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Expect the worst, hope for the best: The valuation of climate risks and opportunities in sovereign bonds

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Expect the worst, hope for the best: The valuation of climate risks and opportunities in sovereign bonds

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Abstract

How climate aspects affect sovereign bonds is still a new field of research. I differentiate between transition, physical, and innovation aspects of climate risks and climate performance and estimate the pricing-in of these climate aspects in sovereign bond yields for a sample of 29 countries, for the time 2008-2021. The results show that the effects differ between countries with higher and lower credit rating, long- and short term maturities, and the periods of analysis. Financial markets seem to expect the worst with regards to physical risk exposure and impacts, which are associated with higher yields for the lower-rated countries' bonds at longer-term maturities. In contrast, they seem to hope for the best with regards to transition risk exposure and innovation opportunities, which are associated with lower bond yields for the countries with higher credit rating, mainly for bonds at shorter-term maturity. The effects are more pronounced for the period after the Paris Agreement and might gain increasing importance as physical and transition risks aggravate in the future.

Keywords: *sovereign bonds yields; climate physical risks; climate transition risks; climate opportunities; LASSO dimensionality reduction*

JEL-classification: G12; G14; Q54; Q55

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1 Introduction

The pricing of climate physical and transition risks in financial assets is an area of increasing interest for researchers. Overall, it seems that market risk premia do not fully price-in the risks Hong et al. (2019); Ehlers et al. (2021), although it has also been shown that an increase in awareness and impacts has led to increased *climate risk exposure* valuations in asset prices Bolton and Kacperczyk (2021). Whilst there is a rapidly growing body of literature to assess whether and how financial markets value firm-level climate transition and physical risks, see for example Kölbel et al. (2020), analyses of the pricing-in of climate risks in sovereign bonds have gained less attention.

In the past, literature focused on the assessment of countries' ESG performance on sovereign bond yield spreads, such as in Hoepner et al. (2016), Berg et al. (2016) and Hübel (2020). Gervich (2011) and Scholtens (2017) argue that environmental indicators could serve as a proxy or even an early warning indicator to assess the financial health of a country before the traditional economic indicators react. Such an assessment has not been explicitly undertaken with regard to climate-related indicators. With regards to governance factors, Gervich (2011) argue that these might be closely related to the institutional strength of a country, and Capelle-Blancard et al. (2019) show that a good social and governance performance reduces sovereign yield spreads, whereas this effect is less pronounced for the environmental indicators. They argue that governance-related factors affect the economy in the near term more than the latter two aspects, which is why they are probably more important for investors.

The explicit impact of climate-related risks on sovereign bonds has only recently gained attention in the academic literature. Of the few analyses, which exist, most papers focus on the analysis of the effect of physical risks, measured by various indicators like extreme temperatures or sea-level rise, on sovereign (or municipal) bond yield spreads. All assessments find an impact of physical climate risks on higher yield spreads, usually compared with the U.S. Treasuries rates, or worsened sovereign ratings. The seminal analysis by Kling et al. (2018) analyses empirically that climate change vulnerability is reflected in sovereign bond yields. Various literature builds on their first paper, for example Kling et al. (2021), Cheema-Fox et al. (2021), and Cevik and Jalles (2022). Böhm (2021) shows that rising temperatures can considerably affect the creditworthiness of emerging economies and that temperature anomalies have a detrimental impact on sovereign bond performance. Klusak et al. (2021) reconstruct various sovereign bond ratings, taking physical climate effects into account. They find that exposure to physical climate risks worsens the sovereign credit ratings of almost all sovereigns. Painter (2020) find that US counties exposed to physical climate risks pay more in underwriting fees and initial yields to issue long-term municipal bonds compared to counties unlikely to be affected by climate change. However, this effect is limited to long-term maturities and does not apply when assessing short-term bonds. Furthermore, Beirne et al. (2021) find that climate change vulnerability seems to be priced-in in sovereign borrowing costs and that it matters more than resilience.

Climate transition risks for sovereign bonds only recently started to gain interest in the empirical literature. To the best of my knowledge, only two existing empirical analyses assess transition risks in sovereign bonds. Beirne et al. (2021) apply a transition-related assessment as a robustness check of the physical *climate risk exposure* analysis and find a lower effect on sovereign bond yields than for physical risks or resilience. They argue that this might capture the widespread concern that financial markets have not yet fully priced in these risks. Ryan et al. (2021) use carbon dioxide emissions, natural resources rents and renewable energy consumption as indicators for transition risk and show that countries with lower carbon emissions incur a lower risk premium on sovereign borrowing costs, and that progress to reduce dependency on earnings from natural resource rents, and increases in renewable energy consumption, are both associated with lower sovereign borrowing costs. They conclude that countries that poorly manage the low-carbon transition will likely face higher borrowing costs and liquidity constraints, which would further worsen their ability to manage the transition or to recover from physical climate shocks. Further conceptual work has been done on the matter, yet without empirical analysis. The role of energy and climate policy risks as an impediment for economic growth have been researched by Bretschger and Schaefer (2017) and Bretschger and Soretz (2018). Their analyses show how policy uncertainty and policies that are misaligned with the climate targets bear the risk of detrimental economic growth effects. Battiston and Monasterolo (2019) assess the effect of a disorderly transition to a 2 degrees scenario on the fossil fuel and renewable energy sectors and estimate the impact of the change in firms' Gross Value Added on the fiscal revenues at the country level, by aid of Integrated Assessment Models. They find by aid of their pricing model that climate alignment of the firms can strengthen the fiscal and financial position of a country by decreasing the bond yield spread. A discussion note on the importance of considering fossil reserves of a country when it comes to assessing its sovereign fiscal health has been issued by Jaffe (2020). To equip financial market participants with the analytics required to make informed decisions, Angelova et al. (2021) argue that sovereign credit ratings should improve by taking climate aspects more explicitly into account.

Climate-related innovation activities and their role for a country's future economic growth and welfare have not been analysed in any of the empirical climate risk analyses for sovereign bonds. Yet, there is a rich body of literature that considers climate-related and clean innovation as important safeguards of future welfare in a resource-constrained world, as for example Bretschger (2005) and Borissov et al. (2019). A country's welfare directly feeds into its ability to serve its debt. It is hence important to assess to which degree financial markets consider climate-related innovation performance and the general climate-related technological opportunities that a country might realize in the future. Innovation data to assess the financial valuation of financial assets have been used in previous research, for example in Guderian et al. (2021) and **?**. However, to the best of my knowledge, this is the first analysis to use climate innovation-related data at country level to assess sovereign bond yields.

The existing research did not differentiate clearly between climate performance and climate risk and did not consider at the same time the three dimensions of transition, physical, and innovation aspects. A comprehensive analysis of which physical, transition and innovation-related aspects are reflected in sovereign bond yields is still lacking. The present analysis is hence the first step to fill this gap.

It is an open debate on which specific climate-related indicators are useful and contain enough explanatory information to assess financial climate risks. I, therefore, start with a very large dataset with more than 150 climate-related variables from a variety of sources. This large dataset is then stepwise condensed towards a reduced version with a few key explanatory variables, by combining data-driven machine learning methods and theoretical considerations. This considerable dimensionality reduction is crucial to ensure the power of the analysis and to prevent an over-fitting of the models. Afterwards, I proceed with three main variables to assess the pricing-in of climate performance and climate risk exposures in sovereign bond yields, for a sample of 29 countries, for the years 2008-2021. The three variables cover each physical aspect, transition aspect, and innovation aspect.

It will be shown that financial markets start to take *climate performance* and *climate risk exposure* into account, yet to varying degree. The effects differ between higher and lower-rated countries, long- and short term maturities, and the periods of analysis. I find that a higher transition performance, lower transition risk exposure and higher transition opportunity exposures are associated with lower long-term maturity government bond yields for the higher-rated countries, especially for the period after the Paris Agreement. I also find that lower-rated countries' physical climate risk performance is associated with higher bond yields.

The remainder of this paper is structured as follows: Section 2 describes the dependent variables, the control variables, and the explanatory variables used for the present analysis. Section 3 explains the sample setup, the hypotheses to be tested, and the regression models. In section 4, I discuss in-depth the various results of the analyses, differentiated by full sample, higher-rated sample, and lower-rated sample. I also provide an overview of the overall findings. Last, section 5 concludes with the main results and implications for practitioners and researchers.

2 Data

The data used for the analysis comes from various sources. I started with a dataset of 784 observations and 232 climate and macroeconomics-related explanatory variables. The climate data were obtained from international organisations like the IMF climate data dashboard or the Worldbank's climate knowledge portal; public and research-based databases like the University Notre Dame Adaptation Initiative, the LSE/GRI climate change laws of the world database, the New Climate & University of Wageningen climate policy database, WRI's climate watch data, Climate Analytics & New Climates' Climate Action Tracker; data from specialised organisations like the ICAP carbon pricing data, REN21 for renewable energies, and *right.based on science*, or NGOs like Germanwatch for climate policy analyses; and for-profit data providers like LexisNexis PatentSight.

Variables with more than 2/3 missing values and countries with more than 2/3 missing values were deleted from the analysis. This reduced the initial sample of 56 countries to 30 countries, for the years 2008-2021. The remaining missing values were forward filled with the respective countries' latest available values. I chose forward filling to capture the positive correlation of the variables over time at the country level, and backward filling where values for forward filling were not available. All data are eventually winzorised at the 0.99 upper- and the 0.01 lower-bound to control for any potential extreme outliers.

2.1 Dependent variables

I identify a set of dependent variables to ensure robustness of the results, and to differentiate the effects depending on whether financial performance in terms of yield or in terms of risk (i.e. yield spread) is assessed. An overview of the variables and the data sources are displayed in table 1. For the main model of analysis, the yield assessment, I run the analyses for 05-year maturities to capture a short-to-medium-run period (SR) and 10-year maturities to capture a medium-to-long-run period (LR). This differentiation is conceptually important, given that various climate-related

	Description	Source
Dependent variables		
Yield_05y	Government bond annual interest yield, 05y maturity	Refinitiv/Datastream
Yield_10y	Government bond annual interest yield, 10y maturity	Refinitiv/Datastream
Control variables		
rating_sp	Macro - General S&P country rating, category	Standard & Poors
debt_gdp	Macro - Ratio of government debt to GDP	OECD, Worldbank
gdp_log	Macro - Log Gross Domestic Product in constant 2010 USD	Worldbank
inflation	Macro - Consumer Price Index	Worldbank
unemployment	Macro - Share of unemployed people of total workforce	Worldbank
eurozone	Macro - Eurozone country dummy	European Commission
patentassetindex_all	Macro - Patent Asset Index	LexisNexis PatentSight
Explanatory variables		
ndgain_overall	Climate Physical - Performance - ND-GAIN Overall index	University Notre Dame
ndgain_exposure	Climate Physical - Risk exposure - ND-GAIN Exposure index	University Notre Dame
ccpi_score	Climate Transition - Performance - Climate Change Performance Index	Germanwatch
ccpi_nationalpolicy_score	Climate Transition - Risk exposure - national climate policy score	Germanwatch
patentassetindex_climate	Climate Transition - Performance - Patent Asset Index for SDG 13	LexisNexis PatentSight
pai_climateshare	Climate Transition - Opportunity exposure - Patent Asset Index climate share	LexisNexis PatentSight

Table 1: Description and sources of the variables.

	Yield 05y maturity	Yield 10y maturity
count	406.00	406.00
mean	3.24	3.15
std	2.22	2.35
min	0.03	0.03
25%	1.58	1.26
50%	3.10	2.84
75%	4.28	4.55
max	10.81	9.31

Table 2: Descriptive statistics of the dependent variables.

risks are likely to materialise within different time frames, and are likely to exhibit different degrees of severity, depending on the time horizon of interest.

With climate-related risks, yield spread analyses pose an additional challenge: The baseline for comparison could not be considered as risk-free. For example, a 10-year maturity US government bond is usually considered as the risk-free benchmark - however, the United States exhibit a relatively high degree of physical *climate risk exposure* vulnerability, due to their geographic exposure, and transition risk, due to the low climate policy performance. I, therefore, specify two different baselines for the spread analyses: The US treasury bill yields, and the German Bund bonds. I apply the same differentiation as for the yields with a 05-years maturity ('SR') and a 10-years maturity ('LR'). I use the spread analyses to check the robustness of the main model results for the sovereign bond yields.

I plot the yield data to visually check for autocorrelation over time, which is a common feature of time-series yield data. Figures 1 and 2 display considerable serial correlation for the full sample and the two sub-samples of higher and lower-rated countries. This observation will be formally tested in the main analysis to inform the appropriate regression setup.

When plotting the density distributions of the independent variables, I see considerable differences in the yields between higher and lower-rated countries, as displayed in figure 3. Furthermore, for the full, I observe a slightly right-skewed distribution, as visible in the stacked plots of figure 3. This is a well-known feature of yield data, due to the general zero-lower bound of bond yields. Whilst log-transforming the

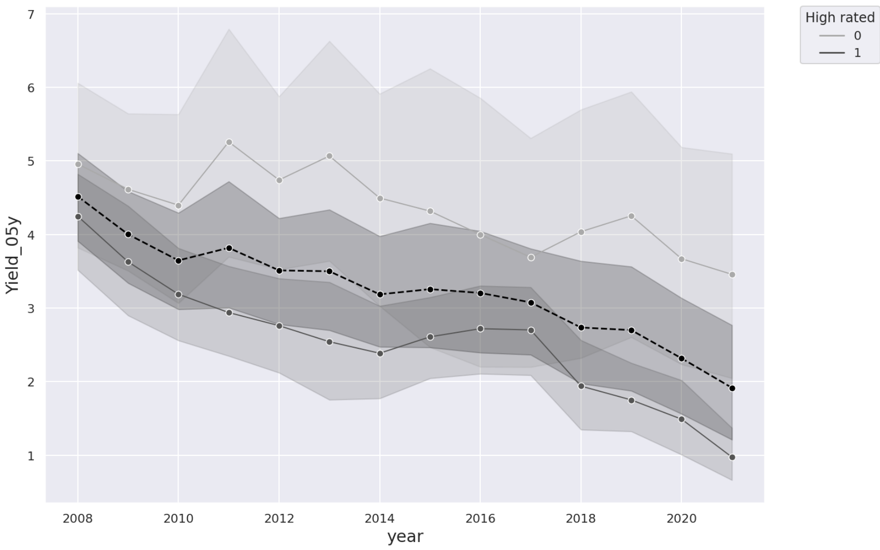


Figure 1: Time series plot of 05-year maturity government bond yields. The figure displays the full sample mean (dashed black line) and differentiated between higher and lower ranked countries (gray lines). Shaded areas indicate the 95% confidence interval.

yield data is common practice for firm-level yield data, this log-transformation produced a strongly left-skewed distribution. I hence decided to follow the literature and use raw yield data for all sample specifications. I consider this to be a reasonable decision since the main interest of the analysis is the difference in the valuation of climate risks for higher versus lower-ranked countries, which do not exhibit a considerable skewness. Maintaining the same scale of values is important for a meaningful comparison of the results.

