Climate Transition Risk in Sovereign Bond Markets

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Abstract

Is climate transition risk factored into sovereign bond markets? We find that carbon dioxide emissions, natural resources rents, and renewable energy consumption, as measures of transition risk, significantly impact yields and spreads. Countries with lower carbon emissions incur a lower borrowing cost. Advanced countries reducing their earnings from natural resource rents and increasing renewable energy consumption are associated with lower borrowing costs, which differs from the effects in developing countries. Given the threat climate change poses to the global economy and the fast materialisation of transition risk, we advocate an increase in the significance of climate transition risk factors as determinants of sovereign bond markets.

Keywords: climate transition risk, sovereign bond yields, carbon dioxide, natural resources rents, renewables

JEL: F34, G15, H63, Q20, Q51

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1. Introduction

Climate transition risks are related to the process of adjustment towards a low-carbon economy.[2] Many investment professionals claim that climate change is not being factored into government bond markets[3]. Therefore, sovereign bond yields do not fully reflect the impact of climate change and a country's efforts to transition to a low-carbon economy in line with the 2015 Paris Agreement.[4] We challenge this narrative. We show that climate transition risks are currently priced into sovereign bond yields and spreads.

There are three main transmission channels of climate risk affecting the financial stability of a country: physical risks, liability risks and transition risks. The Bank of England (2015) defines physical risks as the first-order risks that arise from weather-related events with direct impacts, such as damage to property, and indirectly through disruption to global supply chains or resource scarcity. An extensive body of literature explains the negative physical effects of climate change on economic growth and recovery (Nordhaus, 1991, Dell et al., 2012, Batten et al., 2020). Recently, the finance literature has begun to explore the nexus between physical climate risk and sovereign risk (Kling et al., 2018, Beirne et al., 2021, Cevik and Jalles, 2022). Liability risks stem from parties who have suffered a loss from the effects of climate change and are seeking compensation from those responsible. This has led to widespread ramifications that extend to litigation against companies and governments, which now have an established duty of care.[5]

Transition risks arise due to a country's adjustment process towards a greener economy. ClimateWise (2019) presents both transition risks and opportunities, with transition risks including policy changes, reputational impacts and shifts in market preferences, norms and

[2] Basel Committee on Banking Supervision: https://www.bis.org/bcbs/publ/d517.pdf

[3] See, for example, AFR: https://www.afr.com/policy/economy/investors-not-pricing-climate-change-into-government-bond-risks-20210118-p56uyk; CNBC: https://www.cnbc.com/2021/02/24/climate-risks-not-priced-in-bond-markets-a-risk-for-many-countries-.html

[4] The Paris Agreement's goal is to limit global warming to well below 2, preferably to 1.5 degrees Celsius, compared to pre-industrial levels. This is a legally binding international treaty on climate change adopted by 196 Parties at COP 21 in Paris on December 12 2015. Upon inking the agreement, the target date was 2050. The urgency has increased since the Paris Agreement, and the focus has shifted to reducing emissions by 50% by 2030.

[5] See, for example, ABC: https://www.abc.net.au/news/2021-05-27/climate-class-action-teenagers-vickery-coal-mine-legal-precedent/100169398; Bloomberg: https://www.bloomberg.com/news/articles/2020-07-22/australia-sued-for-not-disclosing-climate-risk-in-sovereign-debt

technology. Transition opportunities are driven by resource efficiency and the development of new technologies, products and services, which could capture new markets and funding sources.[6] Despite the significance of these risks/opportunities in preparing economies for a successful transition, the existing literature is focused primarily on the aforementioned physical risk, with relatively little research investigating the impact of climate transition indicators on sovereign bond yields and spreads.

Climate transition risk variables are chosen for their ability to measure how well a country is transitioning towards a carbon-neutral economy in line with the Sustainable Development Goals (SDGs). Thus, we examine the impact of climate transition risk on sovereign bond yields by employing climate transition risk variables that can be mapped directly to specific SDGs. Specifically, we employ *carbon dioxide emissions*, aligned with SDG Goal 13 Climate Action; *natural resources rents*, aligned with SDG Goal 12 Responsible Consumption and Production; and *renewable energy consumption*, aligned with SDG Goal 7 Affordable and Clean Energy. Carbon dioxide emissions and natural resource rents produce negative climate-related effects. An increase in either reflects a higher reliance on fossil fuels and an increasingly difficult transition to a net-zero economy. Renewable energy consumption has a positively related climate effect, as an increase in renewable energy aligns with progression towards cleaner fuel sources and a more sustainable economic future. We hypothesise that countries with higher carbon emissions and natural resource rents will incur a risk premium on their sovereign borrowing cost. In addition, we hypothesise that countries with higher renewable energy consumption relative to total consumption will be rewarded with a discount on sovereign borrowing costs.

We further suggest that climate transition risk has two avenues via which it can impact yields: directly through the risk factors themselves and indirectly through macroeconomic variables, such as Gross Domestic Product (GDP). For example, concerning the first avenue, countries with poor prospects of transitioning away from a reliance on fossil fuels will likely incur higher costs of funding due to investors penalising countries that are not seen to be

[6]These risks and opportunities vary across geographies, sectors, time horizons and government and business commitments to limit global temperature rises.

pulling their weight with respect to tackling climate change.[7] The second and indirect avenue relates to how much investors think a country's future GDP prospects will suffer if its economy is reliant on a declining industry, such as fossil fuels. The magnitude of direct and indirect influences is expected to increase over the coming years as the impact of climate change intensifies on economies globally. Of course, the physical risk of climate change is currently impacting GDP levels.[8] Accordingly, even if investors are not linking the decline in current levels of GDP to the physical risk of climate change, we can argue that climate risk is being priced into yields and spreads to the extent that investors account for present GDP levels.

We test these hypotheses by employing generic 10-year bond[9] yield data from 23 advanced countries and 16 developing countries from 1999 to 2021, which represented the full sampling period available for the data sets utilised within this research. The estimation results are split by country group under the assumption that a country's transition efforts will be impacted by economic and financial characteristics. This implies that the impact on sovereign bond yield spreads is best observed alongside countries with similar characteristics. In addition, to standardise yields across countries, we estimate yield spreads as a country's 10-year bond yield minus the United States yield of the same maturity. Seven macroeconomic and liquidity variables that are traditional determinants of bond yields are used to control for domestic-specific factors and mitigate against endogenous concerns.

We show that climate transition risk variables significantly impact sovereign yields and spreads through a series of panel country fixed effects regressions. Carbon dioxide emissions are positively related to sovereign bond yield and spreads, a relation that holds for both advanced and developing countries. Thus, carbon dioxide emissions play a dominant role in influencing the sovereign bond market worldwide, with reduced carbon dioxide emissions

[7] https://www.smh.com.au/business/markets/swedendumps-aussie-bonds-as-country-not-known-for-good-climate-work-20191114-p53agw.html

[8] https://www.bloomberg.com/news/articles/2020-02-13/rba-s-lowesays-economic-implications-of-climate-change-profound

[9] The generic bond yields includes the current and historical data for the on-the-run issues of a particular tenor. On-the-run Treasuries are the most recent Treasury released for a certain maturity, while off-the-run Treasuries are those that have been issued before and remain outstanding. The Bloomberg 'generic' price is the market reflective price for corporate and government bonds. The generic prices are calculated by using prices contributed to Bloomberg.

being associated with lowering sovereign borrowing costs. Reduced natural resource rents in advanced countries are related to lower sovereign borrowing costs, revealing a positive impact of climate transition risk on sovereign bond yields and spreads. Interestingly, developing countries with a high dependence on natural resources are also associated with lower sovereign borrowing costs. Further, an increase in renewable energy consumption is associated with reduced sovereign borrowing costs for advanced countries. However, renewable energy consumption is associated with increased sovereign borrowing costs for developing countries.

Several reasons can explain the differences in the effects between advanced and developing countries. Implementing emission reduction strategies, such as technological advancement, less reliance on fossil fuels and consuming cleaner energy sources, is far easier in advanced countries that can borrow at a lower cost, have higher GDP per capita and are more resilient to economic shocks. Developing countries face a unique challenge in this regard, and partnership assistance, financial support and technology transfer from advanced countries are critical for successfully transitioning to cleaner economies. Clean energy adaption and integration have the potential to drive economic growth that would counteract the short-term financial losses arising from the transition away from high-carbon economies and the dependency on natural resources. Nevertheless, given that the future expected costs of transitioning may rely on external support, which is highly uncertain, market participants may demand to be compensated for this uncertainty by way of higher yields. Further, developing countries' yields are often more volatile. They can be dominated by shorter-term "noise" (e.g. geopolitical risk). As such, investors may be much more focused on a developing country's ability to repay debt as a function of shorter-term factors. Finally, advanced countries have the advantage of favourable economic and political conditions to implement strategies to transition to a lower-carbon economy. In contrast, if the high natural resource rents the developing countries command are much higher than the uncertain payoff from transitioning to a carbon-neutral economy and the cost of transitioning is prohibitive, then it makes sense that investors would not value increased renewable energy exposure. A further explanation may be that investors consider transition risk a burden that developed economies may be required to bear – as supported by statements from leaders that partnership assistance and technology transfer will be necessary to meet the Paris Agreement goals (United Nations, 2019).

This research provides valuable insights for investors and policymakers through an analysis of key transition indicators and their impact on the sovereign cost of borrowing in advanced and developing countries. By aligning the variables to SDGs, this paper provides a transparent and easily replicable way for governments, investors and businesses to evaluate climate transition risk concerning sovereign bond yields. Policymakers will have a better understanding of how transition efforts, such as lowering carbon emissions and increasing investment in renewable energy, affect their cost of borrowing and access to financial markets. Further, the sovereign bond market serves several critical purposes: providing a benchmark from which every other asset class is priced, acting as a safe haven asset during market crises and providing liquidity and funding for the banking sector and governments. The global financial system is, therefore, dependent on a well-functioning bond market. Understanding the impact that transition risk has on a country's cost of borrowing is also critical for governments to manage climate transition effectively. This is particularly true if they align their policies and strategies with the United Nations SDGs, goals that many governments appear to be at risk of not achieving.[10] The research is driven by a growing recognition that there is a need to investigate not only the physical risks of climate but also the transition risks countries face in preparing for a more sustainable future.

This paper is organised as follows. Section 2 outlines the relevant literature on climate transition risk factors and potential determinants of sovereign bond yields/spreads. Section 3 describes the data and the methodology used in this study along with the preliminary analysis. Section 4 presents the empirical findings regarding the impact of climate transition risk indicators on sovereign bond yields and spreads. Sensitivity analysis is included in Section 5. Section 6 concludes and discusses implications for policy and investors.

[10] United Nations SDGs: https://www.un.org/sustainabledevelopment/

2. Literature Review

In recent years, the impact of climate risks has attracted the attention of practitioners and academics as a potential determinant of government bond yields. Kling et al. (2018) use the Notre Dame Global Adaptation Initiative (ND-GAIN) indices for vulnerability[11] to climate change – specifically the sensitivity, capacity and social readiness index – and confirm the importance of these indices in determining bond yields from 48 countries, including countries from the V20[12] and G7[13] groups. The analysis is challenged by the lack of variability of the ND-GAIN factors, multicollinearity and a low number of data points for some countries. Similarly, Cevik and Jalles (2022) and Beirne et al. (2021) focus on climate risk vulnerability and readiness[14] measures from the ND-GAIN indices and reveal that an increase in vulnerability and a decrease in readiness lead to rising sovereign bond yields, and these effects are more pronounced in developing countries.

However, this body of literature conflates the potential negative adverse effects climate change can have on society at large through more frequent or severe weather events (physical risk) with the negative economic impacts countries may experience from moving towards less polluting, greener economies (transition risk).[15]

In a first attempt in the literature to separate physical from transition climate risk, Beirne et al. (2021) show that transition risk has lower effects on sovereign bond yields compared to the physical risk, underscoring the fact that transition risk is not well understood and, most importantly, is priced in bond and financial markets. Furthermore, the market does not price climate risk for near-term maturities, and bonds with low credit ratings lead to higher issuance costs for climate risk coverage, as shown by Painter (2020) using municipal bond offerings in US counties. Based on scenario analysis of banking sector sentiments, Dunz et al.

[11]The definition of *vulnerability* according to the ND-GAIN is "Propensity or predisposition of human societies to be negatively impacted by climate hazards".

[12]These are the top 20 nations that are most affected by catastrophes rooted in climate change: Afghanistan, Bangladesh, Barbados, Bhutan, Costa Rica, Ethiopia, Ghana, Kenya, Kiribati, Madagascar, Maldives, Nepal, Philippines, Rwanda, Saint Lucia, Tanzania, Timor-Leste, Tuvalu, Vanuatu and Vietnam.

[13]Canada, France, Germany, Italy, Japan, United Kingdom and the United States.

[14]The definition of *readiness* according to the ND-GAIN refers to the "Readiness to make effective use of investments for adaptation actions thanks to a safe and efficient business environment".

[15]For more detailed definitions of physical and transition risk, see https://www.bankofengland.co.uk/knowledgebank/climate-change-what-are-the-risks-to-financial-stability

(2021) show that government policies and financial regulation can facilitate the transition to a low-carbon economy.

At the firm level, using data from 71 advanced and emerging countries, Kling et al. (2021) demonstrate that for firms in countries with high exposure to climate risk, climate vulnerability increases the cost of debt directly and indirectly in the form of restricted access to financing (financial exclusion). In contrast, the cost of capital is closely associated with the cost of debt. This enforces a climate vulnerability risk premium that leads to lower sovereign (and private) investment and a subsequent curtailing of economic development targeting the climate adaptation of countries. Although Kling et al. (2021) construct an adjusted ND-GAIN climate vulnerability index to control for endogeneity from highly correlated macroeconomic variables, the pressing matter of the climate transition risk has not been addressed.[16]

In this paper, we aim to identify determinants of climate transition risk, avoiding the combined information of ND-GAIN sub-indices – and similar approaches – which may suffer from endogeneity and a lack of time-series variation.[17] We focus on three key transition climate risk indicators: carbon dioxide emissions, natural resources rents and renewable energy consumption,[18] which are aligned with specific SDGs. These are variables a country can influence through appropriate climate policy and strategy. Unlike vulnerability and readiness, which are important risk factors related to the physical burden of climate change, we focus on carbon footprint and intensity indicators to understand how countries are transitioning to lower-carbon economies.

[16]Impact of climate transition risk on financial performance has been assessed using a US and European firm-level carbon risk score by Reboredo and Ugolini (2022), and using a top down approach based on EU Taxonomy by Alessi and Battiston (2022). Nguyen et al. (2022) evaluate exposure of US banks to climate transition risk where prediction of corporate emissions from machine learning algorithms are related to loan-level information and then aggregated to bank-level climate transition risk.

[17]The ND-GAIN index for individual countries does not offer many variations over time, and as such, it does not capture either countries' efforts to combat climate change or their increased vulnerability as the climate continues to change and evidence becomes more abundant.

[18]Climate change indicators are more informative and effective when they capture more detail and are considered individually (Lisa et al., 2015).

