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Look up and ahead: How climate scenarios affect European sovereign credit risk

Luca De Angelis[a], Irene Monasterolo[b,c,d], Luca Zanin[e,*]

[a] *University of Bologna, Italy*
[b] *Utrecht University, The Netherlands*
[c] *WU Wien, Austria*
[d] *CEPR, United Kingdom*
[e] *Prometeia, Piazza Trento e Trieste 3, 40137 Bologna, Italy*

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ABSTRACT

We provide empirical evidence on the potential evolution of future climate-related impacts on sovereign credit risk in Europe, measured through sovereign Credit Default Swap (CDS) spreads and risk-neutral implied probabilities of default. We analyze the interaction between countries' climate risk exposure and their fiscal and financial fundamentals using a panel model estimated with annual data for 24 European countries over the period 2010–2022. The estimated model is then used to project sovereign credit risk up to 2050 under the supervisory climate scenarios developed by the Network for Greening the Financial System (NGFS). Results reveal both temporal and structural dimensions of climate-related sovereign risk. In the short term, adjustments to GDP and fiscal policy induced by climate transition risk increase sovereign risk. Over the long run, however, an orderly transition toward the Net Zero 2050 target leads to lower sovereign credit risk than a delayed or less ambitious transition in greenhouse gas emissions reduction. The increase in sovereign risk is particularly pronounced in economies with carbon-intensive production. Our findings underscore the importance of timely and credible climate policy in enhancing sovereign debt sustainability in Europe amid growing climate change impacts.

1. Introduction

Climate risks are becoming increasingly material for countries' economies (Kreibiehl et al., 2022; Waidelich et al., 2024). Economic losses can propagate to the financial system and ultimately threaten financial stability (Battiston et al., 2017; Roncoroni et al., 2021), a concern increasingly recognized by central banks and financial regulators (Battiston, Monasterolo, & Montone, 2021; BIS, 2024; ECB, 2020; NGFS, 2019). On the one hand, extreme weather and climate-related events impair production and consumption by destroying productive capital and infrastructures, decreasing labor productivity, and reducing economic growth (Mazzocchetti et al., 2025; Noy, 2009). Weaker output, combined with lower fiscal revenues and higher reconstruction costs, deteriorates public finances and ultimately countries' creditworthiness (Campiglio et al., 2025; Hallegatte et al., 2022; Monasterolo et al., 2024). On the other hand, the transition to a low-carbon economy requires a profound restructuring of production systems away from fossil fuels toward cleaner, renewable energy sources (IEA, 2023). Although this process entails near-term adjustment

* Corresponding author.
E-mail addresses: l.deangelis@unibo.it (L. De Angelis), i.monasterolo1@uu.nl (I. Monasterolo), luca.zanin@studio.unibo.it (L. Zanin).

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costs, these are significantly lower than those resulting from a delayed or disorderly transition (Emambakhsh et al., 2023), and can generate long-term co-benefits for growth and resilience (Batini et al., 2022).

A growing number of international financial institutions and supervisory authorities are integrating climate risks (transition and physical) into their risk assessment and stress-testing frameworks (Alqaralleh, 2024; Battiston, Monasterolo, & Montone, 2021; ESM, 2024). Academic research has so far mostly focused on corporate climate risk, while empirical work on sovereign credit risk remains limited and largely backwards-looking, relying on historical emissions or disaster losses (Beirne et al., 2021; Kling et al., 2025; Klusak et al., 2023). Yet, a country's sovereign creditworthiness and debt sustainability may evolve very differently depending on how climate risks and policy responses unfold (Battiston & Monasterolo, 2020).

In this paper, we address this gap by proposing an explicit mapping from forward-looking, country-level decarbonization pathways to market-based sovereign credit risk, proxied by sovereign Credit Default Swap (CDS) spreads. The objective of this study is to quantify the potential impact of climate transition scenarios on sovereign credit risk. We condition the evolution of sovereign credit risk on projected trajectories of emissions-intensity decarbonization and key macro-financial variables under alternative assumptions about climate policy and physical-risk impacts. This approach ensures that the assessment of climate risk impacts on projected sovereign spreads and related default probabilities is internally consistent with the underlying climate mitigation scenarios.

