality_{i,t} + \beta_{11}\, l.Ins.Quality_{i,t} + \beta_{12}\, Time_t + \varepsilon_{i,t}$$

Equation (4) defines the model for robustness check adding carbon tax as an extra explanatory variable:

$$Y_{i,t} = \alpha + +\gamma_1 CO2_{i,t}\gamma_1 + \gamma_2 l.CO2_{i,t} + \gamma_3\, Phy_{i,t} + \gamma_4\, l.Phy_{i,t} + \beta_1\, GDPgrowth_{i,t} + \beta_2\, Inflation_{i,t} + \beta_3\, l.Inflation_{i,t} + \beta_4\, Debt_{i,t} + \beta_5\, l.Debt_{i,t} + \beta_6\, Deficit_{i,t} + \beta_7\, l.Deficit_{i,t} + \beta_8\, Balance_{i,t} + \beta_9\, l.Balance_{i,t} + \beta_{10}\, Ins.Quality_{i,t} + \beta_{11}\, l.Ins.Quality_{i,t} + \beta_{12} Carbontax_{i,t} + \beta_{13} l.Carbontax_{i,t} + \beta_{14}\, Time_t + +\varepsilon_{i,t}$$

5. Results and Interpretation

5.1 Main Results

The results are presented and discussed for the full sample with sovereign bond yields through a Fixed Effects panel model. Table 5 shows two variations of the model. Model A has a one-period lag in some independent variables, whereas Model B includes a time trend in addition to the one-period lag on the explanatory variables. Model B is the final version of the model in which the interpretation is based. Furthermore, four different models are conducted as robustness checks to support the main results and discuss policy and investment implications.

Table 5. Determinants of Sovereign Bond Yields

Dependent variable	(A) Lagged Yield	(C) Lagged and Time Yield
CO2 per capita	0.5011**	-0.2274
	(2.22)	(-1.35)
L.CO2 per capita	0.7108***	0.2409
	(2.93)	(1.08)
Physical risk	-19.501	41.891
	(-0.22)	(0.94)
L.Physical risk	120.340	0.8923
	(1.22)	(0.12)
GDP growth	-0.0655	-0.0311
	(-1.60)	(-0.78)
Inflation	0.0549	0.1746***
	(0.99)	(3.28)
L.Inflation	0.1704*	0.0563
	(2.08)	(0.92)
Current acc. balance	0.0275	0.0649
	(0.70)	(1.61)
L.Current acc. balance	-0.0937**	-0.0223
	(-2.37)	(-0.65)
Institutional quality	0.2855	0.0016
	(0.14)	(0.00)
L.Institutional quality	-10.276	-0.7341
	(-0.46)	(-0.64)
Debt to GDP	-0.0069	0.0288
	(-0.15)	(0.83)
L.Debt to GDP	0.0022	-0.0219
	(0.05)	(-0.77)
Fiscal balance	-0.0023	-0.0013
	(-0.05)	(-0.04)
L.Fiscal balance	-0.2482***	-0.1246***
	(-9.11)	(-8.79)
Time		-0.3416***
		(-8.87)
Constant	-231.540	-34.665
	(-1.02)	(-0.21)
Observations	315	315
R^2	0.69	0.83
Adjusted R^2	0.67	0.82
AIC	970.92	784.12
BIC	1027.20	844.16

Table 5 reports the results for the lagged model and the model including a time trend and one period lag to the explanatory variables beginning with L. ***, **, and * denote statistical significance at 1%, 5%, and 10% level, respectively.

Initially, in the lagged model (column A), carbon emissions per capita is statistically significant with a positive relationship with government bond yields in both versions of the model (non-lagged and lagged). This implies that for one ton increase in CO2 emissions per capita, sovereign bond yields increase by 0.71%, ceteris paribus. It is noteworthy that the lagged CO2 emissions variable has greater significance (1%) than the current value of the variable (5%). The positive relationship indicates that countries experiencing an increase in carbon dioxide emissions per capita can expect, on average, higher 10-year sovereign bond yields. Hence, countries with increased carbon emissions are borrowing against their own future, which raises the cost of sovereign borrowing. However, while the direction of the relationship aligns with the expectations, when adding a time trend to the lagged model (column B), the coefficient of CO2 emissions per capita remains positive but becomes insignificant. Government bond yields decrease 0.341% per year, ceteris paribus. Note that the time effect variable is highly significant at a 1% level of confidence.