2.1. *Carbon dioxide emissions*

Greenhouse gases (GHGs) are the primary contributor to climate change, as they disturb the earth's radiative balance and trap heat in the atmosphere. Of the four main types of GHGs,[19] carbon dioxide accounts for the largest share of radiative forcing – which is the heating effect caused by GHGs in the atmosphere.[20] Carbon dioxide emissions have been well studied in the literature alongside economic growth and energy consumption (Sebri and Ben-Salha, 2014, Cowan et al., 2014). Sebri and Ben-Salha (2014) investigate the direction of causality between GDP, electricity consumption and carbon dioxide emissions in BRICS5[21] countries over the period 1997–2010. Their findings show evidence of a feedback hypothesis for Russia, which has significant implications for energy policies. For instance, in Russia, where electricity consumption causes carbon emissions, policymakers must invest in increasing electricity efficiency so emissions can be reduced without negatively affecting GDP. Omri et al. (2014) demonstrates that foreign direct investment (FDI) inflows, energy consumption and output are determinants of carbon dioxide emissions and, as such, could lead to environmental degradation (see also Marques and Caetano (2020)). These studies are particularly relevant for developing countries and suggest that, depending on the level of external investment, markets may prioritise economic development through natural resources rather than renewable energy technologies. According to environmental transition theory, pollution in developed countries is driven by strong energy consumption associated with urbanisation and industrialisation (Sadorsky, 2014).

Furthermore, the transition from pollution-intensive industrial economies to environmentally cleaner economies due to trade liberation could lower carbon dioxide emissions (Kolcava et al., 2019). In contrast, harvesting, deforestation and the trade of agricultural products have a material impact on carbon dioxide emissions (Balogh and Jambor, 2017). Aller et al. (2021) identify robust determinants[22] of carbon dioxide emissions per capita using panel data

[19] Carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), fluorocarbons (FCs).

[20] Carbon emissions stem from the burning of fossil fuels such as coal, natural gas, and oil for energy use, burning wood and waste materials and cement manufacturing.

[21] Brazil, Russia, India, China, and South Africa (BRICS).

[22] The determinants are GDP per capita, the share of fossil fuels in energy consumption, urbanisation, industrialisation, democratisation, the network effects of trade and political polarisation. These determinants are typically positively associated with carbon dioxide emissions (except political polarisation).

from 92 countries over two decades and confirm the significance of economic and financial development, FDI, international trade and political stability in improving carbon dioxide emissions. Factors such as political stability, corruption control and laws on carbon dioxide emissions play an important role in improving environmental quality in terms of development and income. In turn, they could facilitate a smoother transition to cleaner economies (Muhammad and Long, 2021).

2.2. Natural resource rents

The World-Bank (2003) defines the economic rent of a natural resource as equal to the value of capital services flows rendered by the natural resources or their share in the gross operating surplus; the value of extraction gives it its value. Put another way, natural resource rents are the difference between the price at which an output from a resource can be sold and its respective extraction and production costs, including the normal return, and thus can be conceptualised as abnormal or super-normal profit (Scherzer and Sinner, 2006). Natural resources result in economic rents because they are not produced, unlike produced goods and services, for which competitive forces expand the supply until economic profits are driven to zero.[23] Natural resources, on the other hand, have a fixed supply and typically generate returns that are well above the cost of production at an expected increase in carbon emissions levels. Danish (2020) investigates the cointegration between natural resource rents, water productivity and international trade, finding that all three variables increase carbon emissions levels.

Particular countries have significant earnings from economic rents, contributing to a sizable component of their GDP. Rents from nonrenewable resources, such as fossil fuels, minerals, and over-harvesting of forests, are in effect borrowing against the future of that country (World-Bank, 2019). The liquidation of the country's capital stock to support current consumption represents an unsustainable component of GDP, leading to a tangible transition risk and, thus, an anticipated positive relation with sovereign bond yield spreads. Clarvis et al. (2014) present a framework to integrate natural resources and environmental risks into the sovereign bond market, recognising the financial materiality of these risks to

[23] https://data.worldbank.org/indicator/NY.GDP.TOTL.RT.ZS

a country's economy. Furthermore, Battison and Monasterolo (2020) introduce a financial pricing model that considers forward-looking climate risk in the valuation of sovereign bond yields. By applying a novel methodology to a portfolio, they find that climate policy introduction impacts a country's financial stability. In particular, the earlier a country becomes aligned with climate transition targets, such as those outlined in the Paris Agreement, the lower the yields on its bonds. Conversely, countries that still derive a large portion of their revenue from fossil-fuel-intense industries have higher sovereign yields.

2.3. Renewable energy consumption

The global energy used for electricity, heat and transport accounts for 73% of GHG emissions, with an additional contribution from agriculture/forestry (18%) and industry (5%).[24] Indeed, the global energy transformation and successful transition to clean energy are heavily reliant on renewable electricity. However, renewable energy should be complemented by energy-efficient practices in the industrial, buildings and transport sectors (IRENA, 2019). Along with energy efficiency and renewable energy, "deep" electrification[25] could reduce the energy-related carbon emissions by 90% by 2050 (IRENA, 2017).

The transition to 100% renewable-powered economies has become a "near" target for many countries (primarily advanced countries) due to technological innovations and the reduced financial cost of renewable energy deployment. Further, many advanced economies have committed to financially assisting poorer countries with their renewable energy targets (IRENA, 2017). It is well understood that the key to a successful transition toward decarbonisation lies in reducing energy-related CO_2 emissions mainly sourced by renewable electricity. Thus, the role of energy governance and energy security is critical in fostering the development and deployment of technology that will accelerate the transformation of the energy sector and increase the renewable electricity share in industry, transport and buildings (Wand et al., 2018, Arroyo and Miguel, 2020).

To quantify the challenges associated with the energy transition in terms of planning,

[24] See https://ourworldindata.org/ghg-emissions-by-sector

[25] Electrification of heat and transport applications, such as deploying electric vehicles, heat pumps and renewable hydrogen.

policies and financing, the literature has employed scenario analysis tools[26] to assess the climate transition risk. Fuss et al. (2012) recognise the importance of uncertainties associated with technological innovation, socio-economic and market conditions, policy implications and climate sensitivity in the decision-making regarding biomass-based energy investment. By addressing population and climate change in a global energy mix scenario analysis, Jones and Warner (2016) show that renewable energy plays a vital role in meeting the 2^{o}C goal. Using a comprehensive scenario analysis, Gielen et al. (2019) demonstrate that growth in renewable energy and increased energy efficiency[27] would be able to provide up to 94% of the emissions reduction needed to meet the targets of the Paris Agreement. Thus, renewable energy consumption is an essential indicator of how a country is accelerating its energy transition while ensuring ample energy for economic growth.

Next, we will gauge the impact of these three climate transition risk indicators on sovereign bond yields and spreads to support the notion that climate transition risk serves as a determinant of sovereign borrowing costs.

3. Data and Methodology

3.1. Data

The relationship between climate transition risk indicators and sovereign bond yields and yield spreads is analysed by employing data from 23 advanced countries and 16 developing countries from 1999 to 2021. The main variables of interest are sovereign yield and yield spreads on generic 10-year government bonds. The widely accepted calculation of the yield spread is the difference between the interest rate paid by a country on its external US-denominated debt and the US Treasury bond rate offered on debt of comparable maturity (Hilscher and Nosbusch, 2010, Capelle-Blancard et al., 2019). Within this research, the United States 10-year Treasury bond is treated as the 'benchmark' rate, with the yield spread being the difference between the respective country's yield and the benchmark rate. Sovereign yields are extracted from Bloomberg with a yearly frequency (values related to

[26] Forecast tools are more prevalent in assessing physical climate risk, see Kim and Jehanzaib (2020).

[27] Energy efficiency refers to the goal of reducing the amount of energy required to produce the same goods and services (GDP).

end-of-year yields).

The data on carbon dioxide emissions is extracted from the Our World in Data dataset, sourced from the Global Carbon Project. It is defined as the carbon dioxide (CO_2) emissions from the burning of fossil fuels for energy and cement production, and land-use change is not included.[28] We also consider the mean carbon dioxide emissions per capita, which adjusts the carbon dioxide emissions for the population of each country.

Using environmental economics data from the World Bank, the natural resources rents[29] variable is defined as the sum of oil rents, natural gas rents, coal rents (hard and soft), mineral rents and forest rents relative to GDP (World-Bank, 2019). Renewable energy is computed as a percentage of primary energy and refers to the renewable energy technologies' share in the energy mix, where energy consumption represents the sum of energy used for electricity, transport and heating. It is sourced from the Our World in Data.[30] In 2019, around 11% of global primary energy came from renewable technologies.

Consistent with the literature on the determinants of sovereign bond yields and spreads, nine control variables are included in the analysis. We consider GDP per capita, real GDP growth, inflation, trade openness and current account balance extracted from the World Bank database. The debt-to-GDP ratio is extracted from the IMF World Economic Outlook database.[31] Historical sovereign credit ratings have been obtained from Bloomberg and

[28]The unit is a million tonnes of CO_2 (1 tonne of CO_2 = 3.664× tonnes of carbon).

[29]The World Bank estimates of natural resources rents are calculated as the difference between the price of a commodity and the average cost of producing it. This is done by estimating the price of units of specific commodities and subtracting estimates of average unit costs of extraction or harvesting costs. These unit rents are then multiplied by the physical quantities countries extract or harvest to determine the rents for each commodity as a share of GDP.

[30]Renewable technologies include a combination of hydropower, solar, wind, geothermal, wave, tidal and modern biofuels (traditional biomass, which can be an essential energy source in lower-income settings, is not included). Note that these data are based on primary energy, which is calculated by the 'substitution method'. It attempts to correct the inefficiencies in fossil fuel production by normalising all energy sources to EJ – this accounts for the inefficiencies in fossil fuel production and is a better approximation of 'final energy' consumption. It does this by converting non-fossil fuel sources to their 'input equivalents': the amount of primary energy that would be required to produce the same amount of energy if it came from fossil fuels. https://ourworldindata.org/renewable-energy

[31]A large body of literature is dedicated to identifying and analysing the determinants of government bond yields and sovereign risk. An early contribution to the literature, Edwards (1983), finds that a country's economic fundamentals impact its ability to pay debt and, thus, its cost of debt. Kinoshita (2006), Laubach (2009), Engen and Hubbard (2004) study liquidity and solvency to determine whether a country's debt-to-GDP ratio is positively related to the actual long-term government bond yield. Cantor and Packer (1996) find that high economic growth rates allow a country to service their debt easier, thus reducing their sovereign

represent Moody's historical ratings for local currency long-term government bonds. For the first time in this line of research, the Central Bank Budget Balance as per cent of GDP (CBBB), extracted from Bloomberg, and the nominal effective exchange rate (NEER), extracted from the Bank of International Settlements (BIS), have been included as control variables. CBBB accounts for quantitative easing policy implications on bond yields (Balcilar et al., 2020, Vissing-Jorgensen, 2021, Broeders et al., 2022), and NEER captures the counteractive effects of pegged currency dependencies on sovereign bond yields. Countries with flexible exchange rates are better positioned in financial policy compared to counties with interest rates pegged to other currencies (Obstfeld, 2021). Appendix A.1 defines the variables and data sources and provides more elaborate discussions on the importance of these control variables on sovereign bond markets.

3.2. Preliminary analysis

To inform the selection of countries, we consider a set of advanced and developing countries, with the majority being signatories of the Paris Agreement. Further, we look to the Germanwatch Climate Change Performance Index (CCPI)[32] to evenly select countries from all performance rating categories, i.e. very low, low, medium and high climate performance. The complete list of countries and their CCPI category ratings[33] are available in Table A.3. Importantly, a handful of countries included in the developing country group are also referred to as emerging economies depending on the source. To ease confusion, emerging countries are grouped into the same category as developing countries for this analysis. Data from 1990

bond yield, and credit ratings have an independent influence on yields beyond their correlation with other macroeconomic variables. Also, inflation, seen as a proxy for how well a country manages its fiscal balances, typically increases bond yield spreads (Min, 1998). Similarly, Min (1998) finds that a country's terms of trade have a negative effect on yields, as increased export earnings imply a better ability to repay debt. Since the Global Financial Crisis (GFC) and the European Debt Crisis, the relationship between macroeconomic fundamentals and yield spreads seems to have experienced a structural change. Afonso et al. (2015) study Eurozone bonds and find that the relationship between European Monetary Union (EMU) sovereign bond yields and macroeconomic fundamentals appear to be time-varying.

[32] Germanwatch aims to evaluate countries based on GHG emissions, renewable energy, energy use and climate policy. Using a weighted methodology, countries are ranked in relative terms, with very low indicating a country is managing its transition risk very poorly. More information is available at `https://germanwatch.org/en/CCPI`.

[33] The CCPI rating is compiled by the country classification of the United Nations, data sources, country classifications and aggregation, see `https://www.un.org/en/development/desa/policy/wesp/wesp_current/2014wesp_country_classification.pdf`

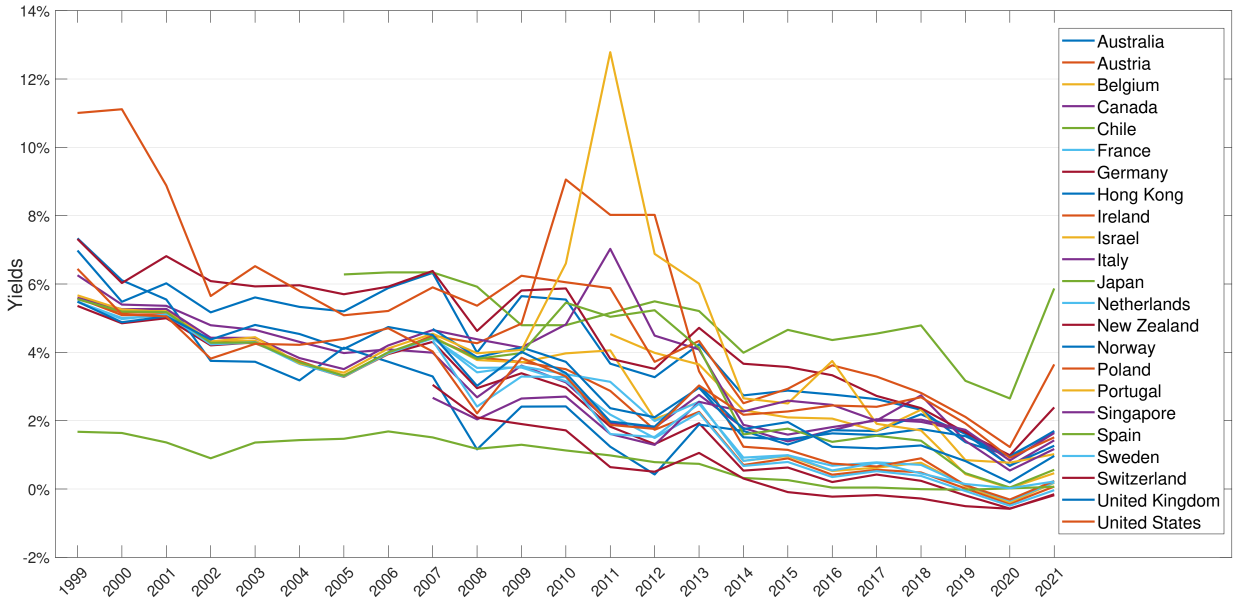


Figure 1: **Sovereign Bond Yields of Advanced Countries**
Figure 1 displays the sovereign bond yields for advanced countries between 1999 and 2021. On the left axis, yields are in percentage form. The legend on the right-hand side displays the country codes for all countries in the sample.

were originally collected as part of the sample. However, the sample period 1999 to 2021 was chosen given the lack of consistency in economic and climate data across many countries in the early 1990s.[34]

Figure 1 presents the 10-year government bond yields for advanced countries from 1999 to 2021. The starting year for the bond data commences when it becomes available for the respective country. The overall trend for bond yields in the last 20 years is downward. In the early 2000s, most advanced government bonds were priced between 5-9%, compared to recent average yields of 2–4%. Some anomalies in the figure stand out, i.e. between 2010 and 2014, Portugal suffered an economic and financial crisis, leading to high unemployment, falling GDP, rising government debt and, not surprisingly, increased bond yields.[35]

Figure 2 presents the 10-year government bond yields for developing countries. Significant yield variance can be seen across all periods, mainly because the emerging country debt market is younger and less sophisticated than the debt markets in advanced nations. As the

[34]We also excluded some countries due to very sample size, such as Kenya, Croatia and Colombia, which have only four observations.