2.2 Control- and explanatory variables

The set of control variables captures the standard macroeconomic variables that are commonly used in the literature to assess sovereign bond yields and yield spreads (Kling et al., 2018; Capelle-Blancard et al., 2019; Painter, 2020; Beirne et al., 2021; Cevik and Jalles, 2022). Table 1describes the variables alongside the data sources. The descriptive statistics for the control variables are displayed in table 3. In line with

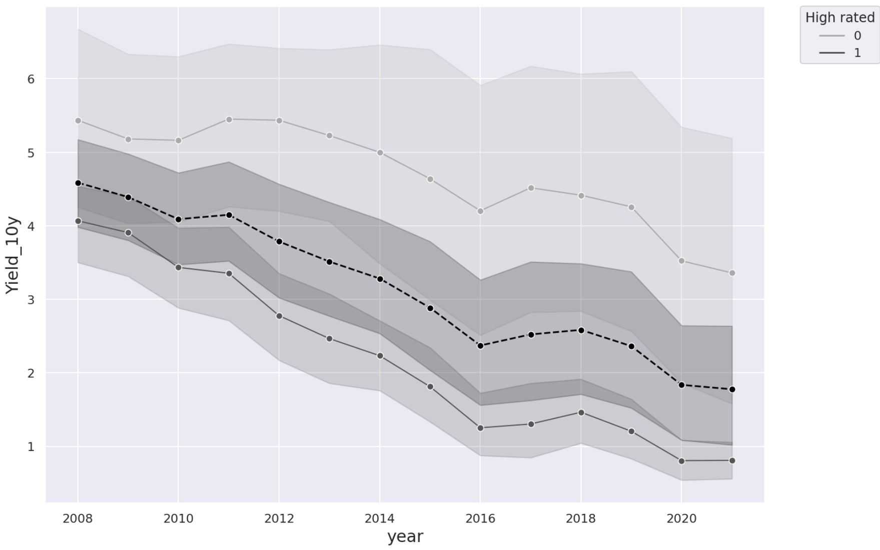
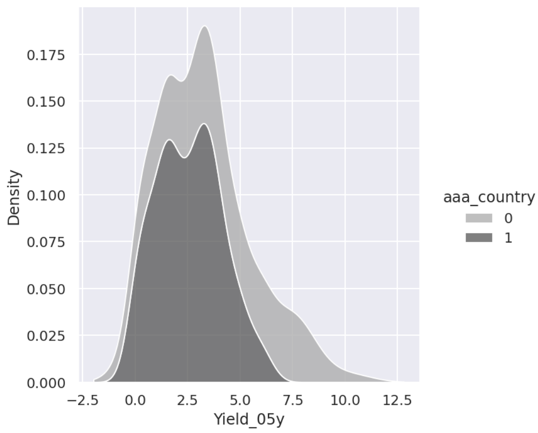


Figure 2: Time series plot of 10-year maturity government bond yields. The figure displays the full sample mean (dashed black line) and differentiated between higher and lower ranked countries (gray lines). Shaded areas indicate the 95% confidence interval.

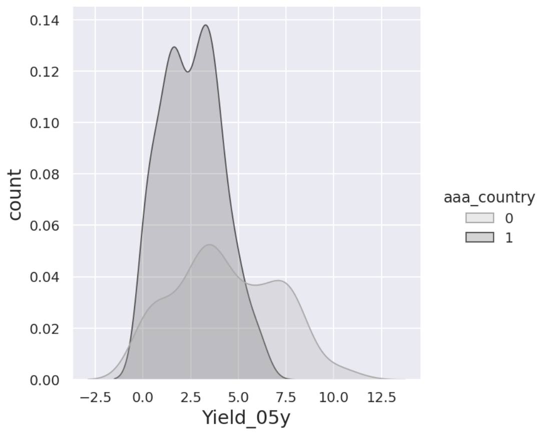
Painter (2020), The country ratings have been transformed into numerical values, starting at 1 for the highest rating (AAA).

For the explanatory variables, I combined data-driven methods and theory to identify a set of few variables, which I considered as most promising in terms of effect importance and capture of important *climate performance* and *climate risk* aspects. The latter guided the theoretical considerations, where it was assessed whether a variable captures risk comprehensively (i.e. capturing exposure, resilience, and adaptability elements) and whether it was able to combine status quo and forward-looking information. The effect importance was assessed using a machine-learning approach with best parameter search and cross-validations to fit a LASSO model to the data.

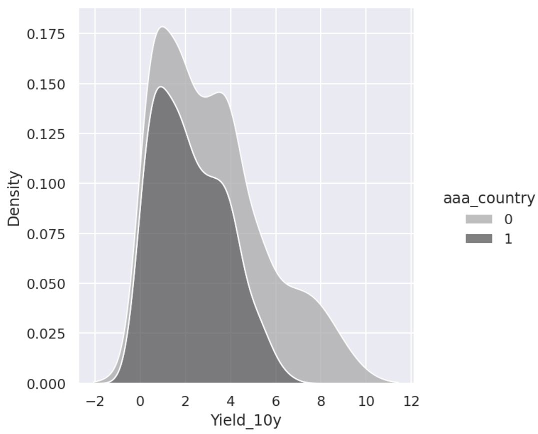
The LASSO regression is useful to reduce dimensionality in a data-driven manner. However, LASSO does not allow for hypothesis-driven variable selection amongst most correlated variables. It is blind to whether a certain variable exhibits importance just because it is highly correlated with another variable, whose importance



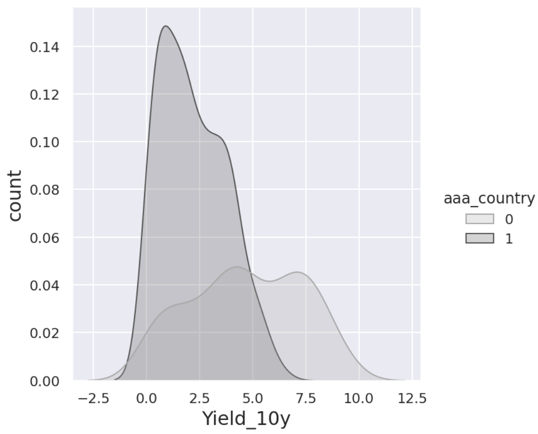
(a) 05-year maturity, stacked



(b) 05-year maturity, separated



(c) 10-year maturity, stacked



(d) 10-year maturity, separated

Figure 3: Density plots of 05-year and 10-year maturity government bond yields. The figures display density plots, differentiated between higher and lower ranked countries. The stacked density plots represent the distribution of the full sample.

	rating_sp	debt_gdp	gdp_log	inflation	unemployment	patentassetindex_all
count	406.00	406.00	406.00	406.00	406.00	406.00
mean	4.31	78.99	27.58	1.98	6.99	10.80
std	3.23	44.22	1.14	1.96	5.04	1.86
min	1.00	25.94	25.76	-1.25	0.63	7.33
25%	1.00	44.11	26.73	0.61	4.10	9.24
50%	3.00	66.73	27.47	1.62	5.62	10.81
75%	7.00	108.18	28.35	2.84	8.01	11.98
max	11.00	234.65	30.48	9.91	27.02	14.91

Table 3: Descriptive statistics of the macroeconomic control variables. The Patent Asset Index is at log scale.

might be also in reality justified, or whether it truly is an important driver. To account for this concern, I proceeded as follows:

I started with 232 potential explanatory variables, of which I dropped those with more than 2/3 missing values. Of the remaining 211 possible variables, I looked at the most correlated variables. To ensure that those variables which satisfy the theoretical considerations are not automatically dropped by the LASSO algorithm due to multicollinearity issues with values that might be less theoretically comprehensive, I followed considerations in the literature and dropped for each correlated pair the variable which is theoretically less compelling. For example, some variables captured only the status quo but were highly correlated with indicators that combined status quo and forward-looking aspects. Given that the LASSO approach would be applied to historic data, the forward-looking climate information has shown to be less important for the algorithm, and theoretically comprehensive indicators were at risk of being dropped because of high correlation with status quo variables.

Second, I applied a LASSO algorithm machine-learning approach, for a data-driven dimensionality reduction. I followed convention and split the data in a train set of size 0.8 and a test set of size 0.2. I feed in the 91 variables which remained after dropping the most correlated ones and used the 10-year government bond yield as the endogenous target variable.[1] Given that backward-looking data is not considered as

[1]This focus on the 10-year maturity government bond yields needs to be taken into account when interpreting the overall model performance of the fitted regression models later on since I apply the explanatory variables there to 05-year and 10-year maturity bonds.

a good proxy for future climate-related pricing-in of yields, due to endogeneity considerations, fat tails and non-linear developments, I do not separate an additional validation set to test the out-of-sample performance. The 5-fold cross-validation yields an alpha of 0.001 as the best regularization parameter. This results in an amount of 61 explanatory variables, which is still too much for the sample size. I hence select those variables with a LASSO-estimated coefficient larger than 0.05, which reduces the dataset to 23 possible explanatory variables. Of these 23 variables, I assessed each variable pair in terms of collinearity and correlation with the dependent variables, by the aid of correlation heatmaps. Based on the literature, I selected those variables which are best suited to test the hypotheses. Eventually, those variables, which survived this last step were again hand-selected based on theoretical considerations. For one of those variables, the climate patent indicator, I transformed the variable by adding the share of climate-related patent activities, because the absolute climate patent indicator was highly correlated with the general patent indicator, and both indicators were very highly correlated with the GDP. By adding this share-indicator to the model, I mitigate potential omitted variable bias for the estimated climate patents coefficients.

I follow the literature and use lag-1 for the climate explanatory variables to account for possible multicollinearity concerns between the climate explanatory variables of interest and the standard macroeconomic variables, and to ensure a meaningful direction of effect (Capelle-Blancard et al., 2019; Hübel, 2020; Beirne et al., 2021). The correlation of the lagged variables with their base variables are high, whilst the correlation with the macroeconomic variables is considerably reduced when using lags.

The Notre Dame All Adaptation Initiative (ND-GAIN) index captures two dimensions of climate physical risks and adaptation - vulnerability and readiness - as can be seen in figure 4. A detailed method documentation is available online.[2]. I use the ND-GAIN index to assess the physical impact performance of

[2] `https://gain.nd.edu/our-work/country-index/methodology/`

	ndgain_overall_lag	ccpi_score_lag	patentassetindex_climate_lag
count	406.00	406.00	406.00
mean	0.65	0.53	2.08
std	0.09	0.10	0.23
min	0.42	0.25	1.55
25%	0.60	0.47	1.90
50%	0.68	0.54	2.12
75%	0.71	0.59	2.24
max	0.77	0.74	2.50

The NDGAIN and CCPI scores have been divided by 100. The Patent Asset Index is at log scale.

Table 4: Descriptive statistics of the explanatory *climate performance* variables.

	ndgain_exposure_lag	ccpi_nationalpolicy_score_lag	pai_climateshare_lag
count	406.00	406.00	406.00
mean	0.42	0.52	0.08
std	0.07	0.24	0.04
min	0.27	0.00	0.03
25%	0.39	0.34	0.06
50%	0.43	0.51	0.08
75%	0.46	0.69	0.09
max	0.57	1.00	0.31

Table 5: Descriptive statistics of the explanatory *climate risk exposure* variables.

a country related to its anticipated physical climate shocks and events. In addition, I use the vulnerability's sub-indicator for *climate risk exposure* to assess the pure physical *climate risk exposure* that a country faces, irrespective of its adaptive capacity. The exposure index captures forward-looking projections for the coming decades, and exhibits therefore relatively low time variance, as can be seen in the pairwise scatterplots in the appendix.

Figure 4: The ND-GAIN setup. The exposure indicator features the vulnerability component. Source: University of Notre Dame

The Germanwatch Climate Change Performance Index (CCPI) is an annual assessment of countries' climate transition performance. It captures four main dimensions: greenhouse gas emissions, renewable energy, energy use, and climate policy, as displayed in figure 5. Detailed documentation of the various components and the individual indicators is available online.[3]. In 2018, the index method has been adapted to keep track of the latest climate science. A higher CCPI score captures a better climate protection performance. I use the CCPI score to assess the association of the climate transition performance of a country with its bond yields, and the national climate policy sub-indicators score to assess the pricing of climate transition risks.

The LexisNexis PatentSight Patent Asset Index (PAI) has been introduced in Ernst and Omland (2011). It is a combination of the country's patents' Market Coverage (i.e. the actual market size in terms of GDP covered by valid patents and

[3] `https://ccpi.org/methodology/`

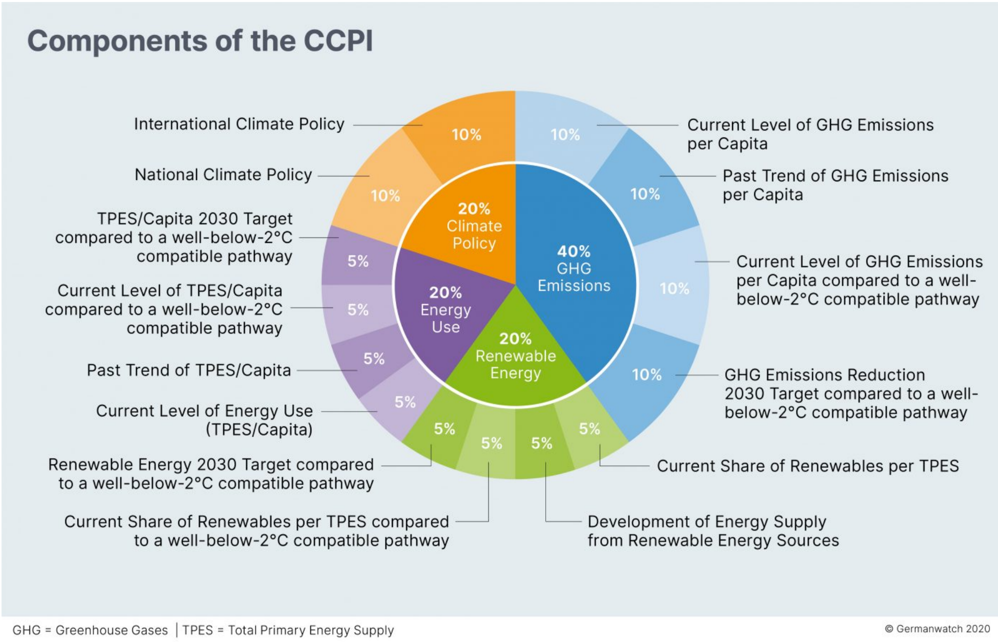


Figure 5: The CCPI setup. The national climate policy score features the general climate policy component. Source: Germanwatch

published pending patent applications), the country's patents' Technology Relevance (i.e. the number of citations received by a patent family as an indicator of its relevance for subsequent technological developments, corrected for patent age, patent office citation practices and citation differences between technology fields), and the overall country's patents Portfolio Size (i.e. the number of active patent families, including the number of granted and valid (active) patents at a specific point of time and the number of patents under examination), as displayed in figure 6.[4] I use the Patent Asset Index values for all patents and climate-related patents, as mapped by LexisNexis PatentSight. In order to identify where an innovation has been developed at first place, patents are mapped to the countries based on the inventors' address. In the present analysis, the climate Patent Asset Index will be used to assess the climate innovation performance of a country. The climate Patent Asset Index rela-

[4] A detailed description of the individual components is available online: `https://www.patentsight.com/patent-asset-index`

tive to the general Patent Asset Index will be used to assess a country's innovation opportunities exposure.