Comparing the R^2 of both models, it is evident that there is a great improvement on the model when incorporating the time effects. The R^2 for model A is 0.69, whereas the R^2 for model B is 0.83, indicating that the time trend leads to a better fit of the model and to more reliable coefficients. Including a time effect absorbs the time-related variation in the data, which could be a general trend or pattern of the dependent variable. This suggests that CO2 emissions per capita are not priced in sovereign bond rates at all, and the previous significant result was a time-variation effect. Instead, there might be a long-term trend or macroeconomic cycle that is affecting the yield, which is not directly related to CO2 emissions per capita. The impact of carbon emissions on bond yields may have a longer-term perspective that is not fully captured by the time trend variable. Hence, in contrast to the first hypothesis stated, when a time trend is considered climate transition risk has no effect on the yields.

Several implications stem from this result for investors and policymakers. The results imply that carbon transition risk is being undervalued in financial markets. The financial consequences of climate risks are not fully accounted for in the market, as a result, sovereign bonds are mispriced. Governments that rely largely on carbon-intensive industries may face greater financial concerns. Consequently, the perceived riskiness of these bonds is likely to increase, triggering a fall in their market value. There is a lack of awareness and understanding among investors and market participants regarding the long-term repercussions of carbon-intensive practices. This raises investors' vulnerability to potential financial shocks once transition risk gets priced in, particularly, in high-emitting countries. Although this can be a sudden or gradual process, in both scenarios investors will get severely hurt due to an abrupt or gradual drop in the price of the bonds, which will lead to financial losses.

On the other hand, knowing that CO2 emissions are not priced in may lower the financial pressure on governments to prioritize climate-related policies. Therefore, there is no alignment of incentives for governments to achieve lower carbon emissions targets, which might set back the recent efforts to minimize climate change repercussions. If governments fail to handle these issues in a timely manner, investors may devalue bonds issued by carbon-intensive economies. The incorporation of CO2 emissions into bond pricing represents a broader market reevaluation of the long-term viability and financial stability of economies that rely largely on fossil fuels. As investors become more aware of the effects of climate change, they may modify their investment strategies and limit their exposure to assets associated with elevated CO2 emissions. This shift may also contribute to a sharp drop in bond prices.

This analysis emphasizes the importance of incorporating these types of risks in investment decision-making processes, as well as encouraging governments to implement environmental sustainability initiatives. It is crucial that investors anticipate and prepare for the potential market repercussions once CO2 emissions are priced into sovereign bond yields by actively managing their exposure to carbon-related assets. Some measures they can take to mitigate the impact are well diversified portfolios, thorough climate risk assessments, and engaging with companies and governments that have sustainable practices and climate-friendly policies.

The outcomes of this research differ from findings of Collender et al. (2022) and Bingler (2022), who found a positive and significant relationship between government rates and carbon emissions. It is important to acknowledge that their analysis does not incorporate the presence of a time trend that could affect the yields, as this study does. Although this research builds upon existing literature, the potential impact of a time trend on the analysis was recognized; therefore, it was appropriate to integrate the time effects into the methodology. Differences in the model estimations could have affected the results obtained. Therefore, the inclusion of time-dependent factors should enhance the accuracy and reliability of the estimations.

Regarding physical risk, results from both models show that physical risk has no explanatory power over sovereign bond yields; dismissing the first sub-hypothesis. Research by Painter (2020), Goldsmith-Pinkham et al. (2022), and Böhm (2021) argue that greater physical risk is associated with higher issuing yields. The difference of the results versus the related literature is how the model is specified. Referenced researchers tested physical risk as the only main independent variable, meanwhile this research combines both transition risk and physical risk in the same model. Furthermore, analysis made by Painter (2020) included long term (bond maturity 25 years or above) and short term (bond maturity up to 25 years). The results were significant only for the long term bonds, referring to bonds with maturities of 25 years or above. In contrast, this study focuses on 10 year bond maturities, reflecting that physical risk might be priced but for longer maturities. Furthermore, Collender et al. (2022) found that the effect was only visible on developing countries. Yields of advanced countries are not pricing this risk as much as developing countries. Thus, considering that the sample consists mostly of European Union advanced countries, the results are in line with the findings of their research.