[35]This provides a reason to exclude Portugal in robustness checks, as bond yields and economic fundamentals are not performing in the same pattern as the other countries over the same period.

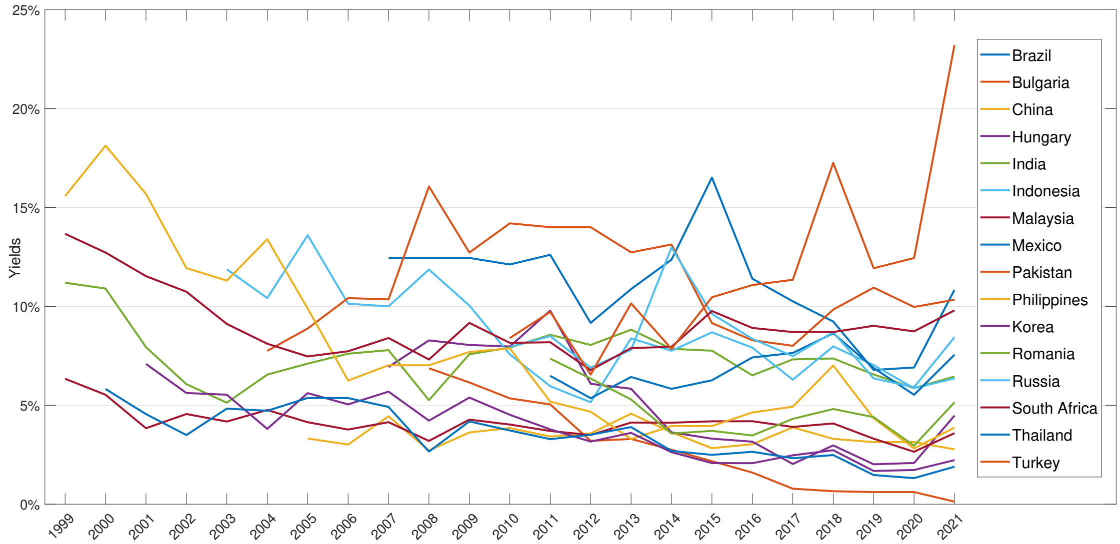
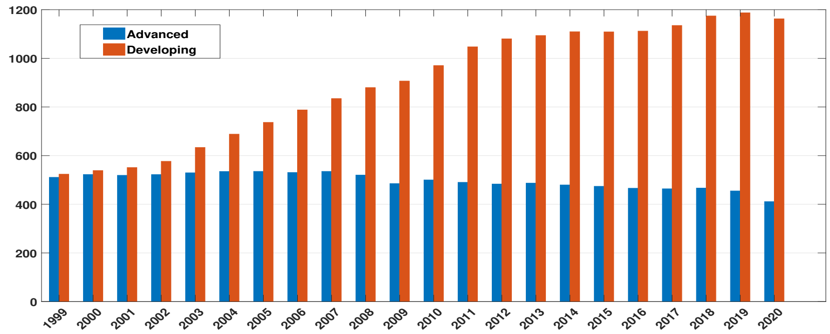


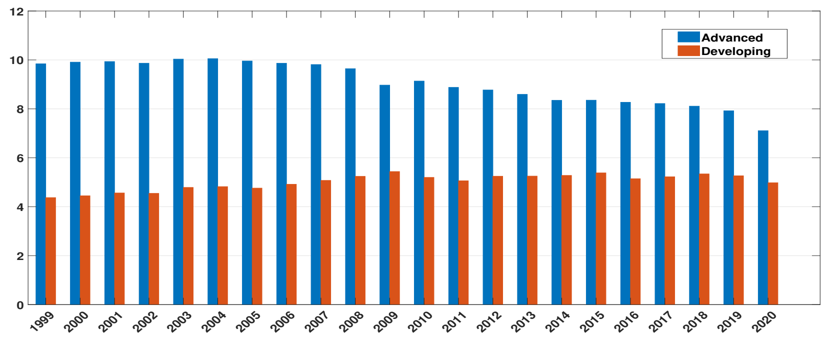
Figure 2: **Sovereign Bond Yields of Developing Countries**
Figure 2 displays the sovereign bond yields for developing countries between 1999 and 2021. On the left axis, yields are in percentage form. The legend on the right-hand side displays the country codes for all countries in the sample. Many developing countries did not issue bonds before 2008; this has been accounted for in the analysis.

implementation of fiscal and monetary policies has grown, so too has the issuance from these countries. The figure shows where each bond yield starts, with many countries only issuing their bonds post-2005. While in the last three years advanced countries have rarely had yield, a cost of borrowing higher than 6%, developing countries have had a large dispersion of yields from 0.25% to 18% in the last two years. The difference in yields is a reason for separating the results of developing countries and advanced countries in this study.

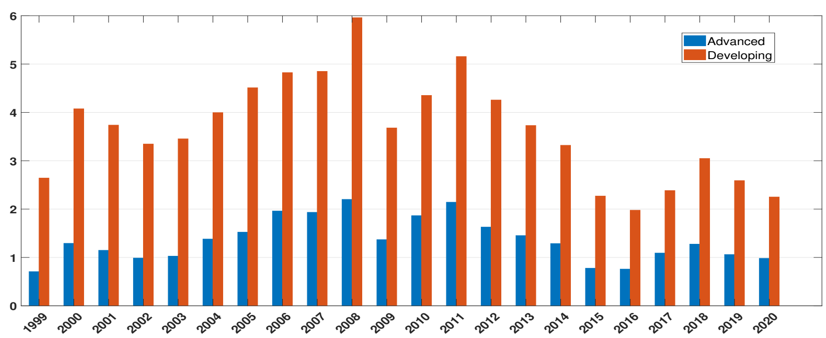
Figure 3 displays average carbon dioxide emissions, mean carbon dioxide emissions per capita, natural resources rents and renewable energy consumption over time for advanced and developing countries. More specifically, Figure 3.a shows that developing countries emit significantly more carbon dioxide than advanced countries each year, while the CO_2 per capita contribution is much higher in advanced countries (compared to developing countries), albeit with a decreasing trend (see Figure 3.b). Although emissions incrementally decreased over the sample period for advanced countries, it is clear that more government frameworks and policies are needed to reduce emissions to zero within this century, with developing countries also displaying an alarming overall average increase in emissions.



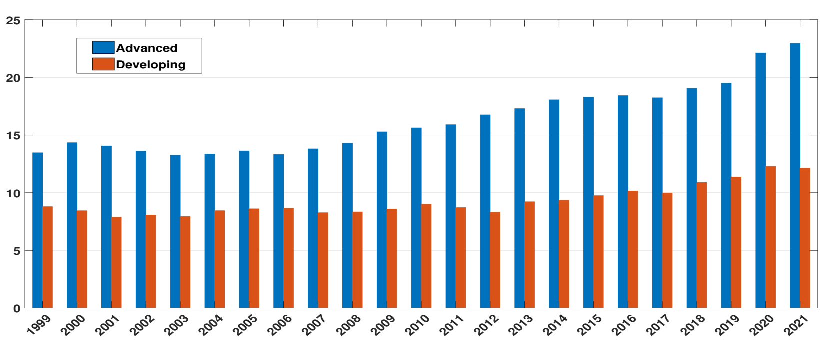
3.a: Mean carbon dioxide emissions



3.b: Mean CO_2 per capita



3.c: Mean natural resources rents



3.d: Mean renewable energy consumption

Figure 3: **Climate Transition Risk Measures**
The figure displays the climate transition risk measures, namely the mean carbon dioxide emissions (panel 3.a), the mean CO_2/capita (panel 3.b), the mean natural resources rents (panel 3.c), and the mean renewable energy consumption (panel 3.d), in advanced countries and in developing countries between 1999 and 2021 (2020).

Figure 3.c illustrates that developing countries earn a higher percentage of GDP from natural resources, averaging around 1–3% higher than advanced countries over the period. Figure 3.d displays the prominence of renewable energy consumption in advanced countries. This is likely due to the greater ability to invest in technological innovation to increase the supply and consumption of renewable energy within their respective populations.

Table 1 presents the descriptive statistics for sovereign bond yields (and spreads), climate change variables and control variables for all countries, split into country groups in the right two panels. The number of observations for each variable does not include missing values, and the varied number of observations shows we have an unbalanced panel. If there were no missing values as in a balanced panel, we would have 897 observations for each of the variables – a total of 39 countries and 23 years, with 529 from advanced markets (23 markets and 23 years) and 368 from developing markets (16 markets and 23 years). An extended description of the control variables can be found in Appendix A.1.1. Assessment of the statistical properties of the variables warrants common transformations, including a square root transform applied to carbon dioxide emissions and natural resources rents and a logarithmic transformation applied to GDP per capita. Given that the country sample size is larger than the time series, i.e. $N > T$: $i \in \{1, \dots, N\}$, where $N = 39$ and $t \in \{1, \dots, T\}$, where $T = 23$, and in addition, the time series is not classified as sufficiently large ($T > 30$), a test for the presence of a unit root would be misleading (Baltagi, 2021).

Echoing the visual analysis of the climate transition risk variables over time, we observe a comparison of the two country groups in Table 1, revealing expected disparities in macroeconomic characteristics. Developing countries, on average, have a lower GDP per capita, higher GDP growth rates, higher inflation, less trade openness and a less favourable current account balance. Not surprisingly, lower credit ratings are observed in developing countries, with an average of Baa3 and Ba1, compared to Aa2 for advanced countries.

Table 1: **Descriptive Statistics of Variables**

The table shows the descriptive statistics for all variables between 1999 and 2021. The statistics are grouped and then split into advanced and developing country groups. The number of observations for each variable does not include missing values. If there were no missing values, a variable should contain 897 observations for all countries (39 countries and 23 years), with 529 from advanced countries and 368 from developing countries. All figures are in percentage form, except GDP per capital, which is in thousands of dollars. The square root transformation of carbon dioxide emissions and natural resources rents and the log transformation of GDP per capita and trade openness are used in the analysis, as explained in Appendix A.1.

	All Countries					**Advanced Countries**					**Developing Countries**				
	Obs.	Mean	St.Dev.	Min.	Max	Obs.	Mean	St.Dev.	Min.	Max	Obs.	Mean	St.Dev.	Min.	Max
Bond yields (local currency)	758	4.410	3.267	-0.579	23.215	479	3.049	2.063	-0.579	12.785	279	6.748	3.613	0.128	23.215
Bond yield spreads (local currency)	735	1.475	3.171	-4.767	21.703	456	-0.038	1.607	-4.767	10.908	279	3.950	3.524	-2.031	21.703
Bond yields (USD)	758	4.190	3.141	-0.579	23.215	479	3.049	2.063	-0.579	12.785	279	6.149	3.668	0.128	23.215
Bond yield spreads (USD)	735	1.248	2.987	-4.767	21.703	456	-0.038	1.607	-4.767	10.908	279	3.351	3.491	-2.538	21.703
Carbon dioxide emissions (sqrt)	858	19.174	17.190	5.502	103.285	506	16.581	14.902	5.502	78.323	352	22.903	19.452	6.119	103.285
Carbon dioxide emissions per capita	858	7.410	4.251	0.717	21.336	506	9.074	3.937	3.387	21.336	352	5.017	3.476	0.717	18.141
Natural resources rents (sqrt)	858	1.140	1.000	0.000	4.690	506	0.787	0.857	0.000	4.150	352	1.646	0.973	0.132	4.690
Renewable energy consumption	889	13.394	14.770	0.001	72.398	521	16.310	16.800	0.001	72.398	368	9.267	9.941	0.234	49.472
GDP per capita (log)	897	5.045	0.861	3.795	7.607	529	4.947	0.680	4.216	7.018	368	5.185	1.054	3.795	7.607
Real GDP growth	897	3.000	3.406	-10.823	25.176	529	2.307	3.104	-10.823	25.176	368	3.996	3.574	-9.518	14.231
Inflation	897	3.609	5.961	-4.478	85.746	529	1.776	1.528	-4.478	9.900	368	6.245	8.461	-1.545	85.746
Debt-to-GDP	884	60.277	37.812	0.052	262.492	521	68.287	43.051	0.052	262.492	363	48.780	24.501	7.446	135.181
Trade openness (log)	894	1.866	0.268	1.258	2.646	526	1.908	0.282	1.258	2.646	368	1.805	0.234	1.322	2.343
Current Account Balance	880	1.199	5.962	-25.756	27.143	512	1.968	6.335	-11.856	27.143	368	0.129	5.222	-25.756	17.474
Credit Rating Scores	897	16.497	4.395	5.000	21.000	529	19.223	2.584	9.000	21.000	368	12.579	3.384	5.000	19.000
Credit Rating Dummy	897	0.867	0.339	0.000	1.000	529	0.981	0.136	0.000	1.000	368	0.704	0.457	0.000	1.000
Central Bank Budget Balance (%GDP)	856	-1.759	4.138	-32.100	18.600	515	-1.701	4.542	-32.100	18.600	341	-1.848	3.443	-13.600	9.100
Nominal effective exchange rate	897	99.904	22.041	19.859	426.521	529	99.266	10.210	70.579	135.581	368	100.820	32.165	19.859	426.521

To inspect the expected relationship between the 10-year bond yields and each of the transition risk variables, we calculate Spearman's correlation for all countries, displayed in Figure 4. Since our data includes non-normally distributed series such as the transition risk variables and includes ordinal variables, for example, the bond rating scores, these properties violate the underlying assumptions of Pearson's correlation. As a result, we examine and report the rank-based Spearman's correlation for all countries. For the majority of advanced countries, carbon dioxide emissions have a positive coefficient concerning 10-year yields, indicating that higher carbon emissions are correlated with higher yields. A notable exception is Australia, which is heavily reliant on the fossil fuel industry and is the leader in coal production per capita, producing 1,100% more than the second-largest producer per capita (Poland) within our advanced countries universe.[36] Similarly, natural resource rents display a negative relationship with 10-year bond yields in Australia. The expected positive correlation of natural resource rents with yields is observable for almost all advanced countries, and renewable energy consumption negatively affects yields for most advanced countries. Climate transition risk variables exhibit the expected coefficient signs, with notable exceptions based on economic drivers.

[36] Source: Our World in Data, BP Statistical Review of World Energy. Ranking of top coal production per capita advanced countries considered in this study, 2019: 1. Australia (144,912 kWh),2. Poland (13,711 kWh), 3. United States (12,072 kWh), 4. Canada (8,278Wh)

There is less consistency across developing countries. A similar rationale for the negative association between carbon dioxide emissions and natural resource rents with 10-year bond yields applies to South Africa, which produces 164% more coal per capita than the next largest producer in the developing countries universe considered in this study.[37] The relationship between 10-year bond yields and renewable energy consumption is more consistent across developing countries compared with the other transition risk variables. However, the results are less consistent than what is observed in advanced countries. The difference between the correlations of the two country groups implies that climate transition efforts will be more significant in determining the sovereign yield spreads of advanced countries than those of developing countries.