To evaluate the impact of climate risks on sovereign credit risk, we consider the long-term climate scenarios developed by the Network for Greening the Financial System (NGFS) (Network for Greening the Financial System (NGFS), 2024), which are now a reference for climate financial risk assessment among central banks, financial institutions and investors (e.g., Aiello et al., 2024; Darracq Paries et al., 2023; Emambakhsh et al., 2023; Holden et al., 2024). These scenarios provide decarbonization pathways compatible with the carbon budget associated to specific temperature targets (e.g., 1.5 °C or 2 °C), while accounting for policy stringency, technological progress, and sectoral characteristics of output by country.[1]

By combining these climate scenarios with an empirical model linking sovereign CDS spreads to macro-financial fundamentals, we project how transition and physical risks, together with associated policy responses, may shape sovereign credit dynamics in Europe.[2]

In the empirical analysis, we focus on a panel of 24 European countries using annual data from 2010 to 2022. Europe offers an ideal setting for this analysis, given its ambitious climate policy framework, anchored in the EU Climate Law (2021) and the Green Deal investment program[3] combined with substantial heterogeneity in economic structures, fiscal positions, sovereign ratings, and climate ambition. This heterogeneity is an important driver of cross-country differences in sovereign risk within Europe (Buchholz & Tonzer, 2016), making the region particularly suitable for assessing how climate-related transition and macro-financial dynamics translate into sovereign credit risk. Differences in debt-to-GDP ratios, exposure to energy shocks, and core macroeconomic fundamentals further enrich the cross-country comparison.[4]

We estimate a fixed-effects panel model of sovereign CDS spreads[5] as a function of macro-financial fundamentals and decarbonization progress. Specifically, the explanatory set of variables considered in the model includes the debt-to-GDP ratio, long-term real interest rates, the change in the unemployment rate, stock market returns, and emissions intensity relative to 1990 levels as proxies for decarbonization progress. To ensure the robustness of our results, we compare fixed-effects OLS estimates with robust estimators that help mitigate the potential influence of outliers. Then, using the estimated model, we project sovereign CDS spreads and the corresponding risk-neutral default probabilities (PDs) up to 2050 under four long-term NGFS scenarios: Current Policies (serving as the baseline), Nationally Determined Contributions (NDCs), Net Zero 2050, and Delayed Transition. The NGFS scenarios provide projections for key macro-financial variables, such as long-term real interest rates, unemployment rates, stock market indices, and emissions, but do not include countries' fiscal indicators, notably the debt-to-GDP ratio. To bridge this gap, we generate projections of the debt-to-GDP ratio under each transition pathway, assuming both fully debt-stabilizing and less responsive debt-stabilizing. The resulting projections are derived from a reduced-form model based on scenario-dependent variables. They should not be interpreted as point forecasts of sovereign spreads or PDs to 2050. Rather, the objective is to assess how climate risks, operating through their effects on fundamental macro-financial variables and decarbonization progress, translate into a sovereign credit risk.

Our results indicate that the credibility and timing of climate policies can significantly influence the trajectory of the impact of future climate risks on sovereign credit risk. A delayed or disorderly transition increases fiscal vulnerabilities, raises sovereign spreads, and undermines investor confidence, as governments face greater revenue losses and higher adaptation costs. Conversely, an orderly and timely transition toward Net Zero yields measurable co-benefits through enhanced economic resilience, lower financing costs, and improved debt sustainability. These findings highlight that credible and early climate action is not only an environmental necessity but also a key pillar of sovereign financial stability.

The remainder of the paper is organized as follows. Section 2 reviews the literature on climate risks and sovereign credit risk. Section 3 outlines the main narratives of the NGFS climate scenarios, focusing on the four considered cases: Current Policies, NDCs,

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[1] Using integrated assessment models and the NiGEM macroeconomic model, the NGFS long-term climate scenarios provide country-specific pathways for a set of macro-financial variables, including GDP, stock market indices, long-term interest rates, and unemployment rates, together with emission-reduction trajectories, which we treat as scenario-consistent fundamentals; see the methodological documentation in NGFS (2024).

[2] Climate risks are inherently forward-looking, nonlinear, and characterized by tail dependencies and endogeneity. Our approach reflects the market's perception of the impact of future climate risks on sovereigns, quantifying how future macro-financial adjustments can affect sovereign risk pricing.

[3] COM/2021/550 final.

[4] See, for instance, the differentiated access to and allocation of Recovery and Resilience funds under the NextGenerationEU program.

[5] We focus on five-year CDS contracts, which are the most liquid maturity.

Net Zero 2050, and Delayed Transition. Section 4 describes the data on CDS spreads and the predictor variables, while Section 5 details the modeling framework. Section 6 presents the estimation results, while Section 7.2 discusses the projections of sovereign credit risk under the alternative scenarios. Finally, Section 8 concludes by highlighting the implications of the results for sovereign financial stability and risk surveillance. Appendices A and B report robustness checks and climate-mitigation scenarios for predictors, respectively. The Supplementary Material contains descriptive statistics, correlation matrices, and plots for all variables considered in the analysis.