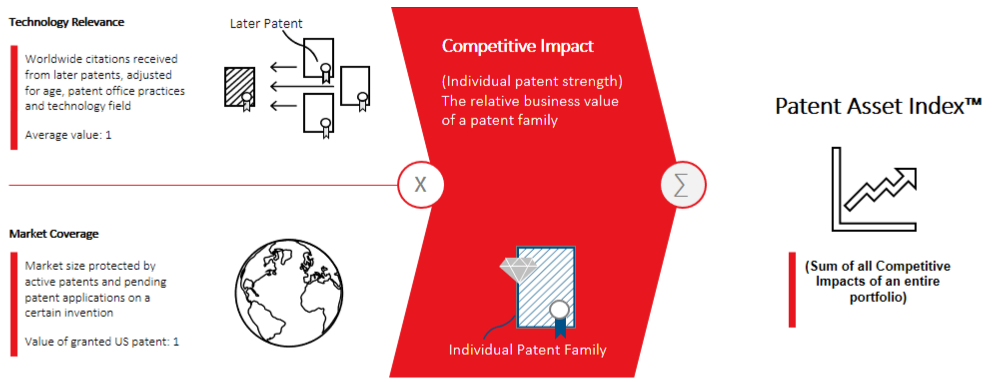


Figure 6: The Patent Asset Index setup. Source: LexisNexis PatentSight

3 Method

All explanatory and dependent variables are plotted in the pariwise scatterplots in the appendix, differentiated for the climate performance and the climate risk exposure variables. The plots show that the patterns of distributions and correlations differ considerably between higher- and lower-rated countries. This provides a first hint that the effects are likely to be non-uniform across the various samples, which will guide the setup of the analysis.

3.1 Samples

Following the literature, and given the extreme outliers due to the financial crisis, I exclude Greece from the sample (Capelle-Blancard et al., 2019). I eventually obtain a balanced panel data set with a total of 406 observations covering 14 years (2008-2021), for 29 countries considered as stable at least in the short term (i.e. rated between AAA to BB according to Standard & Poors' country ratings). The list of

Country	ISO code	High rated	S&P rating	CCPI score	PAI climate share	ND-GAIN exposure
Australia	AUS	1	AAA	36.87	0.092	0.47
Austria	AUT	1	AA+	49.71	0.067	0.35
Belgium	BEL	1	AA	56.94	0.065	0.34
Canada	CAN	1	AAA	36.18	0.078	0.43
Switzerland	CHE	1	AAA	61.04	0.069	0.30
China	CHN	0	A+	47.87	0.051	0.44
Czech Republic	CZE	1	AA-	50.58	0.072	0.27
Germany	DEU	1	AAA	58.63	0.086	0.34
Denmark	DNK	1	AAA	64.07	0.248	0.44
Spain	ESP	0	A	51.63	0.122	0.36
Finland	FIN	1	AA+	56.05	0.055	0.44
France	FRA	1	AA	60.29	0.070	0.39
United Kingdom	GBR	1	AA	65.50	0.085	0.38
Indonesia	IDN	0	BBB-	55.02	0.062	0.51
India	IND	0	BB+	60.65	0.058	0.57
Ireland	IRE	1	AA-	53.50	0.067	0.41
Italy	ITA	0	BBB-	54.54	0.052	0.44
Japan	JPN	0	A+	43.53	0.071	0.51
South Korea	KOR	1	AA	39.92	0.093	0.49
Mexico	MEX	0	BBB-	57.02	0.078	0.48
Netherlands	NLD	1	AAA	52.38	0.080	0.39
Norway	NOR	1	AAA	58.95	0.108	0.38
New Zealand	NZL	1	AA	50.64	0.097	0.45
Poland	POL	0	A-	48.52	0.061	0.33
Portugal	PRT	0	BBB	59.94	0.111	0.39
Sweden	SWE	1	AAA	68.02	0.051	0.41
Thailand	THA	0	BBB+	52.58	0.083	0.45
United States	USA	1	AA+	39.74	0.074	0.48
South Africa	ZAF	0	BB	48.72	0.078	0.43

Climate variables: CCPI = Climate Change Performance Index (provider: Germanwatch), PAI = Patent Asset Index (provider: LexisNexis PatentSight), ND-GAIN = Notre Dame All Adaptation Initiative (provider: University of Notre Dame). All climate variables values reported as country means for the period 2008-2021. A high rating is defined in this analysis as a rating of AAA, AA+, AA, AA-. Rating values as of January 2022.

Table 6: Sample countries' ratings and selected climate variables overview.

countries, their rating (investment grade countries, from AAA to BB), and their climate variables' mean values for the period 2008-2021 are displayed in table 6. I split the sample into higher- and lower-rated countries, in line with the approach of Painter (2020), and acknowledging the considerably differing distributions of the variables between higher and lower rated countries, as shown in the scatterplots in the appendix.

I conduct the analyses for various sample specifications: (1) The full sample, (2) the sample of higher-rated countries (defined as being rated AA- or higher), and (3) the sample of lower-rated countries (defined as being rated below AA-); (a) for all years 2008-2021, and (b) for the years 2015-2021. The latter period represents the years after when the financial sector was starting to more systematically consider physical and transition climate risks after the Paris Agreement in 2015. This period also captures the year 2017, when the Task Force on Climate-related Financial Disclosures (TCFD) released its recommendations that financial actors should consider climate-related risks in their investment decisions. Last, this period covers also the year 2018 when the Intergovernmental Panel on Climate Change (IPCC) released the special report on 1.5 degrees (SR1.5), which highlighted the severe impacts that climate change might have on all countries and the economies of all countries.[5].

3.2 Hypotheses

The Hypotheses build on insights from theoretical models about the effect of climate aspects on economic welfare and financial wealth of sovereigns, and on results from previous empirical analyses on the pricing-in of the *climate performance* and *climate risk exposure* in sovereign bonds.

I follow Gervich (2011) and Scholtens (2017), who argue that environmental indicators could serve as an early warning indicator to assess the financial health of a country before the traditional economic indicators react. I assume therefore that climate aspects add explanatory power to the analyses, compared to models focusing solely on the standard macroeconomic variables. In addition, I build on the findings

[5] `https://www.ipcc.ch/sr15/`

from Kling et al. (2018) and the subsequent empirical analyses from Painter (2020); Beirne et al. (2021); Böhm (2021); Cheema-Fox et al. (2021); Kling et al. (2021); Klusak et al. (2021); Cevik and Jalles (2022), who consistently find that climate physical risk exposures and expected performance to deal with climate physical impacts are expected to worsen the financial performance of sovereigns. With regards to climate transition risks, the hypotheses build on the theory from Bretschger and Schaefer (2017) and Bretschger and Soretz (2018), and on the empirical analyses from Ryan et al. (2021). Bretschger and Schaefer (2017) and Bretschger and Soretz (2018) show that policy uncertainty and climate misaligned policies are detrimental to economic growth. This is also in line with the conceptual findings on the reduced risk from better climate performance of firms within a country, which is mainly induced by stronger climate policies Battiston and Monasterolo (2019). Ryan et al. (2021) conduct an empirical analysis, and use carbon dioxide emissions, natural resources rents and renewable energy consumption as indicators for transition risk. They show that countries with lower carbon emissions incur a lower risk premium on sovereign borrowing costs, and that progress to reduce dependency on earnings from natural resource rents, and increases in renewable energy consumption, are both associated with lower sovereign borrowing costs. The hypotheses around climate innovation build on the theoretical literature about clean innovation and future welfare from Bretschger (2005) and Borissov et al. (2019). They show that clean innovation is the key for sustained long-term economic growth, which is directly related to sovereigns' financial health.

I test the following hypotheses for (a) a regression model focusing on *climate performance* variables, and (b) a regression model focusing on *climate risk exposure* variables.

(a) ***Climate performance***

1. Physical impacts preparedness

    - H1: A higher physical climate impacts preparedness is associated with higher bond yields to compensate for the risk of higher losses if a physical climate event or change affects the country.
    - H0: A higher physical climate impacts preparedness is not associated with higher bond yields.

2. Transition performance

    - H1: A lower climate transition performance is associated with higher bond yields to compensate for the inferior position of the country in the global transition towards low-carbon / decarbonised economies.
    - H0: A lower climate transition performance is not associated with higher bond yields.

3. Innovation performance

    - H1: A higher climate innovation performance is associated with lower bond yields to capture the expected and anticipated economic gains of the country in the low-carbon / decarbonisation transition.
    - H0: A higher climate innovation performance is not associated with lower bond yields.

(b) ***Climate risk exposure***

1. Physical risk exposure

    - H1: A higher physical risk exposure is associated with higher bond yields to compensate for the higher risk of being hit by a climate event or of being detrimentally affected by climate change.

- H0: A higher physical risk exposure is not associated with higher bond yields.

2. Transition risk exposure

   - H1: A higher climate transition risk exposure is associated with higher bond yields to compensate for the higher risk of being exposed to future uncertain disruptive climate policies.
   - H0: A higher climate transition risk exposure is not associated with higher bond yields.

3. Innovation opportunities exposure

   - H1: A higher climate innovation opportunities exposure is associated with lower bond yields to capture the relatively stronger position to realise opportunities in the low-carbon / decarbonisation transition.
   - H0: A higher climate innovation opportunities exposure is not associated with lower bond yields.

3.3 Regression models

To test the hypotheses, I specify the following panel regression model for the *climate performance* analysis:

$$y_{i,t} = \alpha + \beta_M M_{i,t} + \beta_{PP} PP_{i,t} + \beta_{TP} TP_{i,t} + \beta_{IP} IP_{i,t} + \beta_{EZ} EZ_i + \beta_{CR} CR_i + FE_t + \epsilon_{i,t}, \quad (1)$$

with α the intercept, i the country, t the year, y the dependent variable (sovereign bond yield, and yield spreads for the robustness checks), M the macroeconomic control variables as used in the standard literature, PP the variable capturing the physical impacts preparedness, TP the variable capturing the transition performance, and IP the innovation performance.

For the *climate risk exposure* analysis, I specify the following model:

$$y_{i,t} = \alpha + \beta_M M_{i,t} + \beta_{PE} PE_{i,t} + \beta_{TE} TE_{i,t} + \beta_{IE} IE_{i,t} + \beta_{EZ} EZ_i + \beta_{CR} CR_i + FE_t + \epsilon_{i,t}, \tag{2}$$

again with α the intercept, i the country, t the year, y the dependent variable (sovereign bond yield, and yield spreads for the robustness checks), M the macroeconomic control variables as used in the standard literature, and now PE the variable capturing the physical risk exposure, TE the variable capturing the transition risk exposure, and IE the innovation opportunities exposure.

For both models, following Painter (2020), I include FE_t, the time fixed effects to account for unobserved yearly variations and to reduce heteroscedasticity due to the serial non-independence of the error terms. When adding country fixed effects, the explanatory power of the model is considerably reduced, and the TE variable is absorbed by the model. To solve this issue, I follow the literature and add EZ, a time-invariant Eurozone-dummy, to account for the Eurozone-specific country financial governance frameworks.[6] In addition, the time-invariant country rating CR is used as a proxy to account for further investment-relevant, unobservable country characteristics and the associated financial market expectations and sentiments. I use year and entity cluster-robust standard errors to obtain more robust results.

I estimate models with varying maturities (05y, 10y), for various samples (full, higher-rated sample, lower-rated sample), and various timeframes (2008-2021, 2015-2021). In addition, I estimate the models with solely macroeconomic variables, i.e. without the climate-related variables, to get an impression of the additional explanatory power of the climate indicators.

[6] Note that the sample does not include countries which introduced the Euro after 2008, so the dummy is time-invariant.

4 Results

To obtain differentiated results and get a sound understanding of the robustness of estimates, I build on the various findings in the previous literature (Painter, 2020; Ehlers et al., 2021; Cevik and Jalles, 2022) and estimate the *climate performance* and the *climate risk exposure* models for different sample specifications based on higher and lower-rated countries, each for the 05-year government bond maturities and the 10-year maturities, for the period 2008-2021 and the period 2015-2021. I report the results by sample specification in the following sections. For each yield estimate, I estimate the same model with the government spreads against the US treasury bills and to the German Bund bonds as a robustness check. The additional robustness checks confirm all results. They are reported in the appendix for the performance assessments and are available upon request for the risk analyses. Section 4.4 eventually provides the overall findings across all models.