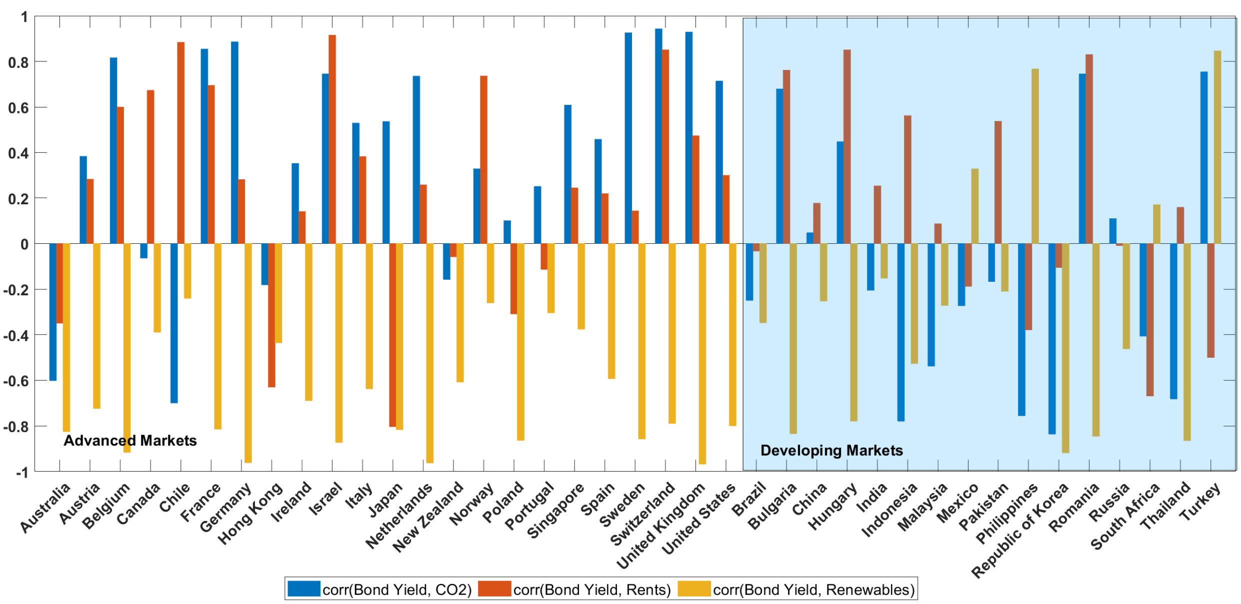


Figure 4: **Country-Based Correlations of Bond Yields and Transition Risk Variables for All Countries**
This figure presents the Spearman correlations of the 10-year bond yield with each of the transition risk variables: carbon dioxide emissions, natural resource rents and renewable energy consumption for each country. We use Spearman correlation instead of Pearson's correlation because our panel data contains non-normally distributed climate transition risk variables and ordinal sovereign bond rating scores.

[37]Source: Our World in Data, BP Statistical Review of World Energy. Ranking of top coal production per capita developing countries considered in this study, 2019: 1. South Africa (28,555 kWh), 2. Russia (17,521 kWh), 3. China (15,464 kWh), 4. Indonesia (15,447Wh)

3.3. Methodology

For this study, we consider a one-way fixed effects model, whereby the models capture country-specific heterogeneity. Fixed effects models are employed to address potential omitted variables, and for which one-way fixed effects models cleanly capture the cross-section dimensions in the panel data. The basis of using fixed effects is that aspects within the country may impact or bias the bond yields (and spreads), and this is controlled by removing the effect of time-invariant characteristics, or put another way, the variation *between* countries, so we can assess the net effect of the predictors and the bond yields (and spreads). This model provides a clear interpretation of results to address the research questions posed.

As presented in (Kropko and Kubinec, 2020), the commonly applied two-way fixed model only has such an interpretation in the difference-in-difference causal framework, for which this empirical application data structure does not meet the criteria. The two-way fixed effects model should not be thought of as a generalized form of difference-in-difference design beyond two time periods. Most importantly, the model utilized for this research requires the ability to assess the significance of transition risk factors in sovereign bond markets, which necessitates the inclusion of country-fixed effects to control for the between-country variation. Because of the restrictive assumptions and difficulty in substantive interpretation of the two-way fixed effects model, this model is only suitable in situations in which the model's interpretation exactly matches the intended research question, and the model's assumptions are taken into account, which is not supported in this research. For further discussion, both theoretically and via simulation, regarding this specification being statistically unidentified, see Kropko and Kubinec (2020).

The empirical investigation focuses on examining whether climate transition risk affects the sovereign borrowing cost across countries. Figure 5 demonstrates the heterogeneity of sovereign bond yields and spreads across the advanced and developing country groups, justifying the use of panel fixed effects regression as an estimation technique. In the subplots of Figure 5, the mean value of bond yields (spreads) by country are marked in circles, with the blue ranges indicating their respective 95% confidence intervals around the means. Figure 5 shows that the mean yields/yield spreads are different across countries for both the advanced and developing country groups, suggesting that country-fixed effect model is more appropriate than simple OLS regression.

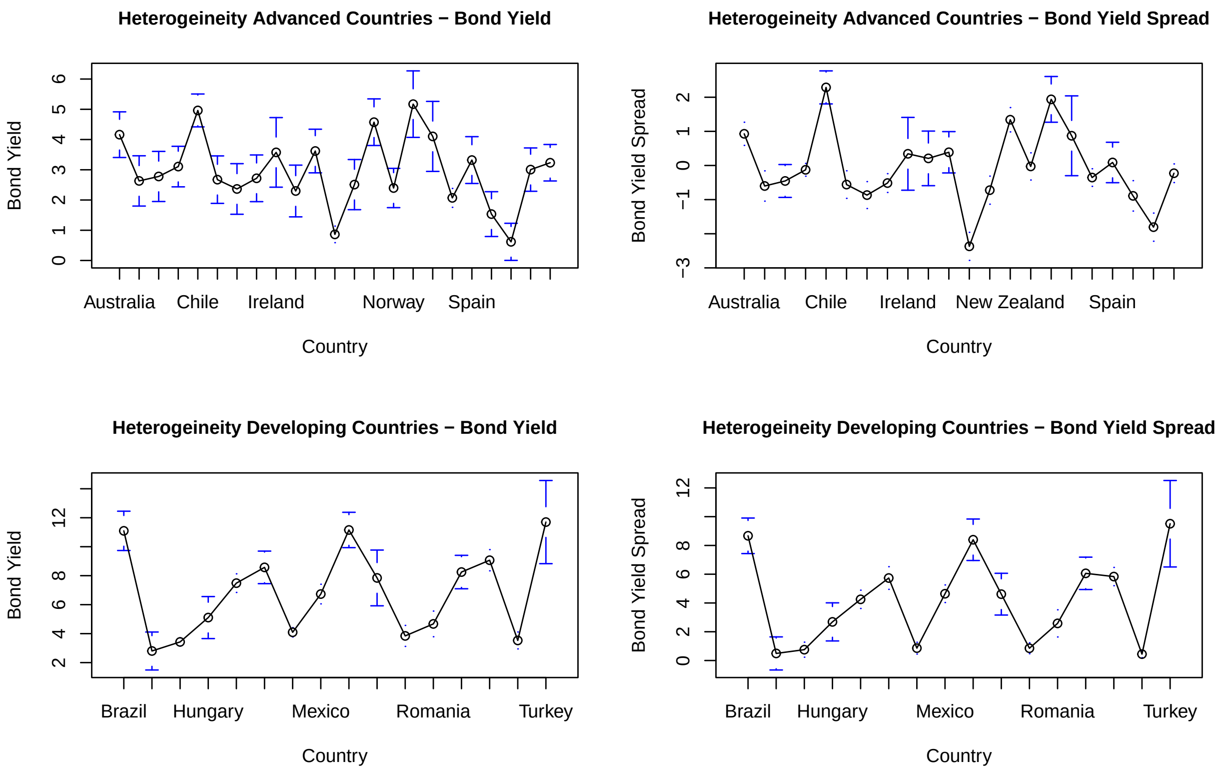


Figure 5: **Heterogeneity of sovereign bond yields and spreads across countries**
The figure displays the heterogeneity of the sovereign bond yields and spreads for the advanced country group (top panels) and the developing country group (bottom panels) between 1999 and 2021. The mean value of bond yields/bond yield spreads by country are marked in circles, with the blue ranges indicating their respective 95% confidence intervals around the means.

Equation (1) specifies the dependent variable as the 10-year government bond yield, $Y_{i,t}$, for the ith country, $i \in \{1, \ldots, N\}$ and time, $t \in \{1, \ldots, T\}$,

$$\begin{aligned} Y_{i,t} =& \gamma_1 CO2_{i,t-1} + \gamma_2 Rent_{i,t-1} + \gamma_3 Renewables_{i,t-1} + \beta_1 GDP_{i,t} + \beta_2 Growth_{i,t} + \beta_3 Inflation_{i,t} + \\ & \beta_4 Debt_{i,t} + \beta_5 Trade_{i,t} + \beta_6 Current_{i,t} + \beta_7 rating_{i,t} + \beta_8 CBBB_{i,t} + \beta_9 NEER_{i,t} + \mu_i + e_{i,t}, \end{aligned} \tag{1}$$

where the climate transition risk variables are: carbon dioxide emissions, $CO2_{i,t-1}$; natural resources rents, $Rents_{i,t-1}$; and renewable energy consumption, $Renewables_{i,t-1}$. The control variables are: GDP per capita, $GDP_{i,t}$; real GDP growth, $Growth_{i,t}$; inflation rate, $Inflation_{i,t}$; debt-to-GDP ratio, $Debt_{i,t}$; trade openness, $Trade_{i,t}$; the current account to GDP ratio, $Current_{i,t}$; Moody's sovereign credit rating, $rating_{i,t}$; the Central Bank budget balance as per cent of GDP, $CBBB_{i,t}$; and the nominal effective exchange rate, $NEER_{i,t}$. Further, μ_i are the country-specific intercepts that capture heterogeneity across countries, and $\epsilon_{i,t}$ are the idiosyncratic error terms. Equation (2) specifies the dependent variable as the 10-year government bond yield spread, $YS_{i,t}$,

$$\begin{aligned}YS_{i,t} =& \gamma_1 CO2_{i,t-1} + \gamma_2 Rent_{i,t-1} + \gamma_3 Renewables_{i,t-1} + \beta_1 GDP_{i,t} + \beta_2 Growth_{i,t} + \beta_3 Inflation_{i,t} + \\ & \beta_4 Debt_{i,t} + \beta_5 Trade_{i,t} + \beta_6 Current_{i,t} + \beta_7 rating_{i,t} + \beta_8 CBBB_{i,t} + \beta_9 NEER_{i,t} + \mu_i + e_{i,t}.\end{aligned} \tag{2}$$

As specified in (1) and (2), the models are estimated with all transition risk variables included. Additional model estimations are undertaken, where the model estimation is performed by incorporating each transition risk variable in turn (inclusive of the control variables).

The choice between fixed and random effects specifications is based on the Hausman test (Hausman, 1978). This test compares the two estimators under the null hypothesis that the model is random effects. If the null hypothesis is rejected, then the fixed effects estimator is chosen. The Lagrange multiplier test (Breusch-Pagan) (Breusch and Pagan, 1980), which assesses time effects for unbalanced panels, is also conducted. The results can be found in Appendix A.2.

The robustness of the models is assessed via several sensitivity analyses. This involves an assessment of both country groups using alternative, dependent variables of the 10-year sovereign bond yields and bond yield spreads. In addition, bond yield spreads are prone to abnormal increases. The impact of countries that demonstrate abnormal movements will be removed from the sample to assess the potential biases introduced into the results.

In similar empirical literature, it is common to include a lagged dependent variable on the right-hand side of the equation to account for persistence inherent in bond yield spreads (Gerlach et al., 2010). However, a significant concern with this inclusion is that the lagged dependent variable is serially correlated with the error terms, which makes the ordinary least square (OLS) estimators biased and inefficient (Baltagi and Chang, 1994). Nickell (1981) finds that while excluding the lagged dependent variable may result in omitted variable bias, including it creates an upward bias of its own since the lagged dependent variable is correlated with the fixed effects of the regression. Beck and Katz (2004) find that this bias can be reduced if the number of time periods is at least 20. As the sample period is 19 years and climate data are only available for annual periods, there is neither a theoretical nor empirical reason to include the lagged dependent variable. It is likely highly correlated with the entity and time effects of the panel regressions.

4. Main Results

This section evaluates the impact of carbon dioxide emissions, natural resource rents and renewable energy consumption, as measures of climate transition risk, on the generic 10-year sovereign yields and spreads denominated in local currencies between 1999 and 2021. The sampling period is determined such that it includes the earliest and the latest generic 10-year sovereign bond yield data available. The estimation results of the models are presented and discussed for advanced and developing countries. Similar to Cevik and Jalles (2022), we report robustness test results with sovereign bond yields/spreads denominated in USD in Tables A.5, A.6 and A.7 of the Appendix. We further conduct robustness checks to support the main results and discuss implications for policy and investors.

4.1. Advanced Country Group

Table 2 presents the effects of the climate transition risk indicators on the 10-year sovereign yields (left panel) and spreads (right panel) for the advanced country group.[38] In columns (1) and (3), all three climate transition risk indicators are included in the regression,[39] and to test the individual strength of these indicators, each of the climate variables is introduced one at a time in columns (2), (4), (5) and (6). Note that the signs of all significant control variables remain consistent in each regression.

4.1.1. Impact on sovereign yields

We find that carbon dioxide emissions and renewable energy consumption significantly affect advanced countries' 10-year sovereign bond yields; see columns (1)–(6) in the left panel.[40] More specifically, the coefficient of carbon dioxide emissions remains positive and highly significant at the aggregate level, as does the per capita allocation for the two model

[38] We find consistent results using dummy sovereign rating indicators as defined in Table A.2 instead of rating scores in all regressions, and the results are available upon request.

[39] Recall that carbon dioxide emissions are assessed as an aggregate measure and as carbon dioxide emissions per capital.

[40] The explanatory power of these regressions is satisfactory, with an adjusted R-squared ranging from approximately 54.4% to 61.1%.

Table 2: **Sovereign Bond Yields/Spreads and Climate Transition Risk - Advanced Countries**

The table reports the estimation results of the panel fixed effects regressions (1) and (2) between the sovereign bond yields and spreads, respectively, and the climate transition risk indicators for the group of the advanced countries. Country fixed effects have been used in all regressions. Standard errors are displayed in parentheses; $p < 0.1^{*}$, $p < 0.05^{**}$, $p < 0.01^{***}$.