2. Literature review

The sustainable finance literature has analyzed the impact of climate risks in financial markets and in the financial sector, focusing both on risk management, see e.g. the growing research on climate risks for financial stability (Battiston, Dafermos, & Monasterolo, 2021), and on a corporate and asset pricing perspective (e.g., Giglio et al., 2021; Prosperi & Zanin, 2024; Zanin, 2023).

Within the literature on climate risk and sovereign risk, Battiston and Monasterolo (2020) developed a methodology to price climate scenarios into sovereign yields and spread, finding that countries with higher Gross Value Added (GVA) contribution from fossil fuels and high carbon activities will incur a higher adjustment of yields, and larger spread, in comparison to countries that have larger investments and share of GVA from low carbon and renewable energy. Collenderm et al. (2023) examined 23 advanced nations and 16 developing nations from 1999 to 2021, finding that climate transition risks are reflected in sovereign bond markets. Their findings also suggest that countries with lower carbon emissions face reduced borrowing costs. (Daki Dominique et al., 2026) examines the relationship between different types of carbon pricing systems and sovereign credit risk across 21 advanced and emerging economies over 2015–2022, showing that the impact of carbon pricing is both regime- and structure-dependent. Emissions trading systems (ETS) are associated with higher sovereign spreads, consistent with investor concerns about transition costs and fiscal pressures, whereas carbon taxes appear broadly neutral, and hybrid regimes (combining tax and trading elements) tend to mitigate risk by enhancing policy credibility and flexibility. They further document that, in diversified economies, institutional quality and energy dependence mediate the pricing of carbon-related risks, whereas in fossil-fuel-dependent countries, carbon pricing itself becomes a primary transmission channel to sovereign spreads.

Sun et al. (2023) suggested that climate vulnerability has emerged as an important factor in the sovereign rating system. Specifically, they found that the effects of climate risks are particularly significant for developing countries and those that have already suffered considerable damage. Additionally, they also suggest that enhancing climate preparedness in these nations could yield substantial benefits. That credit rating agencies are incorporating climate risks in their evaluations of sovereign ratings is also documented by Cappiello et al. (2025). Klusak et al. (2023) estimate instead that climate change could lead to downgrades in sovereign credit ratings with a ripple effect in increasing annual interest payments on sovereign debt, especially under a Representative Concentration Pathways (RCP) 8.5 in terms of emissions. However, they also estimate that implementing climate policies aligning with the Paris Climate Agreement could mitigate these impacts.

Yang and Hamori (2023) investigated the tail dependence of the global sovereign CDS market conditional on global extreme weather events derived from four climatic teleconnection indices (the North Atlantic Oscillation, Arctic Oscillation, Pacific North American Oscillation, and Antarctic Oscillation). They found that climate disasters impact country-specific sovereign risk with heterogeneous network structure outcomes. Moreover, they estimate an asymmetric risk spillover effect in the global sovereign credit network, with the highest risk spillover occurring during extremely hot weather conditions. Cheng and Chang (2025) suggested that rare disaster shocks elevate the risk of sovereign default. However, they also reveal that external debt denominated in local currency can mitigate these adverse effects, offering a strategic buffer against such crises. The contagious effects of natural events on the sovereign CDS spreads have also been documented by Di Tommaso et al. (2023) in exploring EU countries. Pan et al. (2026) explored the relationship between climate change exposure and country sovereign credit risk using annual panel data from 51 countries over the period 2010–2020. They found that climate change exposure significantly increases sovereign credit risk, and this effect operates through economic and fiscal channels.

Naifar (2023) found an impact of the global climate policy uncertainty index among the determinants of the sovereign five-year CDS for 16 nations within the G20. They suggest, based on this finding, how global risk factors can influence the outcome. Anand et al. (2023) found that improved sustainability performance at the corporate level helps reduce market-based (CDS spreads) and structural (distance-to-default) sovereign credit risk. However, they found no impact on sovereign credit ratings. Alessi et al. (2025) explored the impact of the investments in the Recovery and Resilience Facility introduced by the European Commission in 2021 for EU member states. They found that investors are incorporating climate-related investments into their country risk evaluations, as proxied by sovereign bond yields. They observed a decrease in yields on sovereign bonds; the longer the maturity, the greater the decline, driven by climate funds.