4.1 Full sample

Explanatory power First, I assess whether the climate variables add explanatory power to the full sample model estimates, compared to a model with the macroeconomic standard variables, without the *climate performance* and risk variables. Note that due to the time fixed effects, the R-squared (Between) and the corresponding adjusted R-Squared based on the between-estimate are the relevant measures to assess explanatory power. Overall, the models' explanatory power relates to the degree of variation that can be explained by the model for the individual entities, within a certain time interval. The *climate performance* model's explanatory power increases from SR to LR, and from 2008-2021 to 2015-2021. It ranges from 0.8112 (SR, 2008-2021) to 0.8975 (LR, 2015-2021). A similar pattern is observed for the *climate risk exposure* model, where values range from 0.7736 (SR, 2008-2021) to 0.8835 (LR, 2015-2021). In terms of additional explanatory power, however, the adjusted R-squared estimates are lower for the *climate risk exposure* model than for the macro model. The *climate performance* model adds some explanatory power. However, this

	2008-2021 Full (SR)	2015-2021 Full (SR)	2008-2021 Full (LR)	2015-2021 Full (LR)
Dep. Variable	Yield_05y	Yield_05y	Yield_10y	Yield_10y
Estimator	PanelOLS	PanelOLS	PanelOLS	PanelOLS
No. Observations	377	203	377	203
Cov. Est.	Clustered	Clustered	Clustered	Clustered
R-squared	0.6416	0.7222	0.7461	0.8455
R-Squared (Between)	0.8164	0.8610	0.8726	0.9031
R-Squared (Adjusted)	0.8112	0.8690	0.8529	0.8975
F-statistic	68.381	48.348	112.24	101.79
P-value (F-stat)	0.0000	0.0000	0.0000	0.0000
const	11.840**	15.820*	5.3527	2.1607
	(6.0080)	(9.4787)	(4.9065)	(7.3027)
rating_sp	-0.0285	-0.0842	0.0564	0.0669
	(0.1099)	(0.1448)	(0.0992)	(0.1267)
eurozone_yes	-0.3788*	-0.2412	-0.4902**	-0.9555***
	(0.2078)	(0.3242)	(0.2219)	(0.2517)
debt_gdp	-0.0051	-0.0049	-0.0052	-0.0085**
	(0.0043)	(0.0042)	(0.0042)	(0.0040)
gdp_log	0.0193	0.1810	0.3434	0.4922*
	(0.2752)	(0.2826)	(0.2529)	(0.2793)
inflation	0.4259***	0.5890***	0.3298***	0.3690***
	(0.0845)	(0.1331)	(0.0522)	(0.0906)
unemployment	0.0625*	0.0234	0.0859***	0.0910***
	(0.0339)	(0.0402)	(0.0244)	(0.0330)
patentassetindex_all	-7.4978	-14.085	-9.7432	-9.9970
	(7.2125)	(10.240)	(6.3370)	(11.908)
ndgain_overall_lag	-6.9703**	-10.488**	-7.1232**	-9.0674**
	(3.3247)	(4.6535)	(3.1647)	(4.1817)
ccpi_score_lag	1.7258	2.3372*	0.1508	0.8018
	(1.4365)	(1.2327)	(1.2002)	(1.2097)
patentassetindex_climate_lag	-0.8235	1.5192	-0.9035	-1.0048
	(1.5955)	(3.6782)	(1.2939)	(4.4644)
Effects	Time	Time	Time	Time

Std. Errors are reported in parentheses. Statistical significance displayed at the 1% (***), 5% (**) and 10% (*) level. I refer to the 05-year maturities as short-run(SR), and to the 10-year maturities as long run (LR). The estimates represent values for the 05-year (SR) and 10-year (LR) government bond maturities, for the years 2008-2021 and 2015-2021 (i.e. after the Paris Agreement).

Table 7: Regression results of the *climate performance* model for the full sample.

	2008-2021 Full (SR)	2015-2021 Full (SR)	2008-2021 Full (LR)	2015-2021 Full (LR)
Dep. Variable	Yield_05y	Yield_05y	Yield_10y	Yield_10y
Estimator	PanelOLS	PanelOLS	PanelOLS	PanelOLS
No. Observations	377	203	377	203
Cov. Est.	Clustered	Clustered	Clustered	Clustered
R-squared	0.6019	0.6863	0.7078	0.8298
R-Squared (Between)	0.7792	0.8270	0.8446	0.8893
R-Squared (Adjusted)	0.7736	0.8406	0.8179	0.8835
F-statistic	64.354	45.456	103.07	101.33
P-value (F-stat)	0.0000	0.0000	0.0000	0.0000
const	10.426***	5.8884	3.7562	-1.6424
	(3.5483)	(3.5863)	(3.1642)	(3.2452)
rating_sp	0.2102***	0.2442***	0.3146***	0.3660***
	(0.0651)	(0.0655)	(0.0475)	(0.0422)
eurozone_yes	-0.2682	0.0280	-0.4669**	-0.7739***
	(0.2426)	(0.3470)	(0.2084)	(0.2600)
debt_gdp	-0.0111**	-0.0129***	-0.0126**	-0.0168***
	(0.0045)	(0.0040)	(0.0049)	(0.0039)
gdp_log	-0.3444***	-0.2232	-0.1118	0.0322
	(0.1274)	(0.1378)	(0.1085)	(0.1059)
inflation	0.4059***	0.6718***	0.2900***	0.4196***
	(0.0992)	(0.1412)	(0.0699)	(0.1233)
unemployment	0.0601***	0.0176	0.0877***	0.0857***
	(0.0227)	(0.0307)	(0.0157)	(0.0292)
ndgain_exposure_lag	2.9580	4.8146	3.8568	6.1916**
	(3.5546)	(3.3321)	(3.1265)	(3.0431)
ccpi_nationalpolicy_score_lag	0.1279	0.1024	-0.3579	-0.3422
	(0.3905)	(0.5747)	(0.3950)	(0.4721)
pai_climateshare_lag	-1.9301	-1.3667	-4.2356**	-4.8070**
	(2.6103)	(2.4558)	(2.0856)	(2.2712)
Effects	Time	Time	Time	Time

Std. Errors are reported in parentheses. Statistical significance displayed at the 1% (***), 5% (**) and 10% (*) level. I refer to the 05-year maturities as short-run (SR), and to the 10-year maturities as long run (LR). The estimates represent values for the 05-year (SR) and 10-year (LR) government bond maturities, for the years 2008-2021 and 2015-2021 (i.e. after the Paris Agreement). Values are standardised to allow for relative comparisons of the coefficient estimates.

Table 8: Regression results of the *climate risk exposure* model for the full sample.

additional explanatory power is relatively low and ranges across all models around 0.02.

This suggests that the additional *climate performance* and risk variables add only minor additional explanatory power to the full sample regressions. For the full sample, the pricing of government bond yields is to a large extent explained by the macroeconomic standard variables.

Climate performance model The variable to measure the preparedness to deal with the anticipated country-specific climate impacts (ndgain_overall_lag) is consistently significant across all model specifications at the 5% level. It shows that an increase in the variable is associated with a considerable reduction in sovereign bond yields in the full sample. This reduction is more pronounced for the period after the Paris Agreement from 2015-to 2008. For example, for the short-term maturity government bonds since 2015, an increase in the ND-GAIN preparedness by 0.1 unit is associated with a considerable 1.05% bond yield decrease. The climate transition performance variable (ccpi_score_lag) is statistically significant only at the 10% confidence level for the short-term maturity bond yields for the period after the Paris Agreement (SR, 2015-2021). The coefficient estimate suggests that a higher climate transition performance is associated with a higher bond yield. All other coefficients also have a positive sign. However, none is statistically significant. The same holds for the climate innovation performance variable (patentassetindex_climate_lag), where none of the estimated coefficients for the full sample is statistically significant.

Overall, this suggests that financial markets seem to increasingly price-in the climate physical impacts preparedness of a country for the period after the Paris Agreement, and more so for bonds with longer-term maturities. Climate transition performance and innovation seem not to be priced in, yet.

Climate risk exposure model The estimated coefficients for the climate physical risk variable (ndgain_exposure_lag) are only statistically significant for the longer-term maturity government bonds, for the period after the Paris Agreement (LR, 2015-2021). This suggests that an increase in the exposure to physical *climate per-*

*formance*s by 0.1 unit is associated with a 0.62% increase in sovereign bond yields for 10-year maturities. The coefficient estimates for the shorter-term maturities and the periods 2008-2021 are also positive and higher for the 2015-2021 period. However, they are not statistically significant. The climate transition risk variable (ccpi_nationalpolicy_score_lag) coefficients are positive for the shorter term and negative for the longer-term maturities. This suggests that climate policies more in line with the Paris Agreement goals are in the short term associated with higher yields, and in the long run with lower yields. This might capture the notion that climate policies in the short turn might incur additional costs to the economy and the government, whilst for the long term, climate policies tend to reduce the risk for future costs. However, the coefficients are not statistically significant. The estimated coefficients for the climate innovation opportunities variable (pai_climateshare_lag) suggest that for the period after the Paris Agreement, an increase in climate innovation opportunities by 0.1 unit is associated with a 0.48% decrease in the government bond yields for the 10-year maturities (LR, 2015-2021). A slightly lower coefficient is estimated for the 2008-2021 period. Both coefficients are statistically significant at the 5% level. For the 05-year maturities, the estimated coefficients are also negative, but lower. In addition, they are not statistically significant.

The results suggest that financial markets price-in the pure physical risk exposure of countries for bonds with longer-term maturities, for the period after the Paris Agreement. The same implication can be drawn for climate innovation opportunities. Climate transition risks also seem to be increasingly priced in for the period after the Paris Agreement, however, the statistical evidence is not sufficient for a robust conclusion.

4.2 Higher rated sample

Explanatory power For the higher-rated sample, the *climate performance* models explanatory power decreases from SR to LR, and from 2008-2021 to 2015-2021. This stands in complete opposite to the findings of the full sample. The adjusted R-squared ranges from 0.7282 (LR, 2012-2021) to 0.7805 (SR, 2008-2021). Yet, this

	2008-2021 ≥AA- (SR)	2015-2021 ≥AA- (SR)	2008-2021 ≥AA- (LR)	2015-2021 ≥AA- (LR)
Dep. Variable	Yield_05y	Yield_05y	Yield_10y	Yield_10y
Estimator	PanelOLS	PanelOLS	PanelOLS	PanelOLS
No. Observations	234	126	234	126
Cov. Est.	Clustered	Clustered	Clustered	Clustered
R-squared	0.5109	0.4000	0.4882	0.4819
R-Squared (Between)	0.7902	0.7637	0.7456	0.7522
R-Squared (Adjusted)	0.7805	0.7339	0.7409	0.7282
F-statistic	23.814	7.2653	21.749	10.137
P-value (F-stat)	0.0000	0.0000	0.0000	0.0000
const	2.8670	-0.5818	-3.2805	-12.604**
	(3.7239)	(5.5649)	(3.7828)	(6.0119)
rating_sp	-0.2743**	-0.0940	-0.0995	-0.0228
	(0.1369)	(0.1120)	(0.1364)	(0.1206)
eurozone_yes	0.1249	0.3146	-0.1701	-0.5083***
	(0.2461)	(0.2487)	(0.2015)	(0.1805)
debt_gdp	0.0016	-0.0034	0.0034	0.0068*
	(0.0047)	(0.0040)	(0.0039)	(0.0034)
gdp_log	0.7914***	1.0410***	0.7063***	0.5909***
	(0.2729)	(0.2238)	(0.2352)	(0.1817)
inflation	-0.1402	-0.1307	-0.0828	-0.2941***
	(0.1066)	(0.1727)	(0.0960)	(0.0731)
unemployment	0.0402	0.0254	0.1346**	-0.0043
	(0.0462)	(0.0611)	(0.0625)	(0.0317)
patentassetindex_all	-28.156***	-30.782***	-20.579***	-11.397
	(6.2852)	(9.0674)	(5.6276)	(7.8786)
ndgain_overall_lag	2.7689	1.5683	4.9298	10.957**
	(3.4340)	(4.6561)	(3.7726)	(4.5049)
ccpi_score_lag	0.6976	0.7297	-1.3338	-1.9978***
	(1.0440)	(1.0396)	(0.8593)	(0.6873)
patentassetindex_climate_lag	-2.4483	-0.4585	-2.5229***	-4.4388
	(1.8340)	(2.8171)	(0.7508)	(3.2001)
Effects	Time	Time	Time	Time

Std. Errors are reported in parentheses. Statistical significance displayed at the 1% (***), 5% (**) and 10% (*) level. I refer to the 05-year maturities as short-run (SR), and to the 10-year maturities as long run (LR). The estimates represent values for the 05-year (SR) and 10-year (LR) government bond maturities, for the years 2008-2021 and 2015-2021 (i.e. after the Paris Agreement). The higher-rated sample consists of countries that were rated higher or equal to AA- by Standard & Poors as of January 2022.

Table 9: Regression results of the *climate performance* model for the higher-rated sample.

	2008-2021 ≥AA- (SR)	2015-2021 ≥AA- (SR)	2008-2021 ≥AA- (LR)	2015-2021 ≥AA- (LR)
Dep. Variable	Yield_05y	Yield_05y	Yield_10y	Yield_10y
Estimator	PanelOLS	PanelOLS	PanelOLS	PanelOLS
No. Observations	234	126	234	126
Cov. Est.	Clustered	Clustered	Clustered	Clustered
R-squared	0.2519	0.1992	0.2401	0.2960
R-Squared (Between)	0.4171	0.4171	0.4054	0.4924
R-Squared (Adjusted)	0.3928	0.3807	0.3663	0.4482
F-statistic	8.5660	3.0404	8.0416	5.1393
P-value (F-stat)	0.0000	0.0028	0.0000	0.0000
const	18.106***	7.9803	10.586**	7.4553*
	(5.9181)	(5.9448)	(4.5080)	(4.0297)
rating_sp	-0.1023	0.0293	-0.0248	-0.0875
	(0.2243)	(0.1875)	(0.1740)	(0.1333)
eurozone_yes	-0.4541	-0.0449	-0.7228***	-0.8404***
	(0.3505)	(0.2700)	(0.2566)	(0.2405)
debt_gdp	0.0015	-0.0056	0.0023	0.0026
	(0.0090)	(0.0091)	(0.0070)	(0.0052)
gdp_log	-0.5363**	-0.1566	-0.3086*	-0.1986
	(0.2080)	(0.2028)	(0.1595)	(0.1320)
inflation	0.0744	0.2305	0.0963	-0.0418***
	(0.1307)	(0.2009)	(0.0722)	(0.0130)
unemployment	0.0823	0.0667	0.1645*	-0.0194
	(0.0833)	(0.1089)	(0.0894)	(0.0738)
ndgain_exposure_lag	-1.9099	-3.2391	-0.6552	1.5157
	(3.4658)	(3.6062)	(3.0001)	(2.8776)
ccpi_nationalpolicy_score_lag	-0.8828	-1.5161**	-0.8650*	-1.0995*
	(0.5449)	(0.7268)	(0.5090)	(0.6272)
pai_climateshare_lag	0.7651	2.0744	-2.1170	-3.8583*
	(2.7425)	(2.5882)	(3.1827)	(2.2741)
Effects	Time	Time	Time	Time

Std. Errors are reported in parentheses. Statistical significance displayed at the 1% (***), 5% (**) and 10% (*) level. I refer to the 05-year maturities as short-run (SR), and to the 10-year maturities as long run (LR). The estimates represent values for the 05-year (SR) and 10-year (LR) government bond maturities, for the years 2008-2021 and 2015-2021 (i.e. after the Paris Agreement). The higher-rated sample consists of countries that were rated higher or equal to AA- by Standard & Poors as of January 2022. Values are standardised to allow for relative comparisons of the coefficient estimates.