Academic literature argues that there are other relevant macroeconomic determinants that may affect yields. Table 5 illustrates the effect of these variables on government bond rates. In line with previous research (Bernie et al., 2021; Edwards, 1984), fiscal balance has a negative significant relationship with government yields at a 1% confidence level. If the fiscal balance increases by 1%, government rates decrease by 0.124%. This suggests that an optimal level of debt may be associated with lower sovereign bond yields. Lower fiscal balance provides a great insight of the sustainability of a country's public debt. Maintaining a strong fiscal balance reduces the need for excessive borrowing, shows economic stability and a country's financial capacity to manage unanticipated shocks. Therefore, countries with surpluses or small deficits are seen as less risky, resulting in lower government bond yields (Afonso et al., 2015; Cifro et al., 2017).

Inflation (without a one-period lag) has a positive significant coefficient. If inflation increases by 1%, on average, sovereign yields increase 0.174%, ceteris paribus. This reflects that a higher level of inflation is associated with higher bond rates. Central banks manage inflationary pressures through monetary policy. Raising interest rates to reduce money supply leads to higher borrowing costs for governments, and consequently higher sovereign bond yields (Hilscher and Nosbusch, 2010). Lagged current account balance is significant in model A, but insignificant when adding the time effects in model B. Moreover, there is not a significant relationship between GDP growth, institutional quality and debt as a percentage of GDP with sovereign bond yields.

5.2 Robustness tests

Several sensitivity analyses are conducted to verify the consistency of the initial results to various modeling choices.

5.2.1 Alternative dependent variable: Sovereign bond spreads

To gain further insights of the analysis between transition and physical risk, an additional regression was conducted with an alternative dependent variable, sovereign bond spreads. The results of the model, presented in Table 6 column A, provide the results of climate risks on bond spreads. Upon examining the coefficients, it is observed that carbon emissions per capita and physical risk present a positive relationship with government spreads. However, it is important to note that these coefficients did not reach statistical significance, similar to what was found when yields were tested. Moreover, there is no evidence of time effects on the model with sovereign bond spreads as dependent variable.

Traditionally, Germany is considered to be a relatively safe risk-free investment in Europe and it is commonly used in different studies as a benchmark to obtain spreads (Hagen et al., 2011). Nevertheless, in this particular case comparing country-specific transition and physical risk, Germany's yield may not be totally risk-free in terms of climate factors (Boitan et al., 2022; Frondel et al. 2017). Germany has a rather high degree of climate risk due to their geographic exposure and their high industrialized economy, which produces high carbon emissions. Hence, using Germany's yield as a basis to compute the spread for the sample might produce misleading results when analyzing variables related to climate change.

Moving on to the macroeconomic fundamentals, inflation and lagged fiscal balance continue to be significant as the main results in section 5.1. Furthermore, when testing the spreads, another macro-variable becomes significant at a 5% level: GDP growth. An increase of 1% in GDP growth, sovereign bond spreads decreases by 0.08%. This implies that a growing economy comes along with higher government income (from taxes and other sources), increased aggregate demand, and low unemployment rate. As a result, these factors increase investor's confidence, and consequently, investment decision-makers may consider a high-growth GDP economy as less risky.