	Advanced countries											
Dependent variable	Sovereign bond yields						Sovereign bond yield spreads					
	1	2	3	4	5	6	1	2	3	4	5	6
Carbon dioxide emissions	0.114	0.375***					0.272***	0.381***				
	(0.082)	(0.074)					(0.097)	(0.079)				
Carbon dioxide emmisions per capita			0.511***	0.723***					0.508***	0.548***		
			(0.095)	(0.081)					(0.097)	(0.079)		
Natural resources rents	0.446*		0.428*		0.720***		0.671***		0.655***		0.767***	
	(0.240)		(0.232)		(0.254)		(3.056)		(0.214)		(0.223)	
Renewable energy consumption	-0.165***		-0.103***			-0.205***	-0.046*		-0.011			-0.115***
	(0.028)		(0.028)			(0.022)	(0.027)		(0.026)			(0.020)
GDP per capita	-17.876***	-22.745***	-15.252***	-16.823***	-22.589***	-16.112***	-6.589***	-8.806***	-3.555**	-4.463***	-8.153***	-5.028***
	(1.871)	(1.737)	(1.842)	(1.797)	(1.800)	(1.735)	(1.718)	(1.518)	(1.675)	(1.620)	(1.565)	(1.582)
Real GDP growth	0.039	0.060**	0.041*	0.055**	0.083***	0.020	-0.039*	-0.035	-0.034*	-0.032	-0.008	-0.054***
	(0.024)	(0.024)	(0.023)	(0.022)	(0.024)	(0.021)	(0.021)	(0.021)	(0.021)	(0.020)	(0.021)	(0.020)
Inflation	0.168***	0.214***	0.154***	0.180***	0.215***	0.183***	0.372**	0.390***	0.359***	0.370***	0.395***	0.369***
	(0.049)	(0.051)	(0.048)	(0.048)	(0.052)	(0.047)	(0.045)	(0.045)	(0.044)	(0.044)	(0.045)	(0.043)
Debt-to-GDP	-0.014***	-0.013***	-0.004	-0.003	-0.020***	-0.019***	0.004	0.002	0.009**	0.007	-0.002	-0.004
	(0.005)	(0.005)	(0.005)	(0.005)	(0.005)	(0.004)	(0.004)	(0.004)	(0.004)	(0.004)	(0.004)	(0.004)
Trade openness	-2.206	-2.381	-3.676**	-3.836**	-4.600***	-1.240	1.614	3.095**	0.184	1.744	0.409	3.196**
	(1.701)	(1.606)	(1.671)	(1.519)	(1.785)	(1.509	(1.537)	(1.418)	(1.527)	(1.374)	(1.548)	(1.390)
Current account balance	-0.038	-0.042*	-0.047**	-0.053**	-0.063**	-0.013	-0.057***	-0.052**	-0.069***	-0.062***	-0.065***	-0.035*
	(0.024)	(0.024)	(0.023)	(0.023)	(0.025)	(0.022)	(0.021)	(0.021)	(0.021)	(0.021)	(0.022)	(0.020)
Credit rating scores	-0.220***	-0.081*	-0.228***	-0.157***	-0.067	-0.227***	-0.271***	-0.232***	-0.296***	-0.282***	-0.197***	-0.280***
	(0.048)	(0.044)	(0.046)	(0.043)	(0.045)	(0.047)	(0.043)	(0.040)	(0.042)	(0.040)	(0.040)	(0.043)
Central bank budget balance	-0.048**	-0.047**	-0.063***	-0.072***	-0.048**	-0.041**	-0.122***	-0.123***	-0.141***	-0.146***	-0.129***	-0.118***
	(0.021	(0.022)	(0.021)	(0.021)	(0.023)	(0.020)	(0.020)	(0.020)	(0.019)	(0.019)	(0.020)	(0.019)
Nominal effective exchange rate	-0.004	0.004	0.0003	0.007	-0.003	-0.003	0.022***	0.031***	0.026***	0.035***	0.025***	0.026***
	-0.008	-0.008	-0.008	(0.008)	-0.009	(0.008)	(0.008)	(0.007)	(0.008)	(0.007)	(0.008)	(0.007)
R^2	0.617	0.578	0.642	0.625	0.560	0.621	0.442	0.422	0.469	0.455	0.405	0.406
Adj. R^2	0.584	0.544	0.611	0.595	0.524	0.591	0.393	0.374	0.422	0.410	0.356	0.359

specifications (see columns (1) to (4)). This indicates that advanced countries experiencing an increase in carbon dioxide emissions can expect, on average, an increase in their sovereign bond yields. In addition, renewable energy consumption (as a percentage of total consumption) negatively affects the sovereign bond yields. This is significant in models (3) and (6), which account for per capita CO_2 emissions and assess the individual impact of renewable energy consumption on yields. Thus, an increase in renewable energy consumption reduces an advanced country's cost of borrowing by approximately 0.205%, an impact that remains significant when accounting for the effects of the aggregate carbon dioxide emissions.

These results provide evidence that carbon dioxide emissions directly increase a country's bond yields in advanced economies. At the same time, the negative effects of non-renewable energy also tend to increase sovereign bond yields. The results further support the finding of Chaudhry et al. (2020) that carbon emissions increase sovereign risk both economically and statistically. This allows us to draw a conclusion regarding transition risk – when countries experience an increase in emissions, they are effectively borrowing against their future, which leads to an increase in sovereign borrowing costs. Additionally, countries that prioritise consuming more renewable energy as part of their total energy mix are rewarded with a lower cost of debt. Both conclusions align with the goals of the Paris Agreement, i.e. for countries to transition towards renewable technologies and increase energy efficiency. It is clear from the three transition indicators that while energy production may contribute to economic growth, it may also increase sovereign borrowing costs, depending on whether or not it is renewable. The findings support moving towards a climate-neutral world, suggesting that countries may access fixed-income financing at a lower cost by implementing targets to cut emissions from current levels and improve the share of renewable energy in the total energy mix. These findings are highly significant for policymakers and governments, as they show that advanced countries that successfully pursue climate targets and invest in technological innovation could drive economic growth through the renewable energy sector.

4.1.2. Impact on sovereign yield spreads

As a measure of sovereign bond risk, we consider sovereign bond yield spreads, whereby we benchmark the sovereign bond yields of advanced countries against the US. The aim is to gauge the effects for countries whose yields may be directly or indirectly affected by the US yield curve, as all countries do not experience this bellwether impact in the same way. The right panel of Table 2 displays the combined and individual effects of the three climate risk indicators on sovereign yield spreads for the advanced country group.[41]

We find that both measures of carbon dioxide emissions are positively and significantly associated with sovereign bond yield spreads of advanced countries, consistent with the impact on sovereign bond yields. Furthermore, the effect of natural resource rents is also statistically significant, with a positive coefficient ranging between 0.655 and 0.767 (compare columns (1), (3) and (5)). This implies that when countries increase their carbon emissions and natural resource rents, they can expect an increase in their sovereign bond risk and borrowing cost. In addition, the impact of renewable energy consumption on bond yield spreads is negative but not always significant, a result that the exclusion of the US dataset may have biased. Thus, countries that actively increase their renewable energy consumption

[41]The explanatory power of the yield spreads regressions is lower compared to the regression for the sovereign bond yields, with an adjusted R-squared approximately at 40% compared to 59% for the yields. This may be caused by the mandatory exclusion of the US dataset from our sample in constructing the panel data for the bond yield spreads.

(relative to total energy consumption) experience a decrease in sovereign bond yields, with a marginal impact on the yield spreads.

These results illustrate that transition efforts, i.e. those that are significant for a country shifting away from carbon-intense resources, do impact sovereign yields and spreads in advanced countries. A pivotal implementation phase of the Paris Agreement began in 2020 when countries were required to submit their Nationally Determined Contributions (NDCs).[42] In light of this, the way countries manage climate transition risk during this time is likely to garner more interest from bondholders. We expect markets to price in key transition risks into the evaluation of sovereign yields and spreads more significantly in the coming years.

4.1.3. Macroeconomic fundamentals

Examining the effects of the macroeconomic fundamentals shown in Table 2, GDP per capita and real GDP growth display significantly negative coefficients for all bond yield spread models. These results align with the literature and the expected notion that countries with higher GDP and economic growth rates are better equipped to service their central government debt and, thus, to have reduced sovereign borrowing costs. Real GDP growth tends not to have a substantial effect on bond yields. Further, inflation is positively and significantly associated with sovereign bond yields and spreads, confirming that changes in the consumer price index for advanced economies serve as a strong indicator of changes in sovereign bond markets. Debt-to-GDP also positively and significantly affects yield spreads, suggesting governments with higher debt levels incur a risk premium on sovereign yield spreads. In contrast, the effect on the yields is (generally) positive but insignificant. Trade openness typically has a positive impact on yields and spreads, implying that trade is not always beneficial for country's growth and sustainability. Trade openness is key to the external solvency of a country, and high trade openness may suggest that expected trade surpluses are required to meet future foreign debt repayments. Meanwhile, higher trade openness implies a country may be able to refinance its debt in the future via trade surpluses;

[42]NDCs are a country's intended reduction in GHG emissions. For example, Switzerland was the first nation to submit its NDC to the Paris Agreement in 2015 to reduce greenhouse gas emissions by 50% by 2030, see https://www4.unfccc.int/sites/ndcstaging/PublishedDocuments/Switzerland.

country openness has also been associated with a detrimental effect on economic growth in the short term in developing countries. The effect of trade openness on yields and spreads is not significant in advanced countries. Likewise, the current account balance is not significant in advanced countries. Credit rating is highly significant at the 1% level, with a range of -0.229 to -0.161, showing that a favourable increase in rating, i.e. upgrading from Aa1 to Aaa, leads to an average decrease in the yield of approximately 0.20%.

Furthermore, we confirm the significant negative contribution of the 'quantitative easing' monetary policy on the sovereign bond markets of advanced countries, as yields and spreads are negatively and significantly related to the central bank budget balance (as per cent of GDP). In the same vein, the nominal effective exchange rate has a positive and significant coefficient, thus related to an increase in bond yields and widening of spreads. This validates the notion that the higher the nominal effective exchange rate, the higher the dependencies of one currency on other currencies, i.e. stronger pegged currencies. If a domestic currency increases against a 'basket' of other currencies inside a floating exchange rate regime, the nominal effective exchange rate will appreciate. As with all exchange rates, this helps identify which currencies store value more or less effectively. As the rate of one currency increases relative to others, and since the nominal effective exchange rate has inflation embedded, the sovereign bond yields and spreads are also likely to increase.

4.2. Developing country group

Table 3 presents the combined effect (in columns (1) and (3)) and the individual effects (in columns (2), (4)–(6)) of the climate transition risk indicators on the 10-year sovereign yields (left panel) and spreads (right panel) for the developing country group between 1999 and 2021.[43] The results for developed countries are starkly different than those for advanced countries, as explained next.

4.2.1. Impact on sovereign yields

All climate transition risk indicators are significant in explaining sovereign bond yields in developing countries, but their impact differs from those observed in advanced countries.

[43] The explanatory power of these regressions displays an adjusted R-squared ranging from 41% for yields and 32% for yield spreads.

Table 3: **Sovereign Bond Yields/Spreads and Climate Transition Risk - Developing Countries**

The table reports the estimation results of the panel fixed effects regressions (1) and (2) between the sovereign bond yields and spreads, respectively, and the climate transition indicators for the group of developing countries. Country fixed effects have been used in all regressions. Standard errors are displayed in parentheses; $p < 0.1^{*}$, $p < 0.05^{**}$, $p < 0.01^{***}$.

	Developing countries											
Dependent variable	Sovereign bond yields						Sovereign bond yield spreads					
	1	2	3	4	5	6	1	2	3	4	5	6
Carbon dioxide emissions	0.352***	0.373***					0.281***	0.290***				
	(0.071)	(0.075)					(0.070)	(0.070)				
Carbon dioxide emmisions per capita			0.413**	0.298					0.439**	0.385**		
			(0.193)	(0.204)					(0.185)	(0.186)		
Natural resources rents	-1.934***		-2.090***		-2.092***		-0.801**		-0.942**		-0.911**	
	(0.402)		(0.420)		(0.389)		(0.394)		(0.403)		(0.374)	
Renewable energy consumption	0.025		0.037			0.172***	0.013		0.025			0.100
	(0.066)		(0.069)			(0.066)	(0.065)		(0.067)			(0.062)
GDP per capita	-23.727***	-22.905***	-16.928***	-14.818***	-14.626***	-13.655***	-12.934	-12.573***	-8.066***	-7.026***	-5.728***	-4.853**
	(2.680)	(2.786)	(2.288)	(2.327)	(2.012)	(2.229)	(2.625)	(2.596)	(2.198)	(2.124)	(1.937)	(2.068)
Real GDP growth	-0.010	-0.044	-0.039	-0.074	-0.029	0.009	-0.082*	-0.097**	-0.108**	-0.125**	-0.097**	-0.037
	(0.049)	(0.051)	(0.051)	(0.054)	(0.051)	(0.048)	(0.048)	(0.048)	(0.049)	(0.049)	(0.049)	(0.045)
Inflation	0.368***	0.303***	0.363***	0.297***	0.378***	0.411***	0.342***	0.314***	0.333***	0.302***	0.350***	0.411***
	(0.053)	(0.054)	(0.056)	(0.058)	(0.055)	(0.056)	(0.052)	(0.051)	(0.054)	(0.053)	(0.053)	(0.052)
Debt-to-GDP	-0.001	0.006	0.002	0.010	0.002	0.009	0.010	0.013	0.012	0.016	0.012	0.019*
	(0.011)	(0.012)	(0.012)	(0.012)	(0.012)	(0.012)	(0.011)	(0.011)	(0.011)	(0.011)	(0.011)	(0.011)
Trade openness	4.568*	1.240	4.285	0.461	3.745	-1.297	2.452	1.082	2.425	0.726	1.744	-1.023
	(2.475)	(2.472)	(2.596)	(2.600)	(2.536)	(2.641)	(2.452)	(2.304)	(2.494)	(2.374)	(2.441)	(2.450)
Current account balance	-0.061	-0.098**	-0.074*	-0.122***	-0.093**	-0.104**	-0.095**	-0.111***	-0.100***	-0.122***	-0.121***	-0.105***
	(0.038)	(0.039)	(0.040)	(0.041)	(0.039)	(0.040)	(0.037)	(0.036)	(0.038)	(0.038)	(0.037)	(0.037)
Credit rating scores	-0.009	0.013	0.031	0.032	-0.047	0.002	-0.012	-0.004	0.037	0.032	-0.038	-0.050
	(0.099)	(0.097)	(0.107)	(0.105)	(0.096)	(0.107)	(0.097)	(0.090)	(0.103)	(0.096)	(0.092)	(0.099)
Central bank budget balance	0.058	0.047	0.083	0.061	0.049	0.031	0.019	0.014	0.048	0.038	0.011	-0.014
	(0.066)	(0.070)	(0.071)	(0.075)	(0.070)	(0.069)	(0.065)	(0.065)	(0.068)	(0.069)	(0.067)	(0.064)
Nominal effective exchange rate	0.001	-0.008	0.008	-0.001	0.008	-0.010	-0.017	-0.021***	-0.011	-0.015**	-0.012	-0.024***
	(0.008)	(0.008)	(0.008)	(0.008)	(0.008)	(0.008)	(0.008)	(0.008)	(0.008)	(0.008)	(0.008)	(0.008)
R^2	0.531	0.470	0.490	0.417	0.479	0.417	0.417	0.403	0.390	0.370	0.374	0.377
Adj. R^2	0.474	0.410	0.428	0.351	0.421	0.356	0.345	0.336	0.315	0.299	0.304	0.311

More explicitly, carbon dioxide emissions display a positive and significant coefficient of up to 0.352 at the aggregate level and up to 0.373 in the per capita allocation (see columns (1)–(4)). This attests that developing countries with increased carbon dioxide emissions could, on average, expect an increase in their sovereign borrowing costs. In contrast to advanced countries, natural resource rents negatively affect the sovereign bond yield in developing countries (see columns (1) and (3)), a result that is statistically significant at the 1% level. Thus, an increase in earnings from natural resources tends to lead to a decline in sovereign bond yields. Further, renewable energy consumption is positively associated with the sovereign bond yield and is significant in regression (3), accounting for all three transition risk indicators, and in regression (6), assessing the individual impact. Thus, even though natural resource rents and renewable energy consumption are priced in the sovereign bond yields of developing countries, their impact does not motivate alignment with the goals of the Paris Agreement. These results reveal that, in developing economies, earnings from natural resources and non-renewable energy consumption tend to decrease, on average, the country's sovereign borrowing cost. Thus, bondholders in developing countries consider pursuing economic growth and development via existing natural resources to be a higher priority than focusing on climate change transition goals. This may also suggest that developing countries may be financially constrained in their capacity to invest in new technologies, such as renewables. Thus, bondholders consider earnings from natural resources to be a sign of a better ability to repay sovereign debt.