Table 10: Regression results of the *climate risk exposure* model for the higher-rated sample.

decrease is mainly driven by the lower explanatory power of the macro variables from SR to LR and from 2008-2021 to 2015-2021: Here, the adjusted R-squared for the macro model ranges from 0.5634 (LR, 2015-2021) to 0.7647 (SR, 2008-2021). Hence, we see that the *climate performance* model adds some explanatory power to the model. This increase in explanatory power is especially pronounced for the period 2015-2021. The *climate risk exposure* model's adjusted R-squared ranges from 0.3663 (LR, 2008-2021) to 0.4482 (LR, 2015-2021). They are considerably lower than for the macro model on the macroeconomic variables.

This suggests that *climate performance* add explanatory power to the higher-rated samples' yield estimates, which is considerably more pronounced after the Paris Agreement. In contrast, the *climate risk exposure* variables do not exhibit explanatory power for the higher-rated countries' government bond yields.

Climate performance model The coefficient estimates for the climate physical impacts preparedness variable (ndgain_overall_lag) are significant at the 5% level for the longer-term maturities for the period 2015-2008. In contrast to what would be expected, and in contrast to the results of the full sample, a 0.1 unit increase of the preparedness of the higher-rated countries to deal with the anticipated country-specific climate impacts is associated with a 1% increase in the 10-year maturities sovereign bond yields. For the other specifications, the variable coefficients are also positive, yet not significant. Likewise, the estimated coefficient for the climate transition performance (ccpi_score_lag) is statistically significant at the 1% level only for the longer-term maturity bond yields for the period after the Paris Agreement. The coefficient estimate suggests that an increase of the climate transition performance by 1 unit is associated with a decrease of the bond yield by almost 2%. The estimated coefficient for the longer-term maturities for 2008-2021 is also negative, yet lower and not statistically significant. This implies that the performance is increasingly priced-in for long-term maturity bonds for the period after the Paris Agreement. As for the full sample, the climate transition performance estimates for the shorter term are positive and statistically not significant for the shorter-term period. The coefficient estimates for the climate innovation performance variable (pai_climate_lag) display negative signs, which implies that an increase in the climate innovation performance is associated with a decrease in bond yields. Yet, the estimate is only statistically significant for the 2008-2021 longer-term period.

Overall, this suggests that financial markets seem to increasingly price-in the climate physical impacts preparedness for longer-term maturity bonds. However, the estimated coefficient suggests that a better preparedness is associated with a higher yield - which runs counter to what would be expected. Climate transition performance seems to be priced in by financial markets in line with the expectations for the longer-term maturities, especially for the period after the Paris Agreement. climate innovation performance seems not to be consistently priced-in.

Climate risk exposure model For the higher-rated sample, the estimated coefficients for the climate physical risk variable (ndgain_exposure_lag) are not statistically significant for any specification. For the 2015-2021 period, the coefficient exhibits a positive sign, which suggests that an increase in the variable is associated with an increase in the government bond yield. For the other specifications, the sign is negative, contrary to what would be expected. The estimated coefficients for the transition risk variable (ccpi_nationalpolicy_score_lag) display consistently negative signs, which suggests an increase of the national climate policy score, hence a decrease in the transition risk, is associated with a decrease in government bond yields. The estimated effect is larger for the period after the Paris Agreement. In addition, it is higher for the shorter-term maturities. This suggests that it might be expected that a higher climate policy performance, in contrast to the full sample, reduces the risk for the short term maturities bonds even more than for the longer-term maturities. The estimated coefficients are statistically significant only for the period after the Paris Agreement, at the 5% (SR, 2015-2021) and 10% (LR, 2015-2021) confidence level. The climate innovation opportunities' estimated coefficients (pai_climateshare_lag) are positive, yet are not statistically significant, for the short term maturity bonds. For the longer-term maturities, the estimated coefficients suggest that an increase in innovation opportunities is associated with a decrease in bond yields. Yet, the estimates are again insignificant or only at the 10% level of confidence, which is too low for a robust interpretation of the result.

These results imply that climate physical risks are not priced-in for the higher-rated sample. Climate transition risks seem to be priced-in for the higher-rated sample for short- and long-term maturities for the period after the Paris Agreement. Climate innovation opportunities are not consistently priced-in, yet results suggest some degree of increasing importance for long-term maturity bonds for the period after the Paris Agreement.

4.3 Lower rated sample

Explanatory power Overall, the results suggest that the additional explanatory power of the *climate performance* and *climate risk exposure* variables is very limited, compared to the macro model. This additional explanatory power is even lower for the period after the Paris Agreement. Financial markets seem to focus considerably on macroeconomic variables for the pricing of lower-rated countries' sovereign bond yields.

Climate performance model The climate physical impacts preparedness variable's estimated coefficients (ndgain_overall_lag) are significant across all specifications, ranging from the 10% confidence level (SR, 2008-2021) to the highest level of significance at 1% (SR, 2015-2021 and LR, 2008-2021). With a consistently negative sign, the estimates suggest that an increase in the preparedness of the lower-rated countries to deal with the anticipated country-specific climate impacts is associated with a decrease in government bond yields. The coefficient is highest for the 05-year maturities after the Paris Agreement, where it suggests that a 0.1 unit increase of the physical impacts preparedness is associated with a 2% decrease for the lower-rated samples' bond yields. For all other specifications, the coefficient magnitude suggests a 1% decrease. The estimated coefficient for the climate transition performance (ccpi_score_lag) switches sign from a negative association 2008-2021 to a slightly positive estimate after the Paris Agreement. This sign switch has been observed

	2008-2021 <AA- (SR)	2015-2021 <AA- (SR)	2008-2021 <AA- (LR)	2015-2021 <AA- (LR)
Dep. Variable	Yield_05y	Yield_05y	Yield_10y	Yield_10y
Estimator	PanelOLS	PanelOLS	PanelOLS	PanelOLS
No. Observations	143	77	143	77
Cov. Est.	Clustered	Clustered	Clustered	Clustered
R-squared	0.8170	0.8875	0.8780	0.9575
R-Squared (Between)	0.9297	0.9577	0.9805	0.9906
R-Squared (Adjusted)	0.9242	0.9790	0.9505	0.9890
F-statistic	58.056	47.345	93.572	135.11
P-value (F-stat)	0.0000	0.0000	0.0000	0.0000
const	4.8632	24.936	-2.7985	-7.2746
	(19.443)	(20.751)	(9.8863)	(11.564)
rating_sp	0.3658	0.0192	0.3841***	0.4630**
	(0.2558)	(0.3859)	(0.1362)	(0.2006)
eurozone_yes	-0.5448	-0.6849	-0.7295**	-2.0830***
	(0.3751)	(0.6042)	(0.3012)	(0.4296)
debt_gdp	-0.0040	0.0079	-0.0035	-0.0010
	(0.0047)	(0.0064)	(0.0039)	(0.0035)
gdp_log	0.3508	-0.2511	0.8623***	1.3244**
	(0.4835)	(0.8200)	(0.2739)	(0.6074)
inflation	0.3247***	0.5303***	0.2270***	0.1912*
	(0.1151)	(0.1754)	(0.0489)	(0.0964)
unemployment	0.0427	0.0136	0.0656***	0.0850***
	(0.0258)	(0.0293)	(0.0119)	(0.0172)
patentassetindex_all	-8.4241	-5.2135	-15.381**	-27.013**
	(5.4947)	(14.784)	(6.2105)	(10.935)
ndgain_overall_lag	-11.101*	-21.593***	-11.658***	-11.177**
	(6.1440)	(7.3083)	(3.9353)	(4.2633)
ccpi_score_lag	-0.3613	0.4750	-0.5321	1.1692
	(1.1238)	(5.6317)	(1.1919)	(2.6551)
patentassetindex_climate_lag	1.2045	-0.5368	1.4781	3.5126
	(1.8371)	(4.2761)	(1.5579)	(2.7319)
Effects	Time	Time	Time	Time

Std. Errors are reported in parentheses. Statistical significance displayed at the 1% (***), 5% (**) and 10% (*) level. I refer to the 05-year maturities as short-run (SR), and to the 10-year maturities as long run (LR). The estimates represent values for the 05-year (SR) and 10-year (LR) government bond maturities, for the years 2008-2021 and 2015-2021 (i.e. after the Paris Agreement). The lower-rated sample consists of countries that were rated lower than AA- by Standard & Poors as of January 2022.

Table 11: Regression results of the *climate performance* model for the lower-rated sample.

	2008-2021 <AA- (SR)	2015-2021 <AA- (SR)	2008-2021 <AA- (LR)	2015-2021 <AA- (LR)
Dep. Variable	Yield_05y	Yield_05y	Yield_10y	Yield_10y
Estimator	PanelOLS	PanelOLS	PanelOLS	PanelOLS
No. Observations	143	77	143	77
Cov. Est.	Clustered	Clustered	Clustered	Clustered
R-squared	0.8181	0.8961	0.8574	0.9403
R-Squared (Between)	0.9538	0.9699	0.9756	0.9761
R-Squared (Adjusted)	0.9505	0.9738	0.9653	0.9725
F-statistic	65.482	58.463	87.495	106.75
P-value (F-stat)	0.0000	0.0000	0.0000	0.0000
const	-8.8647	-2.2758	-3.7105	-3.7444
	(12.720)	(16.904)	(9.3949)	(14.457)
rating_sp	0.6619***	0.4590	0.5263***	0.5011*
	(0.2435)	(0.3871)	(0.1989)	(0.3000)
eurozone_yes	-0.9878	-1.0610	-0.7389	-1.5713***
	(0.6091)	(0.8735)	(0.5052)	(0.5889)
debt_gdp	-0.0134***	-0.0140***	-0.0185***	-0.0210***
	(0.0035)	(0.0041)	(0.0025)	(0.0030)
gdp_log	0.1933	-0.1427	0.0368	-0.0413
	(0.4515)	(0.5991)	(0.3368)	(0.4996)
inflation	0.2462***	0.4976**	0.1588***	0.2340*
	(0.0880)	(0.2156)	(0.0479)	(0.1328)
unemployment	0.0538**	0.0272	0.0810**	0.0934***
	(0.0251)	(0.0308)	(0.0320)	(0.0339)
ndgain_exposure_lag	3.5242	10.660	8.1094*	12.624**
	(5.7276)	(7.9109)	(4.8415)	(5.9231)
ccpi_nationalpolicy_score_lag	1.0811***	1.3530***	0.0784	-0.1759
	(0.3846)	(0.4811)	(0.2493)	(0.3608)
pai_climateshare_lag	8.9108	18.035	2.0993	7.7827
	(10.403)	(11.703)	(9.8613)	(11.036)
Effects	Time	Time	Time	Time

Std. Errors are reported in parentheses. Statistical significance displayed at the 1% (***), 5% (**) and 10% (*) level. I refer to the 05-year maturities as short-run (SR), and to the 10-year maturities as long run (LR). The estimates represent values for the 05-year (SR) and 10-year (LR) government bond maturities, for the years 2008-2021 and 2015-2021 (i.e. after the Paris Agreement). The lower-rated sample consists of countries that were rated lower than AA- by Standard & Poors as of January 2022. Values are standardised to allow for relative comparisons of the coefficient estimates.

Table 12: Regression results of the *climate risk exposure* model for the lower-rated sample.

when moving from SR to LR estimates for the higher-rated sample, too. It exhibits a differentiated position of financial markets when it comes to pricing in the fundamental *climate performance* of a country. For the lower-rated sample, the coefficients suggest that an increase of the climate transition performance by 1 unit is associated with an increase of the bond yields after the Paris Agreement, which might capture the effect that the Paris Agreement for the first time asked all nations (and not only most developed ones) to implement ambitious climate mitigation policies. The estimated magnitude of the effect is larger for the 10-year maturities (LR, 2015-2021). Yet, none of the coefficients is statistically significant. The coefficient estimates for the climate innovation performance variable (patentassetindex_climate_lag) display a merely positive sign. This implies that, in contrast to the higher-rated sample estimates, an increase in the climate innovation performance is associated with an increase of bond yields, except for the negative coefficient estimate for the 05-year bond yields after the Paris Agreement (SR, 2015-2021). Yet, the estimates are again not statistically significant.

These results show that financial markets price-in the climate physical impacts preparedness for lower-rated countries, with the strongest effect for the 05-year maturities yields in the period after the Paris Agreement. The climate transition performance is not significantly priced-in, yet. The same holds for the climate innovation performance pricing-in.

Climate risk exposure model The coefficient estimates for the lower-rated countries of the climate physical risk variable (ndgain_exposure_lag) are consistently positive and considerably larger for the period 2015-2021. Whilst the estimates are not statistically significant for the lower-rated samples' 05-year maturity bonds, the increase in significance from the 10% level (LR, 2008-2021) to 5% for the 10-year bond yields (LR, 2015-2021). The estimate suggests that an increase in the physical risk by 0.1 units is associated with a 1.2% increase in the lower-rated samples' 10-year maturities' bond yields after the Paris Agreement. In terms of transition risk (ccpi_nationalpolicy_score_lag), the estimated coefficients are positive and highly statistically significant at the 1% level for the 05-year maturities, with an increasing magnitude for the period after the Paris Agreement. More specifically, in contrast to what would be expected, we see that a reduction of the transition risk (i.e. higher national climate policy score) is associated with an increase of the 05-year bond yields for the lower-rated sample, which stands in complete opposite to the higher-rated sample's results. This effect vanishes for the insignificant 10-year estimates, where we observe a negative sign for the period after the Paris Agreement. This suggests that the higher yield effect is less pronounced or even disappears for longer-term maturities. With regards to the climate innovation opportunities' estimated coefficients (pai_climateshare_lag), we see consistently positive signs. This suggests that, in contrast to what would be expected, an increase in the innovation opportunities is associated with an increase in the bond yields - and more so after the Paris Agreement. Yet, the estimates are not statistically significant.