Table 6. Determinants of Sovereign Bond Yields

	(D)	(E)	(F)	(G)
	Alternative Y	Carbon Tax	2006 - 2014	2015 - 2021
Dependent variable	Spread	Yield	Yield	Yield
CO2 per capita	-0.2156	-0.2299	0.6812***	0.4408**
	(-1.13)	(-1.30)	(3.86)	(2.21)
L.CO2 per capita	0.1192	0.2444	0.6839***	0.1178
	(0.50)	(1.03)	(3.03)	(0.64)
Physical risk	-0.8160	46.275	79.361	42.848
	(-0.19)	(1.02)	(0.76)	(0.28)
L.Physical risk	22.252	-0.7374	-119.441	97.712
	(0.26)	(-0.12)	(-1.12)	(0.82)
GDP growth	-0.0802**	-0.0282	-0.0931**	0.0078
	(-2.57)	(-0.74)	(-2.32)	(0.23)
Inflation	0.0990*	0.1764***	0.1774**	0.0016
	(1.79)	(2.90)	(2.23)	(0.03)
L.Inflation	0.0096	0.0525	-0.0135	-0.0153
	(0.15)	(0.81)	(-0.19)	(-0.30)
Current acc. balance	0.0738	0.0843*	0.0477	-0.0038
	(1.66)	(1.89)	(0.76)	(-0.20)
L.Curr. acc. balance	-0.0338	-0.0355	-0.0814*	-0.0141
	(-0.88)	(-0.93)	(-1.78)	(-0.57)
Institutional quality	-0.4482	-0.6214	-17.430	0.4852
	(-0.28)	(-0.40)	(-0.97)	(0.34)
L.Inst. quality	-0.6794	-0.3862	-3.8003**	-0.4150
	(-0.52)	(-0.34)	(-2.36)	(-0.24)
Debt to GDP	0.0078	0.0259	0.0480	0.0145
	(0.65)	(0.82)	(1.10)	(0.90)
L.Debt to GDP	0.0059	-0.0202	-0.0214	-0.0127
	(0.60)	(-0.86)	(-0.64)	(-0.60)
Fiscal balance	0.0154	-0.0027	-0.0165	0.0580*
	(0.64)	(-0.07)	(-0.34)	(1.90)
L.Fiscal balance	-0.1387***	-0.1249***	-0.1200***	-0.0053
	(-6.40)	(-7.94)	(-3.80)	(-0.13)
Ln. Carbon tax		-0.0167		
		(-0.47)		
L.Ln Carbon tax		0.0253		
		(1.59)		
Time	-0.0541	-0.3476***	-0.0099	0.0065
	(-1.27)	(-9.69)	(-0.41)	(0.51)
Constant	0.0646	-11.012	47.446	-269.321
	(0.01)	(-0.08)	(0.16)	(-0.72)
Observations	300	306	168	126
R^2	0.40	0.83	0.58	0.40
Adjusted R^2	0.36	0.82	0.53	0.31
AIC	768.76	760.43	452.15	156.62
BIC	828.02	827.45	502.13	202.00

Table 6 reports the results for the robustness tests. ***, **, and * denote statistical significance at 1%, 5%, and 10% level, respectively. L. denotes one period lag on the variable. All models include a time trend. Carbon tax enters the model as a natural logarithm.

5.2.1 Explanatory variable: Carbon tax

An additional explanatory variable is introduced in the model: carbon dioxide emissions covered by a carbon tax. When adding carbon tax as an independent variable, the results indicate that it does not have significant explanatory power over sovereign bond yields. From the sample, 9 out of 21 countries have implemented a carbon tax over CO2 emissions. This suggests that the adoption of a carbon tax is relatively recent, with only a limited number of countries incorporating it into their regulatory frameworks. Despite the relevance of a carbon tax as a policy tool for reducing CO2 emissions, currently it does not appear to be a factor that is being priced into bond rates.

Implementing a carbon tax is an effective financial mechanism to incentivize the reduction of CO2 emissions, encouraging companies to adopt cleaner and more sustainable practices. Firms with lower carbon emissions have a competitive advantage. However, the introduction of a carbon tax is a gradual and lengthy process for the majority of countries and it might involve political challenges. Thus, since it could negatively affect economic growth, it requires careful economic consideration given that many industries would be directly affected by the tax. Continued assessment of the evolving relationship between carbon taxes and sovereign bond yields is essential, so countries can appropriately manage the challenges and opportunities associated with addressing climate change.

5.2.1 Paris Agreement 2015 (sub-periods)

The dataset is divided into two sub-periods, namely the period prior to the signature of the Paris agreement (2006 - 2014) and the period post-Paris agreement (2015 - 2021). The results are shown in Table 6 columns C and D. Sovereign bond yields were used as the dependent variable. Physical risk remains statistically insignificant even after dividing the sample into sub-periods. At the aggregate level, in section 5.1, there is evidence of a time trend in the sample that altered the results for the main independent variable, CO2 emissions per capita. In this robustness check estimation, the results indicate no presence of a time effect in either regression. By splitting the sample, two distinct time periods are created. This isolates the existence of a possible time trend that the entire sample has. Therefore, by evaluating each sub-period independently, any time effects that may be present in the overall sample are removed from the analysis.