These results underscore the unique challenges faced by low socio-economic countries that experience a greater physical climate risk and vulnerability to natural disasters. In a recent study, Cevik and Jalles (2022) focus on this physical risk, finding that higher climate vulnerability significantly increases the sovereign bond yields of developing countries. In comparison, we focus on three key indicators of transition efforts rather than physical environmental conditions. The three indicators selected are parameters a country may strive to change by committing to technological advancement, becoming less reliant on fossil-fuel-intense industries and consuming cleaner fuel sources. These actions, together with stricter environmental policies, can structurally change an economy (Sarkodie and Strezov, 2019). Implementing these changes is far easier in advanced countries, which can borrow at a lower cost, have higher GDP per capita and are more resilient to economic shocks. At a UN General Assembly committee meeting, Botswana's delegate cited adverse climate change effects that have severely hindered the country's efforts to meet the SDGs. To address these changes, the country is developing a climate policy to reduce greenhouse gas emissions by 15% by 2030. However, this will not succeed if the country does not receive partnership assistance, financing support and technology transfers (United Nations, 2019). This example supports the results of this paper, namely, the effects of climate transition risk, except for carbon emissions, are not priced into the yield spreads of developing countries.

We suggest several reasons for this. First, given that the future expected costs of transitioning depend on external support, which is highly uncertain, market participants may demand to be compensated with higher yields. Further, developing countries' yields are often more volatile, and they can be dominated by shorter-term 'noise' (e.g. geopolitical risk). Investors may be much more focused on a developing country's ability to repay debt as a function of shorter-term factors. Moreover, advanced countries have the advantage of favourable economic and political conditions to implement strategies to transition to a lower-carbon economy. In contrast, if the high natural resource rents that developing countries command are much higher than the uncertain payoff from transitioning to a carbon-neutral economy, and if the cost of transitioning is prohibitive, then it makes sense that investors would not view transition risk exposure favourably.

4.2.2. Impact on sovereign yield spreads

The regression results of the combined impact (in columns (1) and (3)) and the individual impact (in columns (2), (4)–(6)) of climate transition risk on sovereign bond yield spreads for developing countries are displayed in the right panel of Table 3. Similarly to the bond yields, carbon dioxide emissions are significant determinants of sovereign bond yield spreads at the 5% level, with the effects of CO_2 per capita being more pronounced but less significant. Thus, carbon dioxide emissions constitute one of the critical determinants of sovereign bond risk in advanced and developing countries. Similar to the bond yields, natural resource rents negatively contribute to the sovereign bond yield spreads, but the impact is not statistically significant. Potentially, investors in developing countries may be prioritising economic development through natural resource industries rather than other non-renewable energy sources. Furthermore, while renewable energy consumption is not significant for yield spreads (but significant for yields), it presents, on average, a positive coefficient. This suggests that the financial constraints on new technology and renewable energy sources in the short term for developing countries is a consistent finding within the study. These conclusions are echoed by leaders from developing countries, who have argued that resources may need to be transferred if ambitious Paris Agreement goals are to be achieved (United Nations, 2019). Ultimately, the results and conclusions related to the impact of climate transition risk on developing countries are robust to sovereign bond yield and spread measures.

4.2.3. Macroeconomic fundamentals

As expected, most macroeconomic fundamentals considered in the study are significant determinants of the sovereign bond yields in developing countries, including the GDP per capita, real GDP growth, inflation, debt-to-GDP and trade openness. Contrary to advanced countries, the current account balance plays an essential role in determining a country's sovereign borrowing cost. Indeed, trade openness positively affects bond yields and spreads, implying that trade in developing countries with substantial trade resources tends to increase their sovereign bond costs. A likely cause of this may be financial constraints, which do not allow countries to explore the comparative advantage of trade. The effect of the current account balance on sovereign bond yields is negative, emphasising the challenge faced by developing countries, which are more likely to have current account deficits and may not have the funds to finance exports. This low balance, in turn, decreases their sovereign yield spread. The relationship between credit ratings and bond yields/spreads is mixed and not significant in developing countries. Some countries, often referred to as 'frontier markets', where the amount of outstanding public debt is low, and those for which sovereign credit ratings fall below Ba3, may experience idiosyncratic issues related to market illiquidity or other restrictions. In addition, the motivations and methods employed by investors and how they differentiate between the economies of advanced and developing markets differ considerably. A study by Amstad et al. (2016) shows that the importance of the developing markets designation in recent times has led to index-tracking behaviour by investors becoming a powerful force in global bond markets. For the most part, when global investors invest in developing markets, instead of picking and choosing based on country-specific fundamentals, they appear to replicate their benchmark portfolios, where the constituents exhibit minimal change over time.

Furthermore, monetary policy regimes, such as quantitative easing, do not affect the sovereign bond markets of developing countries, while the nominal effective exchange rate negatively (and significantly) impacts bond yield spreads. Note that the volatility of nominal exchange rates may play an important role in appreciating their relation with yield spreads. Ganguly and Breuer (2010) report that the nominal exchange rates of developing countries are 3.5 times more volatile compared to those of advanced countries. A relatively more volatile NEER implies that the currency of these (developing) countries is effectively 'less pegged' to the interest rates of partner markets. Thus, countries with relatively flexible interest rates would be better positioned in terms of not being affected by exchange rate changes. Currency appreciation could be related to a tightening of bond yield spreads, i.e. when money comes in via sovereign bonds, this condenses the spreads down. This could provide an explanation for the (statistically significant) negative coefficient of the nominal effective exchange rate in relation to bond yield spreads in developing countries.

5. Sensitivity analysis

To conduct an aggregate assessment of the impact of climate transition risk on sovereign bond yields and spreads, we also examine the regressions for the entire sample of countries, 39 in total. These results are presented in Table 4.[44]

We find that, for all countries, carbon dioxide emissions are statistically significant and positively related to both sovereign bond yields and spreads, a relation that also holds for both advanced and developing countries. This underscores the dominant role of carbon dioxide emissions in determining the sovereign bond risk of countries and the positive impact of reduced carbon dioxide emissions in lowering the sovereign borrowing cost. Natural resource rents have a significant negative relation with bond yields but not with bond yield spreads. A compelling divergence emerges when compared with the results for the two country groups of advanced and developing countries. Advanced countries reducing their earnings from natural resource rents tend to be awarded lower sovereign borrowing costs while developing countries that increase their dependence on natural resources are awarded lower sovereign borrowing costs. The results on renewable energy consumption at all country levels are inconclusive. Yet, an increase in renewable energy consumption tends to reduce sovereign borrowing costs for the advanced country group and increase sovereign borrowing costs for the developing country group. These results suggest an incapacity and unwillingness of developing countries (potentially due to social-economic conditions and financial constraints) to prioritise climate change transition targets and forgo the short-term financial benefits of dependency on natural resources and invest in new technologies, such as renewable energy projects.

Furthermore, Portugal is removed from the advanced country group results as a sensitivity check to account for the abnormal increase in bond yield spreads from 2010 to 2014. We find quantitatively similar results, which further substantiate the finding that transition efforts do impact sovereign yields and spreads in advanced economies. Results are available upon request.

[44] The explanatory power of these regressions display an adjusted R-squared ranging from approximately 50% for yields and 30% for yield spreads.

Table 4: **Sovereign Bond Yields/Spreads and Climate Transition Risk - All Countries**

The table reports the estimation results of the panel fixed effects regressions (1) and (2) between the sovereign bond yields and spreads, respectively, and the climate transition risk indicators for all countries. Country fixed effects have been used in all regressions. Standard errors are displayed in parentheses; $p < 0.1^{*}$, $p < 0.05^{**}$, $p < 0.01^{***}$.

	All countries											
Dependent variable	Sovereign bond yields						Sovereign bond yield spreads					
	1	2	3	4	5	6	1	2	3	4	5	6
Carbon dioxide emissions	0.364***	0.405***					0.283***	0.297***				
	(0.043)	(0.042)					(0.043)	(0.041)				
Carbon dioxide emmisions per capita			0.563***	0.622***					0.412***	0.429***		
			(0.080)	(0.072)					(0.079)	(0.070)		
Natural resources rents	-0.737***		-0.863***		-0.561**		0.034		-0.052		0.060	
	(0.218)		(0.221)		(0.229)		(0.206)		(0.207)		(0.207)	
Renewable energy consumption	-0.085***		-0.064**			-0.140***	-0.024		-0.011			-0.077***
	(0.027)		(0.029)			(0.025)	(0.025)		-0.0247			(0.023)
GDP per capita	-21.092***	-22.863***	-15.728***	-16.406***	-16.390***	-12.022***	-8.611***	-9.375***	-4.373***	-4.630***	-4.254***	-1.835*
	(1.449)	(1.273)	(1.204)	(1.076)	(1.143)	(1.205)	(1.390)	(1.205)	(1.127)	(0.992)	(1.031)	(1.088)
Real GDP growth	0.007	0.020	0.004	0.012	0.031	0.003	-0.061***	-0.055***	-0.063***	-0.060***	-0.046**	-0.056**
	(0.023)	(0.022)	(0.023)	(0.023)	(0.024)	(0.023)	(0.021)	(0.021)	(0.022)	(0.021)	(0.022)	(0.021)
Inflation	0.288***	0.287***	0.282***	0.271***	0.343***	0.341***	0.319***	0.324***	0.316***	0.316***	0.356***	0.379***
	(0.034)	(0.034)	(0.035)	(0.035)	(0.036)	(0.035)	(0.032)	(0.032)	(0.033)	(0.032)	(0.033)	(0.032)
Debt-to-GDP	-0.009**	-0.007*	-0.002	0.001	-0.014***	-0.009*	0.005	0.004	0.010**	0.010**	0.004	0.005
	(0.004)	(0.004)	(0.005)	(0.005)	(0.005)	(0.005)	(0.004)	(0.004)	(0.004)	(0.004)	(0.004)	(0.004)
Trade openness	1.472	-0.821	-0.062	-2.509**	-3.951***	-3.592***	2.618**	2.457**	1.301	1.029	-0.944	-0.016
	(1.351)	(1.239)	(1.343)	(1.212	(1.327)	(1.286)	(1.276)	(1.165)	(1.258)	(1.127)	(1.199)	(1.169)
Current account balance	-0.040*	-0.053**	-0.043**	-0.057***	-0.056**	-0.046**	-0.069***	-0.069***	-0.071***	-0.071***	-0.074***	-0.058***
	(0.021)	(0.021)	(0.021)	(0.021)	(0.022)	(0.022)	(0.020)	(0.019)	(0.020)	(0.019)	(0.020)	(0.020)
Credit rating scores	-0.120***	-0.052	-0.120***	-0.071*	-0.021	-0.156***	-0.197***	-0.178***	-0.196***	-0.189***	-0.146***	-0.228***
	(0.045)	(0.040)	(0.046)	(0.041)	(0.043)	(0.048)	(0.043)	(0.037)	(0.043)	(0.038)	(0.039)	(0.044)
Central bank budget balance	-0.035	-0.031	-0.047**	-0.044*	-0.030	-0.022	-0.088***	-0.088***	-0.097***	-0.098***	-0.089***	-0.087***
	(0.023)	(0.023)	(0.024)	(0.024)	(0.025)	(0.024)	(0.022)	(0.022)	(0.022)	(0.022)	(0.023)	(0.022)
Nominal effective exchange rate	0.002	-0.005	0.007	0.001	-0.004	-0.009*	-0.003	-0.003	0.001	0.001	-0.005	-0.008*
	(0.005)	(0.005)	(0.005)	(0.005)	(0.005)	(0.005)	(0.005)	(0.005)	(0.005)	(0.005)	(0.005)	(0.005)
R^2	0.522	0.510	0.507	0.495	0.441	0.450	0.372	0.371	0.357	0.356	0.317	0.335
Adj. R^2	0.484	0.472	0.468	0.457	0.399	0.410	0.322	0.323	0.305	0.307	0.265	0.287

6. Conclusion and Implications for Policy and Investors

Since the inauguration of the Paris Agreement, investors have become increasingly focused on understanding the impact of climate risks on sovereign debt markets. A limited body of literature has examined the impacts of physical climate risks, such as a country's vulnerability and resilience to climate shocks and its effect on sovereign bond yields (Beirne et al., 2021, Cevik and Jalles, 2022, Kling et al., 2018). Many physical risks are primarily associated with geographic location and vulnerability to natural disasters. The impact of climate transition risk is crucial for understanding the full extent of climate change, which has immediacy because transition risks materialise much faster than physical risks. Considerations should include the short-term opportunity cost of decreasing reliance on fossil-fuel-intense industries, focusing on renewable energy supply and consumption and impacts on sovereign borrowing costs.

This paper assesses the significance of carbon dioxide emissions, natural resource rents and renewable energy as determinants of sovereign bond yields and spreads. These variables are regressed, along with conventional macroeconomic fundamentals, on sovereign yield spreads for a sample of 39 countries between 1999 and 2021. The sample includes advanced and developing countries, with a diverse range of countries ranked from poor to satisfactory in climate performance. We find a strong positive association between carbon dioxide emissions and sovereign yields and spreads in both country groups. Further, in advanced markets, natural resource rents have a strong positive association, while renewable energy has a negative association with yields and spreads. In contrast, in developing markets, natural resource rents and sovereign yields/spreads are negatively associated, while renewable energy and sovereign yields/spreads are positively associated. Developing economies are less likely to have the resources needed to facilitate a transition from fossil fuel reliance to renewables, and thus they seem not to prioritise climate change targets. The relatively high natural resource rents may explain the negative association between the resource rents that developing markets earn compared to the high cost of transitioning to a clean economy. Investors may value the net present value of the payoff from a transition to renewables at less than that of natural resource rents (in the nearer term). In this case, these countries may suffer more significant transition opportunity costs over the longer term. This research supports the finding that investors in sovereign bond markets price climate transition risk factors in the evaluation of sovereign risk.