More contributions focus on the links between CDS and corporate sustainability. Blasberg et al. (2022) construct a novel measure of transition risk through firms' carbon emission intensity data and shows that this factor is a relevant driver of CDS spreads. Barth et al. (2022) and Christ et al. (2022) focus on ESG ratings as a proxy of a firm's sustainability, and find that better environmental ratings are related to lower CDS spreads. Kölbel et al. (2022) investigate the relationship between the cost of default protection and a measure of transition risk based on corporate disclosure, finding that higher exposure to transition risks increases CDS spreads. Likewise, Carbone et al. (2021) considers climate disclosure practices and prospective emission reduction targets in addition to firms' emission intensity as factors that may influence credit risk. Focusing on energy companies, Campiglio et al. (2025) find that the impact of media-based measures of transition risks on the credit risk of energy companies is significant only when combined with tangible physical climate-related events. Moreover, Cherubini et al. (2024) disentangle the market-implied probability and the severity of an unexpected transition event from CDS and put option prices, finding mixed results on the short-term impact of such climate policy shock on European energy and oil and gas companies and foreshadowing the presence of a too-big-to-fail issue. Other studies support that climate risks affect various firm-level measures of credit risk, including distance-to-default (Capasso et al., 2020; Nguyen et al., 2023).

Apart from Battiston and Monasterolo (2020), the literature on sovereign credit risk relies on past data, either on GHG emissions or natural hazards, using aggregate and proprietary scores. These approaches have two main limitations. On the one hand, these studies likely underestimate sovereign risk by neglecting climate scenarios and future climate impacts. Furthermore, aggregate risk scores provided by the industry are somewhat opaque, leading to substantial divergence among commercial risk scores (Hain et al., 2022) and potentially large underestimation of financial risk for investors (Bressan et al., 2024). Thus, we complement the existing literature on climate risk and CDS by incorporating climate scenarios in this study.

3. Assessing future climate risks: the NGFS climate scenarios

Long-term climate transition scenarios are a valuable tool for understanding the potential risks to the economy and finance, as well as the co-benefits of transitioning to a low-carbon economy. Using climate scenarios for financial risk analysis is crucial (NGFS, 2019) given the characteristics of climate change risk. The climate scenarios used by a growing number of investors, as well as over 140 central banks and financial supervisors, for climate financial risk assessment and climate stress testing, are co-developed by NGFS in collaboration with climate scientists and economists (Network for Greening the Financial System (NGFS), 2024). The NGFS scenarios provide output trajectories for economic sectors based on their energy technologies (e.g., coal, oil, gas, wind, solar), represented at a high level of granularity by country and region worldwide. The scenario shows how, conditioned to a science-based carbon budget aligned to a temperature target (e.g., 1.5 °C or 2 °C), and the timing and magnitude of climate policy (i.e., a carbon tax), the output of economic sectors and technologies should adjust.[6] The current vintage of NGFS scenarios has a high level of granularity in terms of energy technology, by relying on process-based Integrated Assessment Models (IAMs, i.e., GCAM, MESSAGE-GLobiom and REMIND-MagPie), which is a key advantage for conducting scenario-adjusted firms' cash flows and financial valuation (Battiston et al., 2024).

The NGFS scenarios from IAMs provide 5 years of output up to 2050 and 10 years from 2060 to 2100. In our analysis, we use the output trajectories of REMIND-MAgPIE 3.3–4.8 (V vintage). The National Institute of Economic and Social Research uses these trajectories as inputs to derive country-level economic and fiscal variables at an annual frequency from the NiGEM model.

In our analysis, we consider the following main NGFS scenarios:

- **Current policies:** assumes that only the current policies are implemented. Thus, no ambitious climate mitigation policy is assumed to be implemented, thus leading to exceeding 3 °C by 2100. As a result, climate-related physical risk is high, with large economic and financial losses from natural disasters and a growing chronic risk (e.g., sea level rise, temperature increase).
- **Nationally Determined Contributions (NDCs):** includes countries' stated emissions-reduction pledges under the Paris Agreement, including announced targets and associated policy intentions as of March 2024, even where implementation measures are not yet fully specified or legally binding. It thus represents moderate climate ambition relative to the more stringent Net Zero by 2050 scenario.
- **Net Zero 2050:** is an orderly transition scenario, in which ambitious climate policies (i.e., carbon tax) are implemented early to reach net zero CO_2 emissions around 2050 and limit global warming to 1.5 °C by 2100. In the short term, the Net Zero transition incurs economic costs due to the significant structural changes required in the economy, such as shifting from high-carbon and fossil fuels to renewable energy technologies like solar and wind. However, the economic costs (e.g., on GDP losses) are lower than in scenarios characterized by a late and sudden transition (Gourdel et al., 2024). Meanwhile, the transition brings co-benefits of mitigating climate change and reducing the associated risks, which outweigh the costs. Indeed, physical risks are lower due to timely mitigation action.
- **Delayed transition:** is a disorderly transition scenario in which a carbon price is assumed to be implemented only after 2030. This leads to higher economic costs because the carbon price must increase due to a reduced remaining carbon budget, necessitating more ambitious and rapid decarbonization. This, in turn, is expected to drive greater asset price volatility, as investors switch from high-carbon and fossil fuel firms (now less profitable due to the higher costs implied by the tax) to low-carbon alternatives, which are, however, limited. Thus, in a delayed transition, we have a larger transition risk for firms and their investors, with a later yet larger GDP fall and lower fiscal revenues for the governments (since the fall in revenues for high-carbon activities cannot be immediately compensated by the increase in revenues from low-carbon activities). In this context of low or negative GDP growth and lower fiscal revenues, it could be challenging for the government to repay interest on existing debt or to find resources to issue new debt, thus leading to higher sovereign risk and lower credit risk scores (Monasterolo et al., 2024).

These long-term NGFS scenarios have become a reference point for several global stakeholders, including policymakers, central banks, investors, and the productive system.[7] In brief, NGFS scenarios represent a baseline analytical infrastructure for integrating climate risk into global financial stability frameworks and transition policy planning.

[6] https://www.ngfs.net/ngfs-scenarios-portal/explore/

[7] Although with some well-known limitations in the assumptions and estimates, the purpose of this paper is not to discuss the validity of the NGFS scenarios but to use them in the same way practitioners might, for the purpose of projecting sovereign risk under various climate scenarios. The focus here is on applying these scenarios to project the sovereign credit risk, rather than evaluating their accuracy or the comprehensiveness of the underlying assumptions.

4. Data

We construct a comprehensive database by enriching the annual five-year CDS spreads for 24 European countries, obtained by Refinitiv, with economic and financial predictors from the International Monetary Fund (IMF), the World Bank, Datastream, and the International Energy Agency (IEA). The selection of explanatory variables follows the relevant empirical literature on the determinants of sovereign CDS spreads, with particular attention to macroeconomic and financial factors for which annual projections are available in the NGFS climate scenarios.

4.1. Sovereign CDS spread

We use the sovereign credit default swaps (CDS) spread to reflect the risk premia that investors assign to sovereign credit risk.[8] CDS are used by investors to hedge against the probability of default (PD) on sovereign debt securities (Blommestein et al., 2016). These contracts are available for different tenors, such as 1, 5, 10, and 30 years. We focus on the most liquid contracts, i.e. CDS spread with a five-year maturity (Longstaff et al., 2011; Pan et al., 2024), and we consider the sovereign CDS spread of the following European countries: Austria, Belgium, Croatia, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, and the United Kingdom. The sample period covers 2010–2022, and the CDS spread value is reported at the end of each year.[9] The sovereign CDS's time series plots are presented in Figures A.2–A.4 in the Supplementary Material, while descriptive statistics are reported in Table A.2. These plots reveal a spike in CDS spreads during 2010–2012, caused by the sovereign debt crisis in several European countries, including Greece, Ireland, Portugal, and Spain. This crisis had a contagion effect on all the other European countries considered here as well (Bampinas et al., 2023; Beirne & Fratzscher, 2013; Fontana & Scheicher, 2016). Afterwards, we note a gradual reduction in sovereign risk. However, in 2022, countries bordering Russia and Ukraine (Romania, Hungary, Latvia, Lithuania, Estonia, Poland, and Slovakia) experienced an increase in sovereign credit risk. This increase is mainly due to the ongoing war between the two countries (Tong, 2024). Estonia and Romania had the largest spikes in sovereign CDS spreads.

We conducted the Maddala–Wu panel unit root test (Maddala & Wu, 1999) to assess whether non-stationarity characterizes the panel dataset of the CDS spread time series within our dataset.[10] The obtained test statistic ($\chi^2 = 139.64$, p-value < 0.001) strongly indicates rejection of the null hypothesis of non-stationarity. This empirical outcome, which aligns with previous literature on sovereign CDS spreads, suggests that our panel data on CDS spreads are stationary. It is worth noting, however, that the influence of non-stationarity in a panel context tends to be less problematic than in individual time-series analysis; aggregation across units helps mitigate the persistence issues commonly encountered in single-country studies (Anand et al., 2023; Baltagi, 2013).