As a consequence of taking away the time effects, the findings show that for both sub-periods, carbon dioxide emissions are highly significant and positively related to sovereign bond rates. For the first sub-period (2006 to 2015), an increase of one ton of CO2 emission per capita is associated with an increase of 0.681% in government rates, ceteris paribus. For the period after the signature of the Paris agreement of 2015, if CO2 emissions per capita increase one ton, on average, sovereign bond yields increase 0.440%, maintaining the rest constant. This suggests that slow and weak progress in assessing climate transition risk is associated with higher 10-year maturity bond yields. In contrast, countries that have low carbon emissions reflect a better performance in terms of implementing climate-related public policies. As a result, they are perceived as less risky and thus present lower sovereign yields. These results provide evidence that including carbon emissions into sovereign risk assessments adds value to the analysis. The magnitude of the coefficient for the first sub-period is greater than the coefficient for the estimation after the signature of the Paris agreement. There is not a substantial change over the magnitude of the coefficients as expected, leading to the conclusion that the second sub-hypothesis does not hold under these circumstances.

These findings are aligned with the results of Collender et al. (2022) and Bingler (2022) who argue that countries that prioritize transitioning to a zero-emissions economy benefit from lower borrowing costs. Addressing CO2 emissions reduction effectively would bring economic and environmental benefits to society. From a regulatory and policymaking point of view, the results strongly support the transition towards climate neutrality for many reasons. First, governments that establish targets to reduce carbon emissions from current levels and increase the adoption of renewable energy sources may be able to get lower cost fixed-income financing. Second, economic growth can also be achieved through the renewable energy sector. Generating electricity without emitting harmful greenhouse gasses plays a crucial role in mitigating climate change. Therefore, boosting the renewable energy sector through energy sources such as solar, wind, hydro, and geothermal is key to achieve the goals established in the Paris Agreement of 2015. Furthermore, investing in renewable energy can promote energy independence, reducing the reliance on fossil fuels and the vulnerability to price fluctuations. By embracing renewable energy and implementing measures to reduce carbon emissions, countries can pursue both economic growth and environmental sustainability.

6. Discussion and conclusions

Risks associated with climate change on sovereign bonds rates have recently gained attention. These risks arise from the consequences and uncertainty economies, governments and investors will face in the future regarding climate change, which will threaten the development of society on many socioeconomic aspects and investment decisions. This research empirically examines the relationship between climate transition risk, through dioxide carbon emissions per capita, on sovereign bond yields. The analysis focuses on a sample of 21 European Union countries from 2006 to 2021. Through a Fixed effects panel model, the findings of the research show that carbon transition risk is not incorporated yet into government bond rates. Besides, the sample presents highly significant time effects.

This results suggests that financial markets are mispricing sovereign bond yields, undervaluing carbon transition risk. This raises significant financial concerns for governments heavily reliant on carbon-intensive industries, as it increases future transition costs to decarbonize the economy, higher perception of risk and a possible decline in their market value. Investors may lack awareness of the long-term effects associated with bonds issued by carbon-intensive countries, making them vulnerable once transition risk is incorporated into the market. Consequently, a sharp drop in these assets could lead to substantial financial losses for investors, including retail and institutional investors like pension funds. Furthermore, regarding policymakers, the failure to price CO2 emissions in bonds may reduce the financial pressure on governments to implement climate-related policies. Hence, bonds issued by carbon-intensive economies may face devaluation, prompting a broader reevaluation of their long-term viability and financial stability.

By establishing new assumptions, methodological choices and employing an extended period of time, this research provides, from a different perspective, valuable insights on the pricing of climate transition risk and different determinants of sovereign bond yields. Specifically, it recognizes the relevance of introducing a time trend in the analysis and incorporates new independent variables that enrich the assessment. Furthermore, in the scope of this study, carbon transition risk is examined in conjunction with physical climate risk, offering an alternative approach. As a result, these differences lead to new results which expand the knowledge and understanding of this subject.

Multiple economic agents, including governments, business managers, retail investors, pension funds, and public opinion are increasingly becoming more aware of the effects of the actual climate emergency. Addressing this issue is crucial as the impact of climate change directly affects different socioeconomic systems and investors' investments. This paper contributes to the existing literature by providing a more in-depth view for investors and policymakers about how financial markets incorporate climate change risks, particularly carbon transition risk. Investors' expectations play an important role in assessing climate change risks. Recognizing that carbon transition risk is not adequately priced into government bonds, may help investors to actively manage their exposure by modifying their investment strategies. By limiting their involvement in high-carbon assets and diversifying their portfolios, investors can mitigate the potential negative consequences of a sudden decline in bond prices once CO2 emissions are incorporated into the market. Moreover, investors can include such risks into their decision-making processes by seeking out investment opportunities from companies and governments that promote sustainable practices. The growing environmental consciousness, especially among young generations, shapes their investment choices. Hence, sustainable-driven market participants can make well-informed decisions about which assets to invest in that align with their values.