This suggests that physical climate risks seem to be priced-in for the lower-rated sample's bond yields at longer-term maturities. Furthermore, financial markets seem to associate lower climate transition risks with higher short-term government bond yields. Climate innovation opportunities do not seem to be priced-in for the lower-rated sample, yet.

4.4 Summary and discussion

Overall, the results highlight the importance of differentiated analyses to assess the pricing-in of climate aspects in government bonds: (1) Models should differentiate between variables that describe a country's fundamental *climate performance* and variables that serve as indicators for a country's *climate risk exposure*. (2) Analyses should differentiate between different maturities of the government bonds. Climate-related aspects are expected to exhibit different degrees of influence on sovereign bond performance, depending on the time horizon. This might also be captured in financial market expectations, and hence bond pricing. (3) Country sub-sample analyses are important to gain a proper understanding of how climate aspects are priced-in, depending on the generalised sentiment associated with a country by the financial markets. It has for example been shown that results differ to great extent between higher and lower-rated countries. (4) Time-period sub-sample analyses are useful to analyse whether and how the estimated coefficient signs, magnitudes and statistical significances change over time. For example, it has been shown that the estimated associations for most climate-related aspects with the bond yields were stronger or more aligned with the hypotheses for the period after the Paris Agreement. These considerations guide the following summary of results.

4.4.1 Explanatory power

Across the three sample specifications, I generally find that the additional climate variables for the *climate performance* and *climate risk exposure* models add only minor explanatory power, compared to a model with only macroeconomic variables. Only for the higher-rated sample's short- and longer-term maturity bond yields, the *climate performance* model outperforms the macro model considerably after the Paris Agreement. This suggests that for the period after the Paris Agreement in 2015, financial market actors seem to consider *climate performance* for longer-term government bonds for higher-rated countries in addition to the standard macroeconomic variables. To the best of my knowledge, these results are new to the literature. None of the analyses I am aware of assessed the additional explanatory power of the climate variables, compared to a model focusing only on the macroeconomic control variables.

4.4.2 Climate performance

The analysis of the pricing of countries' *climate performance* in sovereign bond yields differentiates between physical impacts preparedness, transition performance and climate innovation.

Physical impacts preparedness For the full and the lower-rated samples, I find that a lower preparedness to deal with climate physical impacts is associated with higher bond yields, and more so for the period after the Paris Agreement and the lower-rated samples' short-term maturity bond yields. For the higher rated sample, I find that a better physical impacts preparedness is associated with a higher yield - yet, the coefficient estimates are not statistically significant. This suggests that financial markets seem to price-in physical impacts preparedness for the lower-rated countries, especially so for the period after the Paris Agreement. The results confirm and refine the findings of the previous literature on the pricing-in of the physical impacts preparedness of sovereigns, which consistently suggest that physical *climate risk exposure* resilience starts to be priced-in for vulnerable, developing, and lower-rated countries (Kling et al., 2018, 2021; Cheema-Fox et al., 2021; Cevik and Jalles, 2022).

Climate transition performance For the higher-rated sample, I find that a higher transition performance score is associated with lower long-term maturity government bond yields, especially for the period after the Paris Agreement. This is not the case for the full and the lower-rated sample. This suggests that financial markets started to price-in transition performance for longer-term maturity bonds in higher-rated countries for the period after the Paris Agreement. The results confirm the results from (Ryan et al., 2021). Their transition risk variables target the climate transition performance of sovereigns and suggest that progress on the climate transition performance is associated with lower 10-year maturity bond yields for the advanced economies, whilst the effect is less pronounced and not consistently observed for the developing economies.

Climate innovation performance The climate innovation performance estimates are not statistically significant, for any sample at any government bond maturity. This suggests that it is not consistently priced-in by financial markets. To the best of my knowledge, the pricing-in of climate innovation performance in sovereign bond markets has not been analysed, yet - despite the fact that climate-related innovation is often considered an important means to ensure future wealth and competitiveness of countries and regions. The results hence add important first insight to the literature, which might be further explored in future research.

4.4.3 Climate risk exposure

The analysis of the pricing of countries' *climate risk exposure* in sovereign bond yields differentiates between physical risk exposure, transition risk exposure, and innovation opportunities exposure.

Physical risk exposure The results show that higher physical risk exposure is associated with higher long-term maturity government bond yields for the full and the lower rated countries sample. The effect is more pronounced for the period after the Paris Agreement. This is not the case for the higher rated countries. This suggests that financial markets price-in lower-rated countries' physical climate risk exposures. The finding confirms the results of the *climate performance* analysis for the physical climate risk preparedness estimates, and is in line with what has been found in most of the literature. Yet, in contrast to the physical impact preparedness, which seems to be priced-in for all maturities of lower-rated countries' bonds, I show that physical risk exposures are especially important for the pricing of long-term maturity bonds after the Paris Agreement. The results, therefore, confirm and reconcile the findings of the various existing analyses on the pricing-in of climate physical risk exposure from Painter (2020), Cevik and Jalles (2022) and Böhm (2021).

Transition risk exposure I find that for higher-rated countries, higher transition risks for the short- and long-term maturities are associated with higher yields, for the period after the Paris Agreement. For the lower-rated sample, I observe the contrary: lower transition risks seem to be associated with higher short-term bond yields. This suggests that climate transition risks are increasingly priced-in by financial markets for longer-term government bonds of higher-rated countries. This is in line with the results on the transition performance from the *climate performance* analysis. For lower-rated countries, financial markets seem to perceive climate policies to be relatively costlier, compared to the reduction in the transition risks. This is a refinement of the results from the performance model, where lower-rated sovereigns' yields were not found to be associated with the countries' general *climate performance*. The results confirm the evidence in the literature on transition risk pricing-in for sovereign bonds by Beirne et al. (2021). Their indicator of transition risk captures the gap between what would be required for 2 degrees compliance in 2050. They focus on 10-year government bond yields and find that a higher climate transition risk is associated with a positive coefficient estimate for the full sample, and a higher estimate for the advanced economies, compared to the emerging economies.

Innovation opportunities exposure For the higher-rated sample, I find that the innovation opportunities exposure is associated with lower bond yields for the long-term maturities for the period after the Paris Agreement. For the lower-rated sample, innovation opportunities do not seem to be associated with bond yields. In contrast to the insignificant climate innovation coefficients from the *climate performance* model, the relative climate innovation opportunities exposure estimates suggests that financial markets have started to price-in innovation opportunities exposure for the long-term maturity higher-rated samples' bond yields. To the best of my knowledge, the pricing-in of climate opportunities exposure in sovereign bond markets has not been analysed, yet. This study, therefore, opens a new field of research and recommends conducting further analyses to assess how climate opportunities could impact and are expected to be relevant for future sovereign bond performances.

5 Conclusion

In the present analysis, I analysed the pricing-in of climate-related aspects in sovereign bond yields, for a sample of 29 countries, for the years 2008-2021. I used well-known and new variables to assess the climate performance and climate risk exposure of sovereigns, differentiated by physical aspects, transition aspects, and innovation aspects. Overall, I have shown that financial markets start to take *climate performance* and *climate risk exposure* into account, yet to varying degree. The effects differ between higher and lower-rated countries, long- and short term maturities, and the periods of analysis.

I found that the additional climate variables for the *climate performance* and *climate risk exposure* models add in general only minor explanatory power to the models with standard macroeconomic variables, with one exception: For the higher-rated sample's short- and longer-term maturity bond yield analyses, the *climate performance* variables add considerable explanatory power for the period after the Paris Agreement.

In terms of *climate performance*, I found that financial markets seem to price-in the physical impacts preparedness for the lower-rated countries. This effect has been shown to be more pronounced for the period after the Paris Agreement, and for the short-term maturities. For the higher-rated countries, in contrast, a better physical impacts preparedness has been associated with a higher yield, but this association was not statistically significant. Whilst the climate transition performance did not seem to be priced-in for the lower-rated countries, a higher transition performance was associated with lower long-term maturity government bond yields, especially for the period after the Paris Agreement, for the higher-rated countries. Furthermore, I found that financial markets do not seem to price-in climate innovation performance, despite the fact that climate-related innovation is often considered an important means to ensure future wealth and competitiveness of countries.

The results on the pricing-in of countries' *climate risk exposure* suggested that financial markets price-in lower-rated countries' physical climate risk exposure, but not so for the higher-rated countries. The pricing effect has been shown to be largest for lower-rated countries' long-term maturity bonds after the Paris Agreement. Climate transition risks are increasingly priced-in for longer-term government bonds of higher-rated countries. For lower-rated countries, a stronger climate policy performance has been for the short-term maturities associated with higher yields. Eventually, I find that financial markets might have started to price-in innovation opportunities exposure for the higher-rated samples' long-term maturity bonds. For the lower-rated countries, this effect was not observed.

In sum, In line with the literature, I have shown that financial markets start to take *climate performance* and *climate risk exposure* into account, to varying degree, and more so for the period after the Paris Agreement. A higher transition performance, lower transition risk exposure and higher transition opportunity exposures are associated with lower long-term maturity government bond yields for the higher-rated countries, especially for the period after the Paris Agreement. The lower-rated countries' physical climate risk performance is associated with higher bond yields.

The results highlight the importance of differentiated analyses to assess the pricing-in of climate aspects in government bonds. First, to the best of my knowledge, the pricing-in of climate opportunities exposure in sovereign bond markets has not been analysed, yet. This analysis opens a new field of research on further analyses to understand better how climate innovation and a relatively higher share of climate innovation opportunities could impact future sovereign bond performances. Second, researchers and practitioners should differentiate between variables that describe a country's fundamental *climate performance* and variables that serve as indicators for a country's *climate risk exposure*. It is equally important to analyse and interpret the results differentiated by varying bond maturities, and the different country rating categories. Last, it has been proven as useful to differentiate between recent and more distant past sub-sample analyses to distinguish whether and how the estimated coefficient signs, magnitudes and statistical significances change over time.

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6 Appendix

6.1 Pairwise scatterplots

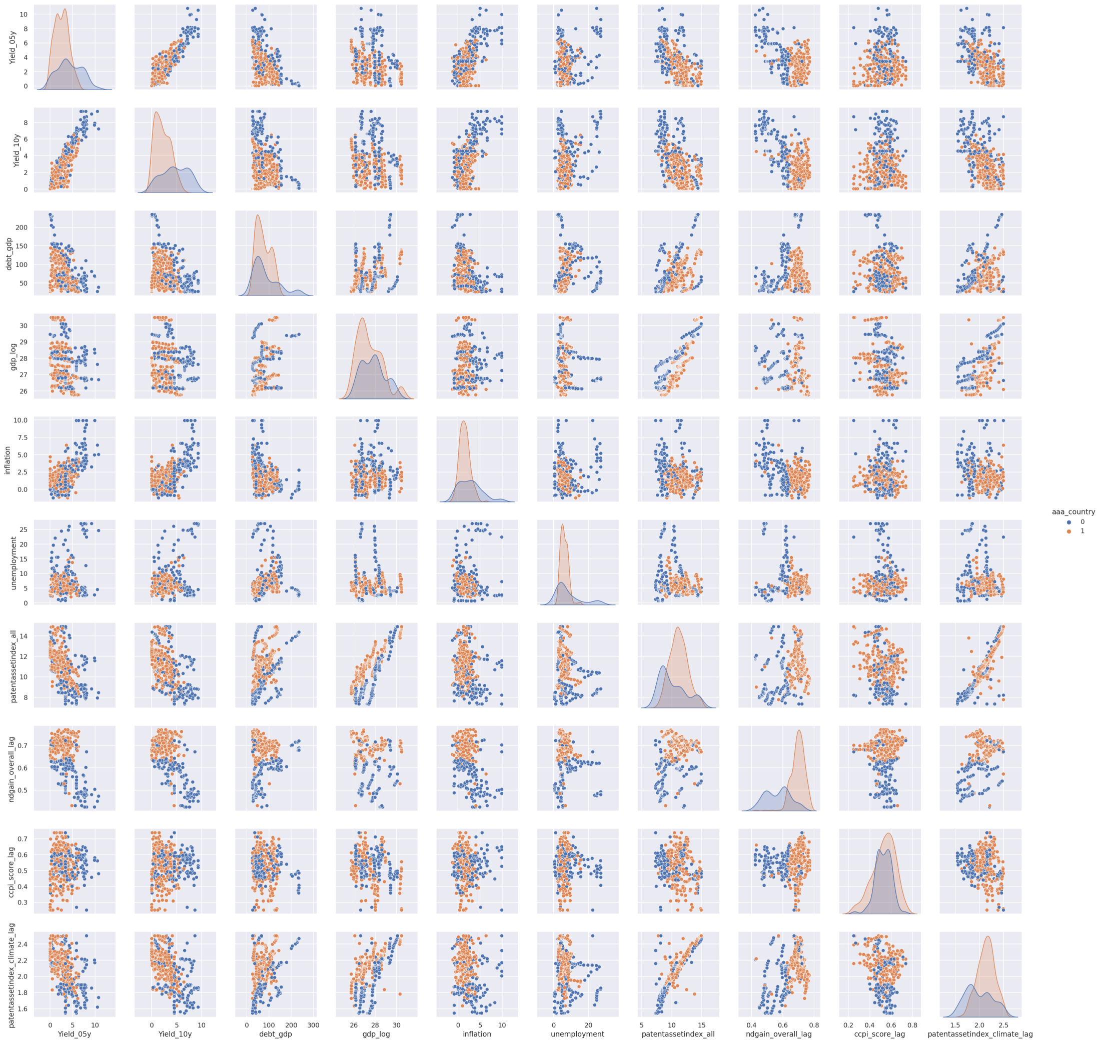

Figure 7: Pairwise scatterplots and distributions of control and explanatory variables for the *climate performance* analysis, differentiated by higher and lower-rated samples.