The evidence presented in this paper has clear implications for policymakers. Since sovereign bond markets are the benchmark from which every other asset class is priced, safe-haven assets and providers of liquidity to the banking sector and governments, the global financial system is highly dependent on them functioning well. While estimates vary in terms of reducing net carbon emissions to zero, it's estimated that to achieve the goals set out by the Paris Agreement by 2050, spending of $50 trillion will be required. This expenditure will be largely financed by governments, with a sizable proportion of this spending allocated to renewable technology. This research shows that prioritising renewable energy supply and consumption while forgoing the short-term opportunity cost of decreased revenue from natural resources would benefit from lowering the cost of borrowing in the sovereign debt market. Cheaper financing may counteract any short-term losses that industries may face from re-evaluating assets. Further, the savings made on funding could be invested into renewable technologies and a just transition away from sectors in decline, such as the fossil fuel industry. Conversely, developing countries that are highly dependent on natural resources are also associated with lower sovereign borrowing costs. A possible reason for this is that the cost of transitioning is high for developing countries, which are forced to rely on uncertain support from other nations for their climate mitigation. Thus, investors may focus instead on short-term factors, such as a developing country's ability to repay debt and the fact that the profits from high natural resource rents may be higher than the uncertain payoff of transition. While yields will rise when carbon emissions increase, they will fall when earnings from natural resources rise, and perversely, yields will also rise when renewable energy consumption increases. This suggests that investors in developing countries' debt prioritise the pursuit of economic growth and profits from natural resources over climate transition goals.

The sovereign debt market is one of the largest asset classes globally and has significant exposure to the full gambit of climate risks. However, unlike equities and even corporate debt markets, the integration of climate change considerations into the investment process has lagged significantly. While equities investors, for example, can consider a plethora of environmentally aware stocks, exchange-traded funds with environmental thematics and others, government bonds have been largely overlooked by investors and, indeed, policymakers. If we couple this with the fact that fixed-income allocations are typically a large component of asset owners' portfolios, focusing on environmental considerations in the equity component falls well short of a multi-asset approach. Moreover, asset owners recognise the impact climate changes can have on government spending, which in turn affects government bond yields. It is undeniable that governments are exposed to transition risk. Whether it is considered through the channel of impacting yields directly or indirectly via macroeconomic variables such as GDP, investors are already starting to penalise advanced countries with poor prospects of transitioning away from fossil fuels. There is clear evidence of a material impact of both transition and physical risks on government debt. These risks are already being priced into government bond spreads alongside traditional risk measures.

Investors will penalise advanced countries with poor prospects of transitioning away from fossil fuels, and they will gauge the impact on a country's future GDP if its economy relies on declining industries. For example, a country's climate risk management reputation may impact the demand for its debt. Swedish Central Bank is one of the first central banks to divest government assets from issuers with a high climate footprint, even if macroeconomic fundamentals are favourable. Looking to the future, governments that perform poorly in managing their climate change transition may encounter difficulty finding investors to buy their sovereign debt. Consequently, liquidity might become an issue, likely increasing the sovereign yield spreads. In a scenario where a country experiences severe climate shocks or natural disasters, this increased yield spread could have ripple effects on its ability to finance its economic recovery.

The findings of this paper give sovereign bond market participants a clear argument to request greater government transparency regarding specific climate risks, strategies and policies that are inherently linked to the bonds they issue. Furthermore, there is growing awareness that timely implementation of climate policies is necessary to achieve climate targets. For now, the approach used in this analysis gives bond fund managers, investors and policymakers a way to assess a country's transition risk that aligns directly with the SDGs, with the advantage of using publicly available data sources.

Ultimately, when Mark Carney spoke the words 'climate change is a tragedy of the horizon which imposes a cost on future generations that the current one has no direct incentive to fix' (Carney, 2015, page 3), he may not have realised that sovereign debt markets were already beginning to impose a cost for climate transition risk directly. In summary, carbon dioxide emissions and natural resources not only negatively affect the environment and inhibit progression towards climate goals but also increase a country's cost to borrow in debt markets. Importantly, the adoption of renewable energy is an economically and statistically significant mitigation strategy, as the supply and consumption of clean fuel sources could drive economic growth, counteracting any short-term financial losses from the non-renewable energy sector.

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Appendix A. Appendix

Appendix A.1. Variables

Table A.1: **Description of Variables**

The table lists the variables used in the study with a brief description of the variables and their data source.

Variable	Data Source	Definition
Sovereign bond yield	Bloomberg	A country's 10-year bond yield
Sovereign bond spread	Bloomberg	A country's 10-year bond yield minus the US treasury bond of the same maturity
Carbon dioxide emissions	Our World in Data	CO_2 emissions from the burning of fossil fuels for energy and cement production
Carbon dioxide emissions per capita	Our World in Data	Total CO_2 emissions divided by population
Natural resources rents	World Bank	Sum of oil, natural gas, coal, mineral and forest rents, divided by GDP
Renewable energy consumption	Our World in Data	Renewable energy consumption (% of total final energy consumption)
GDP per capita	World Bank	A country's current international dollars GDP divided by the mid-year population.
Real GDP growth	World Bank	A country's growth rate based on real GDP figures
Inflation	World Bank	Year-on-year percentage change in Consumer Price Index
Debt-to-GDP IMF	World Economics Outlook Database	Central government gross debt divided by GDP
Trade openness	World Bank	Sum of Exports and Imports divided by GDP
Current account balance	World Bank	Current account balance divided by GDP
Sovereign bond rating	Bloomberg	Moody's historical ratings for local currency long-term government bond.
Central Bank Budget Balance	Bloomberg	Central bank balance sheet divided by GDP
Nominal Effective Exchange Rate	BIS and IMF	An index of some weighted average of bilateral exchange rates

Appendix A.1.1. Extended description of control variables

Consistent with the literature on sovereign bond yield and spread determinants, seven control variables are included in the fixed effects regression analysis. This section provides an additional description of the expected relation to sovereign yield spread. Control variables *GDP per capita*, *Real GDP growth*, *inflation*, *Trade Openness* and *current account balance* are extracted from the World Bank database. *Debt-to-GDP* ratio is extracted from the IMF World Economic Outlook database. Historical *sovereign credit ratings* have been obtained from Bloomberg and represents Moody's historical ratings for local currency long-term government bonds. For summarised definitions of the control variables, please refer to Table A.1.

GDP per capita, measures the total monetary value of all goods and services produced in a country in each period over its total population, and it is the current international dollars GDP divided by the mid-year population. It is converted by a purchasing power parity conversion factor that controls for price level differences between countries.[45] The coefficient of this estimator is expected to be negative, as a higher GDP per capita indicates a more favourable economic position. As a result, a lower sovereign yield spreads as the country is better able to service its debt.

Real GDP growth is the annual percentage growth rate of GDP at market prices based on constant local currency, which measures the year-on-year per cent change in productivity across the sample countries. Constant series are used to measure the true growth of a series,

[45] The per capita values for the gross domestic product (GDP) are expressed in current international dollars converted by purchasing power parity (PPP) conversion factor. The conversion factor is a spatial price deflator and currency converter controlling price level differences between countries. The total population is a mid-year population based on the de facto definition of population, which counts all residents regardless of legal status or citizenship.

i.e. adjusting for the effects of price inflation. In contrast, the current series is influenced by the impact of price inflation. Higher GDP growth rates in countries are expected to have a negative association with the sovereign yield spread, as they are better equipped to service debt in the future Cantor and Packer (1996).

The *inflation* measure is calculated as the per cent change in the Consumer Price Index (CPI), which measures price changes related to the spending pattern and consumption of households. The effect of inflation on bond yield spread remains somewhat ambiguous, as early studies identified inflation as a signal of how well a country can manage its fiscal balances Min (1998). The higher the inflation, typically, the more economically in-stable the country is. Conversely, countries with higher inflation rates have a larger tax base on which to pay their debt in real terms, which would imply a negative association with the yield spread Nickel et al. (2011). Due to the ambiguity of this effect, the sign coefficient may be different depending on the country group.

The *Debt-to-GDP* ratio is calculated as central government gross debt relative to GDP. Laubach (2009) studies a 30-year sample of government debt and treasury yields, finding a debt-to-GDP has a statistically significant effect on government borrowing cost. The variable is expected to have a positive coefficient sign. Countries with higher debt levels proportional to their GDP are considered less creditworthy and likely to pay a higher cost of debt.

Trade Openness is calculated as the sum of exports plus imports of goods and services as a per cent of gross GDP. It measures the scale of trade in an economy relative to the size of that country. Trade openness has a positive effect on economic growth both in the short and long run, particularly for developing countries (You et al., 2015, Keho, 2017). There is an argument that trade openness may affect the sustainability of a country, as the higher the trade openness, the more a country captures comparative advantages concerning its resources. However, some very large economies exhibit low trade openness, e.g. the United States, which may suggest its significance concerning advanced countries has diminished over time. Suppose one assumes that trade is fundamentally beneficial for growth, allowing governments to monetise their comparative advantages. In that case, the estimation of trade openness is expected to contribute to positive sustainability outcomes, thus having a negative association with sovereign yield spread. They are signifying that an increase in trade openness will lead to a decrease in sovereign borrowing costs.

A country's *current account balance* is taken relative to GDP. The calculation of the current account balance is the total net exports from goods and services, net primary income, and net secondary income. This variable is expected to negatively affect yield spread, as it indicates a country's competitiveness in the global market and ability to raise money for debt servicing. A current account deficit is more likely to be observed in developing countries, as they may not receive enough funds from exports to finance their imports. Hence, a larger current account balance is more favourable, and a lower yield spread is expected to follow any increases to a country's current account.

The most prominent credit rating agencies globally are Moody's, Standard & Poor, and Finch, with Moody *Sovereign credit ratings* being utilized for this research. Moody's was the first rating agency to consider both physical and transition climate change risks in sovereign rating assessments in response to the Paris Agreement in 2015 Mathiesen (2018). While Moody's does not disclose how much weight they give climate change risk when assessing countries' ratings, they do shed light on their climate change methodology. The methodology focuses on exposure and resilience to physical climate change factors and their effect on a sovereign's ability and willingness to repay debt Praagh et al. (2016). Although this methodology has only been applied to credit ratings in recent years, it will be important for future empirical research of a similar nature. Moreover, Cantor and Packer (1996) conducted an event market study into credit rating changes, showing announcements of upgrades and downgrades are followed by statistically significant bond yield movements in the intuitive direction. To account for country rating changes that may have occurred within the sample time period, credit ratings are applied on a yearly basis to all models in the analysis. The ratings have been transformed from their alphabetical value to a numerical value in accordance with the knowledge that higher sovereign credit ratings are associated with lower yield spreads Afonso et al. (2015). Using a similar format as Gaillard (2012) and Safiullah et al. (2021), an Aaa rating converts to 21, and a C converts to 1, Table A.2.

The *Central Bank Budget Balance as per cent of GDP (CBBB)* is a proxy for central bank monetary policy regimes, such as quantitative easing (QE) or quantitative tightening (QT). Past literature has shown that central bank QE policy (e.g., bond purchase programs in the Federal Reserve and European Central Bank) lowers long-term bond yields (e.g. Broeders et al., 2022, Vissing-Jorgensen, 2021, Balcilar et al., 2020, Hofmann and Takáts, 2015). We believe it is important not only to account for US QE, but also QE of other central banks, e.g., ECB, Bank of Japan etc., and the measure of *CBBB* is a standard and straightforward way of achieving this goal. In addition, CBBB is easily available in a standard database such as Bloomberg. We did not use a dummy indicator for the QE as in Broeders et al. (2022) because the dummy QE measure will be stable across time, leading to problems in our panel regression.

The *nominal effective exchange rate (NEER)* is an indirect measure of whether a local currency is likely pegged to another currency. The *NEER* is an index proposed by the Bank of International Settlements (BIS), and the variation of this measure accounts for the free float of a local currency compared with its base currency. Base currency is the largest trade partner of a country/market. The less volatile the NEER, the more likely that a currency is either pegged in practice or is effectively pegged because its interest rates move in line with the interest rates of trading partners. The reason we include this control is due to the potential counteractive impacts in government bond yields if a market has its currency pegged to the other currency while the two markets have different monetary policies. Obstfeld (2021) finds that countries with a flexible exchange rate are far better positioned in their financial policy than those that have their interest rates pegged to other currencies. The NEER data is from BIS Statistic Explorer broad indices (`https://stats.bis.org/statx/toc/XR.html`) except for Pakistan, which is from the International Monetary Fund (IMF) Data. The reason we do not prefer the IMF NEER data is because it is either weighted by the CPI of the main trading partner (base currency) or weighted by the unit costs of labour of main trade partner. Hence, BIS definition is more appealing.

Table A.2: **Credit Rating Numerical Transformation**

This table shows the numerical transformation of the credit rating. The ratings have been transformed from their alphabetical value to a numerical value in accordance with the knowledge that higher sovereign credit ratings are associated with lower yield spreads (Afonso et al., 2015). Using the same format as Safiullah et al. (2021), an Aaa rating converts to 21 and a C or lower converts to 1.

Moody's Rating	Numerical Transformation	Rating Dummy
Aaa	21	1
Aa1	20	1
Aa2	19	1
Aa3	18	1
A1	17	1
A2	16	1
A3	15	1
Baa1	14	1
Baa2	13	1
Baa3	12	1
Ba1	11	0
Ba2	10	0
Ba3	9	0
B1	8	0
B2	7	0
B3	6	0
Caa1	5	0
Caa2	4	0
Caa3	3	0
Ca	2	0
C	1	0

Appendix A.1.2. Climate Change Performance Index (CCPI) of countries

Table A.3: **Full List of Countries with CCPI Rating**

The table presents a list of the countries used in the study and their Climate Change Performance Index (CCPI). The categorisation of countries as advanced or developing is informed by the United Nations country classification. CCPI rating is based on 2019 rankings, as this is the final year of the sample dataset. Very low indicates poor climate performance relative to other countries, similarly very high indicates high climate performance. NR indicates the country is not rated.

Advanced (23)	*CCPI* Rating	Developing (16)	*CCPI* Rating
Australia	Very low	Brazil	Medium
Austria	Low	Bulgaria	Low
Belgium	Medium	China	Medium
Canada	Very low	Hungary	Low
Chile	NR	India	High
France	High	Indonesia	Low
Germany	Medium	Malaysia	Very low
Hong Kong	NR	Mexico	Medium
Ireland	Very low	Pakistan	NR
Israel	NR	Philippines	NR
Italy	Medium	Republic of Korea	Very low
Japan	Very low	Romania	Medium
Netherlands	Medium	Russian Federation	Very Low
New Zealand	Low	South Africa	Low
Norway	High	Thailand	Low
Poland	Low	Turkey	Very low
Portugal	High		
Singapore	NA		
Spain	Low		
Sweden	High		
Switzerland	High		
United Kingdom	High		
United States	Very low		

Appendix A.2. Additional Results

The choice between fixed and random effects specifications is based on the Hausamn Test (Hausman, 1978). The Hausman test is based on the comparison of two sets of estimates (Hausman, 1978) Specification testing in panel models, in essence, involves testing for poolability and for time unobserved effects. This test compares the two estimators under the null that the model is random effects. Suppose the null hypothesis is rejected, then the fixed effects estimator is chosen. The Lagrange Multiplier Test (Breusch-Pagan) (Breusch and Pagan, 1980) testing for time effects for unbalanced panels is conducted, along with the F test for individual effects. The results are presented in Table A.4

Table A.4: **Hausman Test and Lagrange Multiplier Test (Breusch-Pagan)**

The table displays the Hausman Test and Breusch-Pagan Lagrange multiplier statistics for the advanced and developing country models. We consider both the 10-year bond yield model (1) and the 10-year bond yield spread model (2). For all cases, the Hausman test rejects the null hypothesis at the 5% level. Therefore we use fixed effects. The Lagrange Multiplier Test (Breusch- Pagan) and the F test reject the null hypothesis that no time-fixed effects are needed for the advanced countries and the developing country 10-year bond yield models. However, for the developing country's 10-year yield spread model (2), the Lagrange Multiplier test fails to reject the null hypothesis, whereas the F-test rejects the null hypothesis. We proceed with using time-fixed effects for all models

Country	Hausman Test χ^2 test-stat (p-value)	Lagrange Multiplier Test $C\chi^2$ test-stat (p-value)	F-test F-stat (p-value)
Advanced			
10 Year Bond Yield (full model)	167.52 (¡2.2e-16)	164.86 (¡2.2e-16)	10.009 (¡2.2e-16)
10 Year Bond Yield Spread (full model)	62.879 (3.724e-10)	759.26 (¡2.2e-16)	11.229 (¡2.2e-16)
Developing			
10 Year Bond Yield (full model)	111.69 (¡2.2e-16)	4.3771 (0.03643)	1.8091 (0.02716)
10 Year Bond Yield Spread (full model)	116.21 (2.2e-16)	1.7406 (0.187)	2.1759 (0.005318)

Table A.5: **Sovereign Bond Yields/Spreads in USD and Climate Transition Risk - Advanced Countries**

The table reports the estimation results of the panel fixed effects regressions (1) and (2) between the sovereign bond yields and spreads denominated in USD rather than local currencies and the climate transition risk indicators for the group of the advanced countries. Country fixed effects have been used in all regressions. Standard errors are displayed in parentheses; $p < 0.1^{*}$, $p < 0.05^{**}$, $p < 0.01^{***}$.