4.2. Predictor variables

The annual time series of five-year sovereign CDS spreads for each country is then merged with a set of macroeconomic and financial indicators in order to account for the determinants of sovereign default risk. Specifically, the analysis considers the general government gross debt-to-GDP ratio, the unemployment rate, stock market returns, the long-term government bond yield, and the change in emission intensity compared to 1990 levels, which serves as a proxy for the country's exposure to transition risk.

The literature suggests that a country's risk of default is closely linked to its government's debt dynamics (e.g., Alesina et al., 1992; Beirne & Fratzscher, 2013; Singh et al., 2021). A lack of fiscal space may also imply persistently higher credit spreads and more distortionary taxation, which in turn can exert a significant drag on productivity and growth (Baum et al., 2013; Cecchetti et al., 2011; Checherita-Westphal & Rother, 2012; Chudik et al., 2017; Reinhart et al., 2012; Woo & Kumar, 2015).

Sovereign credit risk is negatively affected by fiscal uncertainty (Hantzsche, 2022) as well as by adverse market reactions and interest rate adjustments (Fournier & Fall, 2017). Higher credit spreads arising from limited fiscal space may, in turn, hamper productivity and economic growth (Baum et al., 2013; Cecchetti et al., 2011; Woo & Kumar, 2015).

We use IMF data on the debt-to-GDP ratio to identify countries with the highest levels of indebtedness. Investors typically perceive countries with higher debt-to-GDP ratios as more exposed to sovereign credit risk, particularly during economic downturns. In such circumstances, governments may need to increase debt levels further to finance countercyclical fiscal policies and social expenditures (Novelli & Barcia, 2021).

Another macroeconomic variable commonly included in studies of sovereign CDS spreads is the unemployment rate (e.g., Arakelian et al., 2019; Boeck et al., 2023). This variable, retrieved from the IMF database, is one of the fundamental indicators used to monitor a country's economic performance over the business cycle. Consistent with Okun's law, an inverse and statistically significant relationship between unemployment and GDP growth is expected, as documented by several empirical studies (Donayre,

[8] The sovereign CDS spread should reflect the spread of the reference obligation with a certain maturity over the risk-free rate. We expect the risk premia to be related to the sovereign credit risk of the underlying assets. The CDS spread is expressed in basis points and quoted in US dollars.

[9] The choice of 2022 as the end of the sample period is consistent with the starting year of the NGFS projections, which span from 2022 to 2050 with annual steps.

[10] The test applies a Fisher-type approach that aggregates the results of individual Augmented Dickey–Fuller (ADF) tests across all cross-sectional units in the panel. The null hypothesis assumes that all series contain a unit root (are non-stationary), whereas the alternative hypothesis allows for at least some series to be stationary. The Maddala–Wu statistic is obtained by summing the log-transformed p-values of the individual ADF tests, which, under the null, follows a chi-squared distribution with $2n$ degrees of freedom, where n denotes the cross-section sample size.

2022; Mussida & Zanin, 2023; Zanin, 2014). Following the principle of parsimony in econometric modeling, we therefore focus exclusively on the dynamics of the unemployment rate. The importance of this variable is also emphasized in studies showing that higher unemployment may generate both an endogenous and an actual cost of sovereign default risk (Balke, 2023). Governments typically aim to promote economic growth, reduce unemployment, and mitigate sovereign default risk.

Long-term interest rates, defined as yields on ten-year government bonds, are also considered predictors of sovereign CDS spreads. The data are of source OECD. These rates are influenced by expectations regarding future inflation, economic growth, monetary policy, and investor risk appetite. Lower long-term yields typically signal confidence in stable inflation and moderate growth, thereby encouraging investment; conversely, higher rates may reflect anticipated inflation or increased risk perceptions, which raise borrowing costs and slow investment (e.g., Berument & Froyen, 2006). As a predictor of sovereign CDS, we consider long-term real interest rates adjusted for inflation, thus reflecting the cost of borrowing and the real return to investors after accounting for changes in purchasing power. The long-term real rate r_t can be approximated using the Fisher equation:

$$r_t = \frac{1 + i_t}{1 + \pi_t^e} - 1. \tag{1}$$

where i_t denotes the nominal interest rate and π_t^e the expected or realized inflation over the same horizon.