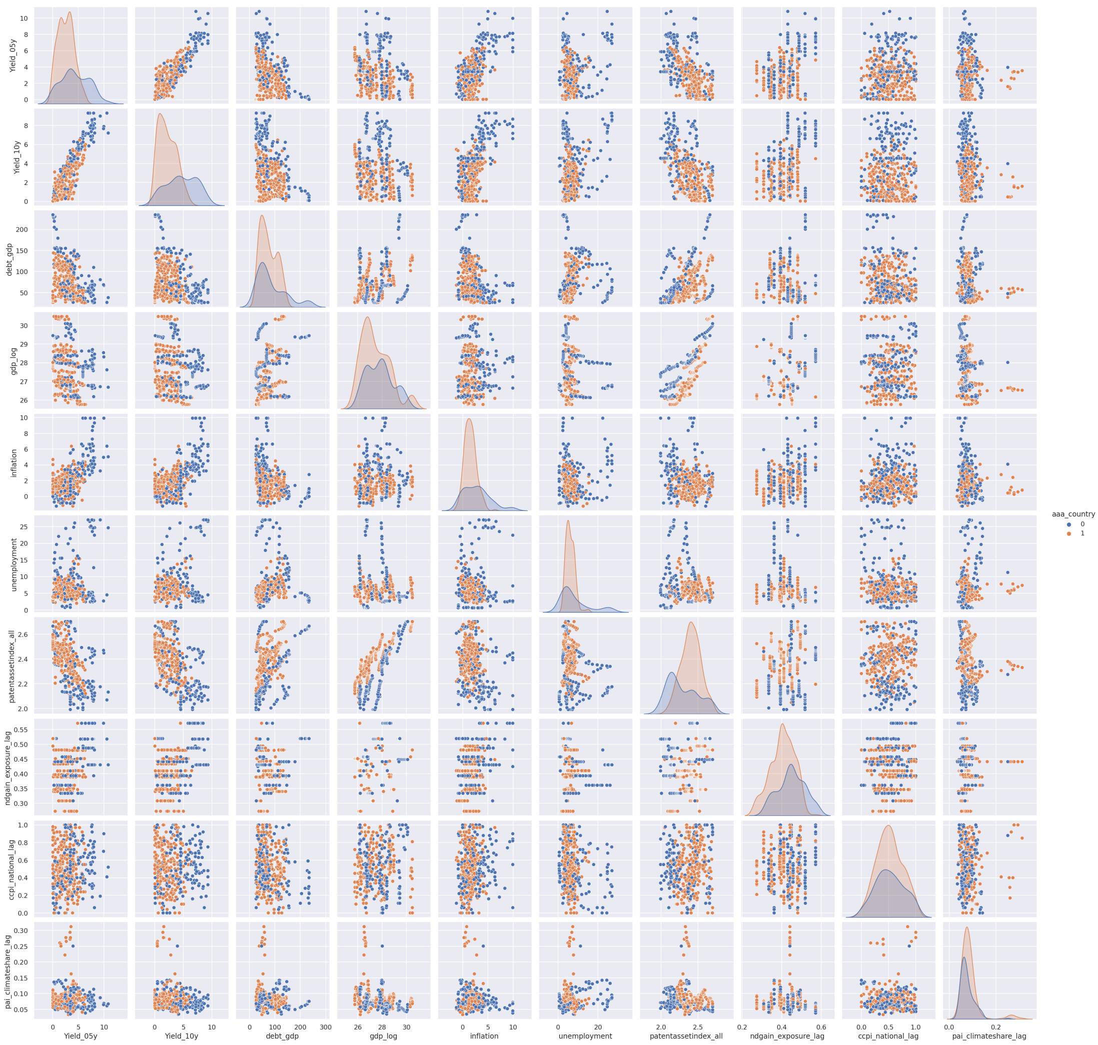

Figure 8: Pairwise scatterplots and distributions of control and explanatory variables for the *climate risk* analysis, differentiated by higher and lower-rated samples.

6.2 Macro models explanatory power

	2008-2021 Full (SR)	2015-2021 Full (SR)	2008-2021 Full (LR)	2015-2021 Full (LR)
Dep. Variable	Yield_05y	Yield_05y	Yield_10y	Yield_10y
Estimator	PanelOLS	PanelOLS	PanelOLS	PanelOLS
No. Observations	406	203	406	203
Cov. Est.	Clustered	Clustered	Clustered	Clustered
R-squared	0.6131	0.6940	0.7207	0.8313
R-Squared (Between)	0.8002	0.8378	0.8681	0.8919
R-Squared (Adjusted)	0.7961	0.8654	0.8311	0.8874
F-statistic	87.158	61.239	141.90	133.07
P-value (F-stat)	0.0000	0.0000	0.0000	0.0000
const	6.7387**	1.4887	-1.3710	-7.7427**
	(3.3087)	(2.9802)	(3.4314)	(3.9013)
rating_sp	0.1303	0.1651	0.2138**	0.2844***
	(0.1147)	(0.1092)	(0.0948)	(0.0746)
eurozone_yes	-0.2114	0.0102	-0.3867*	-0.7766***
	(0.2434)	(0.3261)	(0.2219)	(0.2300)
debt_gdp	-0.0089**	-0.0110***	-0.0088**	-0.0138***
	(0.0044)	(0.0034)	(0.0042)	(0.0032)
gdp_log	0.1204	0.3613	0.4821*	0.7350***
	(0.3029)	(0.2590)	(0.2698)	(0.2628)
inflation	0.4513***	0.6943***	0.3523***	0.4593***
	(0.0989)	(0.1282)	(0.0679)	(0.0927)
unemployment	0.0524	0.0130	0.0791***	0.0782**
	(0.0341)	(0.0431)	(0.0250)	(0.0360)
patentassetindex_all	-9.1749	-11.067	-11.799*	-12.905**
	(7.8004)	(6.7470)	(6.6057)	(5.7027)
Effects	Time	Time	Time	Time

Std. Errors are reported in parentheses. Statistical significance displayed at the 1% (***), 5% (**) and 10% (*) level. I refer to the 05-year maturities as short-run (SR), and to the 10-year maturities as long run (LR). The estimates represent values for the 05-year (SR) and 10-year (LR) government bond maturities, for the years 2008-2021 and 2015-2021 (i.e. after the Paris Agreement).

Table 13: Regression results of the macro variables model for the full sample.

	2008-2021 ≥AA- (SR)	2015-2021 ≥AA- (SR)	2008-2021 ≥AA- (LR)	2015-2021 ≥AA- (LR)
Dep. Variable	Yield_05y	Yield_05y	Yield_10y	Yield_10y
Estimator	PanelOLS	PanelOLS	PanelOLS	PanelOLS
No. Observations	252	126	252	126
Cov. Est.	Clustered	Clustered	Clustered	Clustered
R-squared	0.4922	0.3926	0.4388	0.3666
R-Squared (Between)	0.7723	0.7517	0.6622	0.5914
R-Squared (Adjusted)	0.7647	0.6510	0.7347	0.5634
F-statistic	31.988	10.341	25.801	9.2600
P-value (F-stat)	0.0000	0.0000	0.0000	0.0000
const	10.079***	3.0884	3.4399	1.2179
	(3.2941)	(3.0707)	(2.8085)	(2.5892)
rating_sp	-0.3003**	-0.1284	-0.1553	-0.1165
	(0.1403)	(0.1081)	(0.1239)	(0.0985)
eurozone_yes	0.1265	0.3085	-0.2272	-0.6042***
	(0.2725)	(0.2669)	(0.2182)	(0.2058)
debt_gdp	0.0008	-0.0030	0.0018	0.0019
	(0.0054)	(0.0047)	(0.0038)	(0.0029)
gdp_log	0.7696***	0.9897***	0.7395***	0.6632***
	(0.2840)	(0.2158)	(0.2528)	(0.1689)
inflation	-0.1819*	-0.1549	-0.0902	-0.2167**
	(0.1017)	(0.1626)	(0.1034)	(0.0855)
unemployment	0.0486	0.0237	0.1438**	0.0343
	(0.0481)	(0.0724)	(0.0581)	(0.0421)
patentassetindex_all	-32.148***	-31.427***	-25.117***	-20.122***
	(6.4086)	(5.3131)	(6.1120)	(4.5045)
Effects	Time	Time	Time	Time

Std. Errors are reported in parentheses. Statistical significance displayed at the 1% (***), 5% (**) and 10% (*) level. I refer to the 05-year maturities as short-run (SR), and to the 10-year maturities as long run (LR). The estimates represent values for the 05-year (SR) and 10-year (LR) government bond maturities, for the years 2008-2021 and 2015-2021 (i.e. after the Paris Agreement). The higher-rated sample consists of countries that were rated higher or equal to AA- by Standard & Poors as of January 2022.

Table 14: Regression results of the macro variables model for the higher-rated sample.

	2008-2021 <AA- (SR)	2015-2021 <AA- (SR)	2008-2021 <AA- (LR)	2015-2021 <AA- (LR)
Dep. Variable	Yield_05y	Yield_05y	Yield_10y	Yield_10y
Estimator	PanelOLS	PanelOLS	PanelOLS	PanelOLS
No. Observations	154	77	154	77
Cov. Est.	Clustered	Clustered	Clustered	Clustered
R-squared	0.8003	0.8642	0.8585	0.9477
R-Squared (Between)	0.9301	0.9403	0.9777	0.9827
R-Squared (Adjusted)	0.9262	0.9764	0.9332	0.9806
F-statistic	76.133	57.279	115.31	162.99
P-value (F-stat)	0.0000	0.0000	0.0000	0.0000
const	-11.311	-14.151	-20.193***	-31.101***
	(10.624)	(14.519)	(5.9386)	(10.090)
rating_sp	0.6705***	0.6727**	0.7014***	0.8021***
	(0.1813)	(0.2536)	(0.1151)	(0.1290)
eurozone_yes	-0.8228	-1.1341*	-1.0278**	-2.1032***
	(0.5040)	(0.6020)	(0.3936)	(0.2719)
debt_gdp	-0.0119***	-0.0074**	-0.0118***	-0.0094***
	(0.0032)	(0.0032)	(0.0022)	(0.0018)
gdp_log	0.5061	0.7788	1.0199***	1.6365***
	(0.3859)	(0.5503)	(0.2781)	(0.4408)
inflation	0.2983***	0.5440**	0.1991***	0.2163**
	(0.1129)	(0.2092)	(0.0667)	(0.1051)
unemployment	0.0418	0.0020	0.0657***	0.0795***
	(0.0260)	(0.0376)	(0.0159)	(0.0208)
patentassetindex_all	-4.4708	-10.839**	-10.740***	-19.508***
	(3.3145)	(5.1385)	(3.9106)	(4.2707)
Effects	Time	Time	Time	Time

Std. Errors are reported in parentheses. Statistical significance displayed at the 1% (***), 5% (**) and 10% (*) level. I refer to the 05-year maturities as short-run (SR), and to the 10-year maturities as long run (LR). The estimates represent values for the 05-year (SR) and 10-year (LR) government bond maturities, for the years 2008-2021 and 2015-2021 (i.e. after the Paris Agreement). The lower-rated sample consists of countries that were rated lower than AA- by Standard & Poors as of January 2022.

Table 15: Regression results of the macro variables model for the lower-rated sample.

6.3 Robustness checks

6.3.1 Spreads - US treasury bills

	2008-2021 Full (SR)	2015-2021 Full (SR)	2008-2021 Full (LR)	2015-2021 Full (LR)
Dep. Variable	Spread_05y_USA	Spread_05y_USA	Spread_10y_USA	Spread_10y_USA
Estimator	PanelOLS	PanelOLS	PanelOLS	PanelOLS
No. Observations	406	203	406	203
Cov. Est.	Clustered	Clustered	Clustered	Clustered
R-squared	0.6431	0.7224	0.7510	0.8456
R-Squared (Between)	0.8181	0.8612	0.8771	0.9031
R-Squared (Adjusted)	0.8130	0.8736	0.8532	0.8975
F-statistic	68.821	48.394	115.20	101.85
P-value (F-stat)	0.0000	0.0000	0.0000	0.0000
const	10.430*	14.519	3.3019	0.2849
	(5.9630)	(9.4640)	(4.8301)	(7.3035)
rating_sp	-0.0260	-0.0829	0.0614	0.0685
	(0.1090)	(0.1446)	(0.0972)	(0.1260)
eurozone_yes	-0.3823*	-0.2453	-0.4912**	-0.9510***
	(0.2072)	(0.3249)	(0.2195)	(0.2528)
debt_gdp	-0.0052	-0.0048	-0.0054	-0.0085**
	(0.0042)	(0.0041)	(0.0041)	(0.0039)
gdp_log	0.0107	0.1722	0.3287	0.4944*
	(0.2708)	(0.2808)	(0.2424)	(0.2797)
inflation	0.4257***	0.5888***	0.3299***	0.3682***
	(0.0843)	(0.1332)	(0.0509)	(0.0897)
unemployment	0.0621*	0.0230	0.0840***	0.0889***
	(0.0338)	(0.0402)	(0.0236)	(0.0323)
patentassetindex_all	-7.3132	-13.887	-9.4112	-9.9437
	(7.1594)	(10.181)	(6.1894)	(11.897)
ndgain_overall_lag	-6.9527**	-10.496**	-7.0804**	-9.0053**
	(3.3167)	(4.6340)	(3.1488)	(4.1591)
ccpi_score_lag	1.6784	2.2951*	0.0768	0.7918
	(1.4279)	(1.2358)	(1.1759)	(1.2018)
patentassetindex_climate_lag	-0.8172	1.5011	-0.8715	-1.0255
	(1.5859)	(3.6660)	(1.2847)	(4.4625)
Effects	Time	Time	Time	Time

Std. Errors are reported in parentheses. Statistical significance displayed at the 1% (***), 5% (**) and 10% (*) level. I refer to the 05-year maturities as short-run (SR), and to the 10-year maturities as long run (LR). The estimates represent values for the 05-year (SR) and 10-year (LR) government bond maturities, for the years 2008-2021 and 2015-2021 (i.e. after the Paris Agreement). The spreads represent the individual country's yield spread against the US treasury bills of the same maturity.

Table 16: Regression results US spreads *climate performance* model for the full sample.