Policymakers, through the results of this study, might identify key areas to address in order to combat climate associated risks. For instance, policymakers particularly from high-intensive carbon countries, can consider allocating additional resources towards policies that incentivize CO2 emissions reduction, implementing carbon taxes for high-emitting companies, and prioritizing investments in renewable energy projects and infrastructure. By taking proactive measures, governments can mitigate the impact on their debt issuances when CO2 emissions get priced into the market. It is essential to factor in climate policy when issuing new debt instruments, since stricter regulations are likely to be implemented as climate change worsens. These measures could benefit the economy financially and environmentally, facilitating a smoother transition process towards greener economies. As a result, borrowing costs could decrease, leading to lower sovereign yields.

The study presents certain limitations. First, future analysis of climate risk variables over government yields could explore country specific sub-samples, differentiating between advanced and developing countries. It is relevant to examine whether the outcomes hold for both types of countries. Usually, advanced countries present more favorable economic and political conditions to implement strategies to transition to a low-carbon economy than developing countries. It is also recommended to consider different maturities. Further studies in this field could include different maturities of government bonds to assess the degree of influence depending on the time horizon. Given the lack of studies exploring the financial consequences of climate change, academic research should keep expanding in size and influence, so that climate finance effectively contributes and addresses the challenges of global warming

Overall, this paper significantly contributes from a new perspective a deeper understanding of the effects of climate-related risks on borrowing sovereign costs. Although transition risk has not yet been fully priced into government rates, these findings highlight the importance for investors to consider the future financial consequences associated with holding sovereign bonds from high CO2 emitting countries, reassessing their exposure to such assets. Furthermore, these results can serve as a catalyst for policymakers to adopt stronger measures aimed to achieve carbon neutrality. By recognizing the implications of carbon risk on sovereign bond yields, policymakers may be further motivated to implement policies and initiatives that promote sustainable practices and reduce carbon emissions. It remains crucial to recognize and account for carbon risk to mitigate the economic and environmental implications economies will face.

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9. Appendices

Appendix A | Country selection process

The following table shows the countries that are included in the model:

Table 1. List of countries included

Austria	Germany	Poland
Belgium	Hungary	Portugal
Bulgaria	Ireland	Romania
Czech Republic	Italy	Slovakia
Denmark	Latvia	Slovenia
Finland	Lithuania	Spain
France	Netherlands	Sweden

The European Union is constituted by 27 countries. The scope of this research was the entire sample of European Union Nations, however five countries did not have available data of their 10-year benchmark bond yields from 2006. Instead, these five countries had data available from 2016 or 2017, the reason why they were removed from the sample. Greece is removed from the sample as it is considered an outlier that can distort the findings of the estimations.

Table 2. List of countries excluded

Croatia	Estonia	Malta
Cyprus	Greece	Luxembourg

Appendix B | Description Institutional quality indicators

Institutional Quality is composed by six governance indicators from The World Bank, measured as z-scores ranging from -2.5 to 2.5. It includes the estimate of Government Effectiveness that measures perceptions of the quality of public services, civil services, policy formulation and the credibility of the government's commitment to such policies. Control of corruption refers to the perceptions if public power is exercised for private gain, including the state of elites and private interests. Political Stability and Absence of Violence/Terrorism captures perceptions of political instability and political-motivated violence. Regulatory quality measures the ability of the government to formulate and implement policies to promote private sector development. Rule of Law captures the confidence in abiding the rules of society. The last governance factor is Voice and Accountability which measures the perceptions of participation to select their government and freedom of expression. Finally, Sovereign credit Ratings reflect creditworthiness of a country assigning a score that includes socioeconomic factors into account (World Bank, 2022).

Appendix C | Hausman Test

Table 3 displays the Hausman Test for the sample to determine whether to use the Fixed effects regression or the Random Effects model. The Hausman test rejects the null hypothesis of Random Effects at 5% of significance level. Considering the results of table 3, the null hypothesis is rejected. Therefore, the estimations were done through Fixed effects.

Table 3. Hausman Test: Examining whether Fixed Effects or Random Effects is preferred

χ^2	257.26
p-value for χ^2	0.0000***

***, **, and * denote statistical significance at 1%, 5%, and 10% level, respectively.