Stock market returns can serve as an additional proxy for domestic economic conditions. Investors are sensitive to news on macroeconomic developments, political stability, and policy measures (Bjørnland & Leitemo, 2009; Flannery & Protopapadakis, 2002), including information or expectations regarding climate policies and the uncertainty surrounding their implementation (Ardia et al., 2023; Monasterolo & De Angelis, 2020; Prosperi & Zanin, 2024). Consequently, stock market returns incorporate much of this information and can help explain cross-country variation in sovereign CDS spreads, as shown in prior empirical research (Dieckmann & Plank, 2011; Wang et al., 2022). These studies generally find an inverse relationship between stock market performance and sovereign CDS spreads. Our empirical analysis relies on the country-level stock market return indices retrieved from Datastream. Except for Latvia (OMX RIGA) and Slovakia (SAX index), we consider each country's MSCI stock market index. Figure A.5 in the Supplementary Material reports the annual correlations between stock markets. The most evident finding is that Slovakia's stock market performance is correlated only with Hungary's, while its correlation with other European markets is not statistically significant. This descriptive evidence illustrates how national stock markets may share common risk factors that, in turn, affect sovereign risk across countries. Furthermore, consistent with recent literature, we assume that investors increasingly incorporate aspects of climate risk into asset pricing (see e.g., Alessi et al., 2021; Bolton & Kacperczyk, 2021; De Angelis & Monasterolo, 2024; Prosperi & Zanin, 2024; Zanin, 2023).

As a direct measure of a country's transition-risk exposure, we use the change in energy-related emissions intensity (hereafter, emissions intensity) relative to its 1990 level.[11] Emissions intensity is defined as the ratio of energy-related emissions to GDP, and its deviation from the 1990 benchmark is intended to capture a country's progress, or lack thereof, toward decarbonization.[12] Countries lagging in decarbonization are likely to face higher sovereign credit spreads due to market perceptions of increased vulnerability and transition risk. Investor pricing of sovereign risk increasingly reflects climate policy credibility: slow decarbonizers face greater uncertainty about future regulations, potential losses in public revenues, and fiscal adjustment costs, all of which undermine debt sustainability (e.g., Collenderm et al., 2023; Moramarco & Zanin, 2025).

Descriptive statistics for all predictors are reported in the Supplementary Material (Tables A.3–A.7 and Figure A.6).

5. Methodology

This section outlines the methodological framework used to assess the contribution of climate-related risks to sovereign credit risk, measured by five-year sovereign CDS spreads, conditional on the projected evolution of key macro-financial variables under alternative climate mitigation scenarios (i.e., a scenario-conditional analysis). The framework follows a two-step approach. First, we estimate an econometric model that relates sovereign CDS spreads to their underlying (lagged) macro-financial determinants. Second, we combine the estimated relationships with scenario-specific projections of these determinants provided by the NGFS to obtain conditional CDS paths.

The objective is not to forecast sovereign CDS spreads, but to show how climate-related risks affect sovereign credit risk through their impact on macro-fundamental dynamics.[13] As discussed in Section 3, exogenous shocks such as geopolitical events, financial crises, changes in market sentiment, or abrupt policy reversals are outside the scope of the NGFS long-term scenarios and are therefore not considered in the projection exercise.

Section 5.1 introduces the benchmark panel regression model, grounded in the existing literature on the determinants of sovereign CDS spreads (see, e.g., Aizenman et al., 2013; Anand et al., 2023; Fontana & Scheicher, 2016; Pan et al., 2024), and discusses alternative estimation strategies to mitigate the influence of outliers. Section 5.2 then explains how the estimated coefficients

[11] Emissions from energy use are the primary source of anthropogenic greenhouse gas emissions.

[12] The year 1990 is commonly recognized as a baseline for international climate action and serves as a reference point for policy targets established by global treaties and programs.

[13] Forward-looking projections differ fundamentally from forecasts. A forecast aims to identify the most probable outcome and explicitly evaluates the size and distribution of forecast errors. By contrast, a forward-looking projection is a conditional "what-if" exercise that traces the implications of alternative assumptions or policy paths over time. Such projections are designed for scenario and stress analysis, showing how outcomes would evolve when key drivers or constraints are deliberately modified.

are combined with projections of the macro-financial determinants to generate CDS spreads conditional on the NGFS long-term scenarios. Since the NGFS framework does not provide explicit projections for country-specific fiscal variables, such as the debt-to-GDP ratio, we propose a coherent procedure to project these variables in line with the scenario-implied macroeconomic paths. Finally, Section 5.3 explains how we translate scenario-conditional CDS projections into sovereign default probabilities (PDs) under a risk-neutral framework. This mapping allows us to quantify the contribution of climate transition risk to sovereign credit risk by comparing changes in PDs under a mitigation scenario with those under the baseline scenario.