	2008-2021 ≥AA- (SR)	2015-2021 ≥AA- (SR)	2008-2021 ≥AA- (LR)	2015-2021 ≥AA- (LR)
Dep. Variable	Spread_05y_USA	Spread_05y_USA	Spread_10y_USA	Spread_10y_USA
Estimator	PanelOLS	PanelOLS	PanelOLS	PanelOLS
No. Observations	252	126	252	126
Cov. Est.	Clustered	Clustered	Clustered	Clustered
R-squared	0.5082	0.3973	0.4855	0.4815
R-Squared (Between)	0.7875	0.7613	0.7421	0.7526
R-Squared (Adjusted)	0.7778	0.7302	0.7382	0.7287
F-statistic	23.557	7.1857	21.517	10.121
P-value (F-stat)	0.0000	0.0000	0.0000	0.0000
const	1.4588	-1.6380	-5.3005	-14.259**
	(3.7004)	(5.5400)	(3.6840)	(5.9736)
rating_sp	-0.2636*	-0.0878	-0.0771	-0.0189
	(0.1354)	(0.1107)	(0.1310)	(0.1190)
eurozone_yes	0.1186	0.3111	-0.1855	-0.5104***
	(0.2463)	(0.2493)	(0.1958)	(0.1809)
debt_gdp	0.0014	-0.0036	0.0029	0.0067*
	(0.0047)	(0.0040)	(0.0039)	(0.0034)
gdp_log	0.7741***	1.0296***	0.6661***	0.5869***
	(0.2713)	(0.2210)	(0.2227)	(0.1819)
inflation	-0.1349	-0.1260	-0.0605	-0.2923***
	(0.1041)	(0.1706)	(0.0820)	(0.0724)
unemployment	0.0404	0.0266	0.1349**	-0.0035
	(0.0465)	(0.0613)	(0.0626)	(0.0315)
patentassetindex_all	-27.740***	-30.671***	-19.528***	-11.323
	(6.2726)	(9.0648)	(5.2597)	(7.9211)
ndgain_overall_lag	2.8320	1.4549	4.9902	10.940**
	(3.4171)	(4.6002)	(3.6793)	(4.4849)
ccpi_score_lag	0.6540	0.7137	-1.3976*	-2.0124***
	(1.0476)	(1.0536)	(0.8427)	(0.6867)
patentassetindex_climate_lag	-2.3815	-0.3247	-2.3893***	-4.3827
	(1.7640)	(2.8354)	(0.7100)	(3.1612)
Effects	Time	Time	Time	Time

Std. Errors are reported in parentheses. Statistical significance displayed at the 1% (***), 5% (**) and 10% (*) level. I refer to the 05-year maturities as short-run (SR), and to the 10-year maturities as long run (LR). The estimates represent values for the 05-year (SR) and 10-year (LR) government bond maturities, for the years 2008-2021 and 2015-2021 (i.e. after the Paris Agreement). The higher-rated sample consists of countries that were rated higher or equal to AA- by Standard & Poors as of January 2022. The spreads represent the individual country's yield spread against the US treasury bills of the same maturity.

Table 17: Regression results US spreads *climate performance* model for the higher-rated sample.

	2008-2021 <AA- (SR)	2015-2021 <AA- (SR)	2008-2021 <AA- (LR)	2015-2021 <AA- (LR)
Dep. Variable	Spread_05y_USA	Spread_05y_USA	Spread_10y_USA	Spread_10y_USA
Estimator	PanelOLS	PanelOLS	PanelOLS	PanelOLS
No. Observations	154	77	154	77
Cov. Est.	Clustered	Clustered	Clustered	Clustered
R-squared	0.8168	0.8874	0.8782	0.9576
R-Squared (Between)	0.9296	0.9575	0.9804	0.9908
R-Squared (Adjusted)	0.9241	0.0.9788	0.9502	0.9891
F-statistic	57.942	47.285	93.764	135.57
P-value (F-stat)	0.0000	0.0000	0.0000	0.0000
const	3.4127	23.721	-5.0413	-9.4461
	(19.443)	(20.787)	(9.9012)	(11.509)
rating_sp	0.3642	0.0192	0.3812***	0.4615**
	(0.2556)	(0.3853)	(0.1364)	(0.1996)
eurozone_yes	-0.5443	-0.6706	-0.7150**	-2.0772***
	(0.3742)	(0.6015)	(0.2995)	(0.4233)
debt_gdp	-0.0039	0.0080	-0.0034	-0.0009
	(0.0047)	(0.0064)	(0.0038)	(0.0034)
gdp_log	0.3518	-0.2522	0.8672***	1.3445**
	(0.4833)	(0.8210)	(0.2739)	(0.6092)
inflation	0.3263***	0.5331***	0.2290***	0.1935**
	(0.1149)	(0.1754)	(0.0479)	(0.0937)
unemployment	0.0425	0.0130	0.0643***	0.0829***
	(0.0258)	(0.0292)	(0.0116)	(0.0158)
patentassetindex_all	-8.4719	-5.2372	-15.468**	-27.289**
	(5.4957)	(14.823)	(6.1885)	(10.868)
ndgain_overall_lag	-11.120*	-21.659***	-11.661***	-11.025**
	(6.1458)	(7.3067)	(3.9489)	(4.2653)
ccpi_score_lag	-0.4209	0.2707	-0.5525	1.2667
	(1.1282)	(5.5934)	(1.2045)	(2.6696)
patentassetindex_climate_lag	1.2049	-0.5375	1.4753	3.5307
	(1.8352)	(4.2873)	(1.5531)	(2.6655)
Effects	Time	Time	Time	Time

Std. Errors are reported in parentheses. Statistical significance displayed at the 1% (***), 5% (**) and 10% (*) level. I refer to the 05-year maturities as short-run (SR), and to the 10-year maturities as long run (LR). The estimates represent values for the 05-year (SR) and 10-year (LR) government bond maturities, for the years 2008-2021 and 2015-2021 (i.e. after the Paris Agreement). The lower-rated sample consists of countries that were rated lower than AA- by Standard & Poors as of January 2022. The spreads represent the individual country's yield spread against the US treasury bills of the same maturity.

Table 18: Regression results US spreads *climate performance* model for the lower-rated sample.

6.3.2 Spreads - German Bund bonds

	2008-2021 Full (SR)	2015-2021 Full (SR)	2008-2021 Full (LR)	2015-2021 Full (LR)
Dep. Variable	Spread_05y_DEU	Spread_05y_DEU	Spread_10y_DEU	Spread_10y_DEU
Estimator	PanelOLS	PanelOLS	PanelOLS	PanelOLS
No. Observations	406	203	406	203
Cov. Est.	Clustered	Clustered	Clustered	Clustered
R-squared	0.6436	0.7224	0.7546	0.8455
R-Squared (Between)	0.8185	0.8611	0.8799	0.9030
R-Squared (Adjusted)	0.8134	0.8765	0.8531	0.8974
F-statistic	68.983	48.413	117.47	101.81
P-value (F-stat)	0.0000	0.0000	0.0000	0.0000
const	10.115*	13.897	4.0816	1.4814
	(5.9463)	(9.4679)	(4.7801)	(7.2399)
rating_sp	-0.0256	-0.0828	0.0642	0.0667
	(0.1090)	(0.1444)	(0.0962)	(0.1268)
eurozone_yes	-0.3820*	-0.2424	-0.4963**	-0.9381***
	(0.2066)	(0.3236)	(0.2137)	(0.2476)
debt_gdp	-0.0052	-0.0049	-0.0055	-0.0084**
	(0.0042)	(0.0042)	(0.0041)	(0.0040)
gdp_log	0.0109	0.1791	0.3160	0.4984*
	(0.2705)	(0.2827)	(0.2347)	(0.2771)
inflation	0.4254***	0.5889***	0.3297***	0.3721***
	(0.0843)	(0.1331)	(0.0499)	(0.0917)
unemployment	0.0622*	0.0232	0.0826***	0.0871***
	(0.0337)	(0.0403)	(0.0231)	(0.0321)
patentassetindex_all	-7.2944	-14.012	-9.0558	-10.035
	(7.1728)	(10.232)	(6.0952)	(11.801)
ndgain_overall_lag	-6.9433**	-10.460**	-7.0871**	-8.9962**
	(3.3170)	(4.6444)	(3.1412)	(4.1869)
ccpi_score_lag	1.6892	2.3266*	0.0603	0.8049
	(1.4299)	(1.2307)	(1.1655)	(1.2074)
patentassetindex_climate_lag	-0.8163	1.5140	-0.8926	-1.0343
	(1.5853)	(3.6754)	(1.2840)	(4.4322)
Effects	Time	Time	Time	Time

Std. Errors are reported in parentheses. Statistical significance displayed at the 1% (***), 5% (**) and 10% (*) level. I refer to the 05-year maturities as short-run (SR), and to the 10-year maturities as long run (LR). The estimates represent values for the 05-year (SR) and 10-year (LR) government bond maturities, for the years 2008-2021 and 2015-2021 (i.e. after the Paris Agreement). The spreads represent the individual country's yield spread against the German bund bonds of the same maturity.

Table 19: Regression results German spreads *climate performance* model for the full sample.

	2008-2021 ≥AA- (SR)	2015-2021 ≥AA- (SR)	2008-2021 ≥AA- (LR)	2015-2021 ≥AA- (LR)
Dep. Variable	Spread_05y_DEU	Spread_05y_DEU	Spread_10y_DEU	Spread_10y_DEU
Estimator	PanelOLS	PanelOLS	PanelOLS	PanelOLS
No. Observations	252	126	252	126
Cov. Est.	Clustered	Clustered	Clustered	Clustered
R-squared	0.5080	0.3990	0.4816	0.4820
R-Squared (Between)	0.7873	0.7628	0.7390	0.7522
R-Squared (Adjusted)	0.7775	0.7270	0.7399	0.7282
F-statistic	23.545	7.2351	21.181	10.144
P-value (F-stat)	0.0000	0.0000	0.0000	0.0000
const	1.1181	-2.4272	-4.4656	-13.105**
	(3.7005)	(5.5745)	(3.6147)	(6.0074)
rating_sp	-0.2615*	-0.0911	-0.0625	-0.0233
	(0.1352)	(0.1116)	(0.1273)	(0.1206)
eurozone_yes	0.1182	0.3133	-0.1959	-0.5080***
	(0.2459)	(0.2478)	(0.1903)	(0.1806)
debt_gdp	0.0014	-0.0036	0.0026	0.0068**
	(0.0047)	(0.0040)	(0.0040)	(0.0034)
gdp_log	0.7728***	1.0374***	0.6388***	0.5915***
	(0.2717)	(0.2235)	(0.2151)	(0.1818)
inflation	-0.1325	-0.1282	-0.0434	-0.2945***
	(0.1026)	(0.1726)	(0.0724)	(0.0732)
unemployment	0.0404	0.0255	0.1338**	-0.0043
	(0.0466)	(0.0612)	(0.0627)	(0.0317)
patentassetindex_all	-27.687***	-30.693***	-18.790***	-11.412
	(6.2912)	(9.0455)	(5.0281)	(7.8825)
ndgain_overall_lag	2.8952	1.5448	4.9940	10.960**
	(3.4133)	(4.6445)	(3.6137)	(4.5073)
ccpi_score_lag	0.6545	0.7262	-1.4100*	-1.9970***
	(1.0401)	(1.0413)	(0.8310)	(0.6866)
patentassetindex_climate_lag	-2.3696	-0.4208	-2.3145***	-4.4449
	(1.5370)	(2.8229)	(0.6847)	(3.1979)
Effects	Time	Time	Time	Time

Std. Errors are reported in parentheses. Statistical significance displayed at the 1% (***), 5% (**) and 10% (*) level. I refer to the 05-year maturities as short-run (SR), and to the 10-year maturities as long run (LR). The estimates represent values for the 05-year (SR) and 10-year (LR) government bond maturities, for the years 2008-2021 and 2015-2021 (i.e. after the Paris Agreement). The higher-rated sample consists of countries that were rated higher or equal to AA- by Standard & Poors as of January 2022. The spreads represent the individual country's yield spread against the German bund bonds of the same maturity.

Table 20: Regression results German spreads *climate performance* model for the higher-rated sample.

	2008-2021 <AA- (SR)	2015-2021 <AA- (SR)	2008-2021 <AA- (LR)	2015-2021 <AA- (LR)
Dep. Variable	Spread_05y_DEU	Spread_05y_DEU	Spread_10y_DEU	Spread_10y_DEU
Estimator	PanelOLS	PanelOLS	PanelOLS	PanelOLS
No. Observations	154	77	154	77
Cov. Est.	Clustered	Clustered	Clustered	Clustered
R-squared	0.8170	0.8874	0.8793	0.9573
R-Squared (Between)	0.9297	0.9576	0.9799	0.9909
R-Squared (Adjusted)	0.9242	0.9783	0.9504	0.9893
F-statistic	58.026	47.303	94.678	134.62
P-value (F-stat)	0.0000	0.0000	0.0000	0.0000
const	3.0719	23.022	-3.8565	-7.5544
	(19.445)	(20.758)	(9.7956)	(11.456)
rating_sp	0.3655	0.0189	0.3656***	0.4548**
	(0.2558)	(0.3861)	(0.1338)	(0.1971)
eurozone_yes	-0.5462	-0.6895	-0.7050**	-1.9630***
	(0.3749)	(0.6055)	(0.2960)	(0.4180)
debt_gdp	-0.0040	0.0079	-0.0030	-0.0010
	(0.0047)	(0.0064)	(0.0036)	(0.0033)
gdp_log	0.3510	-0.2507	0.8580***	1.3139**
	(0.4835)	(0.8200)	(0.2742)	(0.6058)
inflation	0.3248***	0.5300***	0.2291***	0.2071**
	(0.1151)	(0.1753)	(0.0499)	(0.0997)
unemployment	0.0427	0.0137	0.0640***	0.0790***
	(0.0258)	(0.0292)	(0.0120)	(0.0170)
patentassetindex_all	-8.4267	-5.2154	-15.345**	-26.646**
	(5.4922)	(14.771)	(6.0100)	(10.856)
ndgain_overall_lag	-11.106*	-21.591***	-12.143***	-11.290***
	(6.1436)	(7.3167)	(3.7972)	(4.0701)
ccpi_score_lag	-0.3621	0.4853	-0.4997	0.8151
	(1.1233)	(5.6389)	(1.1374)	(2.4771)
patentassetindex_climate_lag	1.2031	-0.5395	1.4123	3.3420
	(1.8366)	(4.2720)	(1.5018)	(2.6976)
Effects	Time	Time	Time	Time

Std. Errors are reported in parentheses. Statistical significance displayed at the 1% (***), 5% (**) and 10% (*) level. I refer to the 05-year maturities as short-run (SR), and to the 10-year maturities as long run (LR). The estimates represent values for the 05-year (SR) and 10-year (LR) government bond maturities, for the years 2008-2021 and 2015-2021 (i.e. after the Paris Agreement). The lower-rated sample consists of countries that were rated lower than AA- by Standard & Poors as of January 2022. The spreads represent the individual country's yield spread against the German bund bonds of the same maturity.

Table 21: Regression results German spreads *climate performance* model for the lower-rated sample.

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