	Advanced countries											
Dependent variable	Sovereign bond yields						Sovereign bond yield spreads					
	1	2	3	4	5	6	1	2	3	4	5	6
Carbon dioxide emissions	0.114	0.375***					0.272***	0.381***				
	(0.082)	(0.074)					(0.097)	(0.079)				
Carbon dioxide emmisions per capita			0.511***	0.723***					0.508***	0.548***		
			(0.095)	(0.081)					(0.097)	(0.079)		
Natural resources rents	0.446*		0.428*		0.720***		0.671***		0.655***		0.767***	
	(0.240)		(0.232)		(0.254)		(3.056)		(0.214)		(0.223)	
Renewable energy consumption	-0.165***		-0.103***			-0.205***	-0.046*		-0.011			-0.115***
	(0.028)		(0.028)			(0.022)	(0.027)		(0.026)			(0.020)
GDP per capita	-17.876***	-22.745***	-15.252***	-16.823***	-22.589***	-16.112***	-6.589***	-8.806***	-3.555**	-4.463***	-8.153***	-5.028***
	(1.871)	(1.737)	(1.842)	(1.797)	(1.800)	(1.735)	(1.718)	(1.518)	(1.675)	(1.620)	(1.565)	(1.582)
Real GDP growth	0.039	0.060**	0.041*	0.055**	0.083***	0.020	-0.039*	-0.035	-0.034*	-0.032	-0.008	-0.054***
	(0.024)	(0.024)	(0.023)	(0.022)	(0.024)	(0.021)	(0.021)	(0.021)	(0.021)	(0.020)	(0.021)	(0.020)
Inflation	0.168***	0.214***	0.154***	0.180***	0.215***	0.183***	0.372**	0.390***	0.359***	0.370***	0.395***	0.369***
	(0.049)	(0.051)	(0.048)	(0.048)	(0.052)	(0.047)	(0.045)	(0.045)	(0.044)	(0.044)	(0.045)	(0.043)
Debt-to-GDP	-0.014***	-0.013***	-0.004	-0.003	-0.020***	-0.019***	0.004	0.002	0.009**	0.007	-0.002	-0.004
	(0.005)	(0.005)	(0.005)	(0.005)	(0.005)	(0.004)	(0.004)	(0.004)	(0.004)	(0.004)	(0.004)	(0.004)
Trade openness	-2.206	-2.381	-3.676**	-3.836**	-4.600***	-1.240	1.614	3.095**	0.184	1.744	0.409	3.196**
	(1.701)	(1.606)	(1.671)	(1.519)	(1.785)	(1.509	(1.537)	(1.418)	(1.527)	(1.374)	(1.548)	(1.390)
Current account balance	-0.038	-0.042*	-0.047**	-0.053**	-0.063**	-0.013	-0.057***	-0.052**	-0.069***	-0.062***	-0.065***	-0.035*
	(0.024)	(0.024)	(0.023)	(0.023)	(0.025)	(0.022)	(0.021)	(0.021)	(0.021)	(0.021)	(0.022)	(0.020)
Credit rating scores	-0.220***	-0.081*	-0.228***	-0.157***	-0.067	-0.227***	-0.271***	-0.232***	-0.296***	-0.282***	-0.197***	-0.280***
	(0.048)	(0.044)	(0.046)	(0.043)	(0.045)	(0.047)	(0.043)	(0.040)	(0.042)	(0.040)	(0.040)	(0.043)
Central bank budget balance	-0.048**	-0.047**	-0.063***	-0.072***	-0.048**	-0.041**	-0.122***	-0.123***	-0.141***	-0.146***	-0.129***	-0.118***
	(0.021	(0.022)	(0.021)	(0.021)	(0.023)	(0.020)	(0.020)	(0.020)	(0.019)	(0.019)	(0.020)	(0.019)
Nominal effective exchange rate	-0.004	0.004	0.0003	0.007	-0.003	-0.003	0.022***	0.031***	0.026***	0.035***	0.025***	0.026***
	-0.008	-0.008	-0.008	(0.008)	-0.009	(0.008)	(0.008)	(0.007)	(0.008)	(0.007)	(0.008)	(0.007)
R^2	0.617	0.578	0.642	0.625	0.560	0.621	0.442	0.422	0.469	0.455	0.405	0.406
Adj. R^2	0.584	0.544	0.611	0.595	0.524	0.591	0.393	0.374	0.422	0.410	0.356	0.359

Table A.6: **Sovereign Bond Yields/Spreads in USD and Climate Transition Risk - Developing Countries**

The table reports the estimation results of the panel fixed effects regressions (1) and (2) between the sovereign bond yields and spreads denominated in USD rather than local currencies, and the climate transition risk indicators for the group of the developing countries. Country fixed effects have been used in all regressions. Standard errors are displayed in parentheses; $p < 0.1^{*}$, $p < 0.05^{**}$, $p < 0.01^{***}$.

	Developing countries											
Dependent variable	Sovereign bond yields						Sovereign bond yield spreads					
	1	2	3	4	5	6	1	2	3	4	5	6
Carbon dioxide emissions	0.328***	0.347***					0.256***	0.263***				
	(0.072)	(0.075)					(0.071)	(0.072)				
Carbon dioxide emmisions per capita			0.454**	0.336*					0.481**	0.423**		
			(0.192)	(0.202)					(0.187)	(0.188)		
Natural resources rents	-1.510***		-1.665***		-1.851***		-0.376		-0.516		-0.669*	
	(0.404)		(0.418)		(0.391)		(0.401)		(0.407)		(0.381)	
Renewable energy consumption	0.107		0.120*			0.214***	0.095		0.108			0.141**
	(0.067)		(0.069)			(0.066)	(0.066)		(0.067)			(0.063)
GDP per capita	-23.729***	-22.367***	-17.754***	-15.126***	-14.611***	-14.115***	-12.937***	-12.035***	-8.891***	-7.334***	-5.713***	-5.313**
	(2.697)	(2.780)	(2.281)	(-0.084)	(2.020)	(2.225)	(2.677)	(2.643)	(2.221)	(2.144)	(1.970)	(2.104)
Real GDP growth	-0.016	-0.054	-0.045	-0.084	-0.042	0.009	-0.088*	-0.107**	-0.115**	-0.135***	-0.109**	-0.037
	(0.049)	(0.051)	(0.051)	(0.053)	(0.051)	(0.048)	(0.049)	(0.049)	(0.050)	(0.050)	(0.050)	(0.045)
Inflation	0.332***	0.267***	0.324***	0.259***	0.335***	0.386***	0.306***	0.279***	0.294***	0.264***	0.307***	0.387***
	(0.053)	(0.054)	(0.056)	(0.057)	(0.055)	(0.056)	(0.053)	(0.052)	(0.054)	(0.053)	(0.054)	(0.053)
Debt-to-GDP	0.001	0.009	0.004	0.013	0.006	0.009	0.012	0.016	0.014	0.019	0.016	0.019*
	(0.011)	(0.012)	(0.012)	(0.012)	(0.012)	(0.012)	(0.011)	(0.011)	(0.011)	(0.011)	(0.011)	(0.012)
Trade openness	3.324	1.026	3.188	0.397	3.185	-2.031	1.209	0.869	1.328	0.663	1.184	-1.757
	(2.491)	(2.467)	(2.588)	(2.573)	(2.546)	(2.636)	(2.472)	(2.345)	(2.520)	(2.395)	(2.483)	(2.492)
Current account balance	-0.079**	-0.107***	-0.088**	-0.126***	-0.104***	-0.107***	-0.113***	-0.119***	-0.114**	-0.126***	-0.132***	-0.109***
	(0.038)	(0.039)	(0.040)	(0.041)	(0.039)	(0.040)	(0.038)	(0.037	(0.039)	(0.038)	(0.038)	(0.038)
Credit rating scores	-0.005	-0.033	0.043	-0.007	-0.086	-0.010	-0.008	-0.050	0.048	-0.006	-0.078	-0.062
	(0.099)	(0.096)	(0.106)	(0.104)	(0.096)	(0.107)	(0.098)	(0.092)	(0.104)	(0.097)	(0.094)	(0.101)
Central bank budget balance	0.131**	0.122*	0.161**	0.140*	0.123*	0.092	0.092	0.089	0.126*	0.116*	0.085	0.047
	(0.067)	(0.070)	(0.071)	(0.075)	(0.070)	(0.069)	(0.066)	(0.067)	(0.069)	(0.070)	(0.068)	(0.065)
Nominal effective exchange rate	0.004	-0.001	0.010	0.005	0.013	-0.004	-0.014	-0.014**	-0.009	-0.010	-0.007	-0.018**
	(0.008)	(0.008)	(0.008)	(0.008	(0.008)	(0.008)	(0.008)	(0.008)	(0.008)	(0.008)	(0.008)	(0.008)
R^2	0.514	0.459	0.481	0.415	0.462	0.411	0.377	0.364	0.360	0.240	0.334	0.341
Adj. R^2	0.454	0.399	0.418	0.349	0.402	0.348	0.301	0.292	0.281	0.266	0.259	0.272

Table A.7: **Sovereign Bond Yields/Spreads in USD and Climate Transition Risk - All Countries**

The table reports the estimation results of the panel fixed effects regressions (1) and (2) between the sovereign bond yields and spreads denominated in USD rather than local currencies, and the climate transition risk indicators for the group of the all countries. Country fixed effects have been used in all regressions. Standard errors are displayed in parentheses; $p < 0.1^{*}$, $p < 0.05^{**}$, $p < 0.01^{***}$.

	All countries											
Dependent variable	Sovereign bond yields						Sovereign bond yield spreads					
	1	2	3	4	5	6	1	2	3	4	5	6
Carbon dioxide emissions	0.358***	0.391***					0.276***	0.281***				
	(0.043)	(0.042)					(0.044)	(0.041)				
Carbon dioxide emmisions per capita			0.582***	0.620***					0.435***	0.428***		
			(0.080)	(0.072)					(0.080)	(0.071)		
Natural resources rents	-0.585***		-0.681***		-0.440*		0.183		0.102		0.178	
	(0.219)		(0.221)		(0.228)		(0.208)		(0.209)		(0.208)	
Renewable energy consumption	-0.069***		-0.044			-0.129***	-0.009		0.009			-0.066***
	(0.027)		(0.029)			(0.025)	(0.025)		(0.027)			(0.023)
GDP per capita	-21.404***	-22.843***	-16.234***	-16.622***	-16.522***	-12.399***	-8.911***	-9.321***	-4.895***	-4.848***	-4.389***	-2.213**
	(1.455)	(1.272)	(1.203)	(1.071)	(1.139)	(1.209)	(1.406)	(1.218)	(1.135)	(0.999)	(1.036)	(1.103)
Real GDP growth	0.014	0.023	0.010	0.016	0.034	0.008	-0.055**	-0.052**	-0.057***	-0.057***	-0.043**	-0.051**
	(0.023)	(0.022)	(0.023)	(0.023)	(0.024)	(0.023)	(0.022)	(0.021)	(0.022)	(0.021)	(0.022)	(0.021)
Inflation	0.027***	0.270***	0.262***	0.253***	0.321***	0.325***	0.301***	0.307***	0.297***	0.297***	0.334***	0.363***
	(0.034)	(0.034)	(0.035)	(0.035)	(0.036)	(0.035)	(0.033)	(0.032)	(0.033)	(0.033)	(0.033)	(0.032)
Debt-to-GDP	-0.008*	-0.007	-0.001	0.002	-0.013***	-0.008*	0.006	0.005	0.011**	0.011**	0.005	0.005
	(0.004)	(0.004)	(0.005)	(0.005)	(0.005)	(0.005)	(0.004)	(0.004)	(0.004)	(0.004)	(0.004)	(0.004)
Trade openness	0.669	-1.159	-0.784	-2.706**	-4.397***	-4.115***	1.796	2.073*	0.576	0.815	-1.398	-0.569
	(1.357)	(1.238)	(1.343)	(1.206)	(1.323)	(1.290)	(1.290)	(1.178)	(1.267)	(1.135)	(1.206)	(1.185)
Current account balance	-0.046**	-0.056***	-0.049**	-0.060***	-0.061***	-0.048**	-0.075***	-0.072***	-0.077***	-0.074***	-0.079***	-0.606***
	(0.021)	(0.021)	(0.021)	(0.021)	(0.022)	(0.022)	(0.020)	(0.019)	(0.020)	(0.020)	(0.020)	(0.020)
Credit rating scores	-0.113**	-0.057	-0.111**	-0.077*	-0.028	-0.153***	-0.190***	-0.182***	-0.188***	-0.195***	-0.153***	-0.226***
	(0.045)	(0.040	(0.046)	(0.041)	(0.043)	(0.048)	(0.043)	(0.038)	(0.043)	(0.039)	(0.039)	(0.044)
Central bank budget balance	-0.022	-0.019	-0.035	-0.032	-0.017	-0.011	-0.074***	-0.075***	-0.085***	-0.085***	-0.067***	-0.075***
	(0.023)	(0.023)	(0.024)	(0.024)	(0.025)	(0.024)	(0.022)	(0.022)	(0.022)	(0.022)	(0.023)	(0.022)
Nominal effective exchange rate	0.004	-0.002	0.009*	0.004	-0.001	-0.006	-0.001	-0.0001	0.003	0.004	-0.002	-0.005
	(0.005)	(0.005)	(0.005)	(0.005)	(0.005)	(0.005)	(0.005)	(0.005)	(0.005)	(0.005)	(0.005)	(0.005)
R^2	0.513	0.505	0.502	0.495	0.438	0.442	0.348	0.347	0.338	0.337	0.298	0.308
Adj. R^2	0.474	0.467	0.463	0.457	0.396	0.401	0.295	0.296	0.284	0.286	0.244	0.257