5.1. Panel linear model

Let $\boldsymbol{X}_{i,t}$ be the k-dimensional vector containing the fundamental macro-financial variables used as regressors (see Section 4.2) and characterizing the country i, for $i = 1, \dots, n$, at time t, for $t = 1, \dots, T$ in years. In our analysis, this vector is defined as follows:

$$\boldsymbol{X}_{i,t} = \begin{pmatrix} \log(\text{Debt/GDP})_{i,t} \\ \Delta\text{Unemployment rate}_{i,t} \\ \text{Long-term real interest rate}_{i,t} \\ \text{Stock market return}_{i,t} \\ \text{Emissions intensity vs 1990}_{i,t} \end{pmatrix} \tag{2}$$

where Δ identifies the first difference operator.

The linear panel model used to estimate the relationship between sovereign CDS spread and the regressors in (2) is specified as follows:

$$\log(\text{CDS spread})_{i,t} = \quad \boldsymbol{\beta}'\boldsymbol{X}_{i,t-1} + \varphi_i + \mu_t + \delta_{1,i} d_{1,i,t} + \delta_{2,i,t} d_{2,i,t} + \varepsilon_{i,t} \tag{3}$$

where $\boldsymbol{\beta} = (\beta_1, \beta_2, \dots, \beta_k)'$ is the vector of coefficients for the predictor variables, φ_i denotes country-fixed effects, μ_t denotes time-fixed effects, and $\varepsilon_{i,t}$ is the error term, assumed i.i.d. with $E(\varepsilon_{i,t}) = 0$ and $V(\varepsilon_{i,t}) = \sigma^2$. The model also includes two sets of dummy variables: $d_{1,i,t}$ captures the impact of the Russo–Ukrainian conflict in $t = 2022$ for countries bordering Russia and Ukraine,[14] while $d_{2,i,t}$ captures sovereign risk crisis episodes, i.e., whenever the five-year CDS spreads exceed 1000 basis points.[15] The corresponding coefficients are $\delta_{1,i}$ and $\delta_{2,i,t}$.

To address potential endogeneity concerns, all predictors in (2) enter into the model (3) with a one-year lag. Consistent with standard practice in the literature, this approach ensures that the explanatory variables are predetermined with respect to the sovereign CDS spread (Demiralay et al., 2024).[16] Moreover, lagged fundamentals are intended to capture the persistent component of sovereign credit risk associated with the gradual evolution of underlying macro-financial conditions (Crump et al., 2024; Martin-Valmayor et al., 2024).

The specification in (3) is intentionally static in the dependent variable. While a dynamic panel model with a lagged CDS term could capture residual persistence in sovereign risk premia, our objective is not to model the full stochastic process of CDS spreads. Rather, the model is designed to estimate a scenario-conditional response function linking sovereign CDS spreads to macro-financial fundamentals. Including a lagged dependent variable would absorb a large share of the variation in CDS spreads, particularly at annual frequency, thereby attenuating the estimated marginal effects of fundamentals and weakening the interpretability of scenario-conditional responses (e.g., Aizenman et al., 2013). In a scenario-based projection framework, this would shift the propagation of shocks primarily to autoregressive CDS dynamics, rather than to the macro-financial paths implied by the NGFS scenarios, blurring the link between climate-induced adjustments and sovereign credit risk.

We estimate model (3) using the within fixed-effects estimator, which isolates within-country variation over time and thereby removes the influence of time-invariant heterogeneity across countries. To obtain valid inference, we apply the Cluster-Robust 2 (CR2) correction to standard errors, a bias-reduced covariance estimator that improves finite-sample reliability in panels with a small or moderate number of clusters while preserving robustness to heteroskedasticity and within-cluster correlation (Bell & McCaffrey, 2002; Imbens & Kolesár, 2016).

To mitigate the influence of potential outliers beyond those already controlled for in model (3), we also estimate two robust M-estimators based on Gaussian and Huber weighting schemes. The Gauss estimator uses a Gaussian-type weighting function that progressively down-weights large residuals while preserving high asymptotic efficiency under near-normal error distributions. The Huber estimator (Huber, 1964) relies on the Huber loss function, which combines the properties of least squares and least absolute deviations by assigning quadratic weights to small residuals and linear weights to large ones. This formulation limits the

[14] Geopolitical tensions and armed conflicts have been shown to raise sovereign risk through risk-aversion and contagion channels (Afonso et al., 2024), so the war dummy captures additional investor concern not explained by macro-financial fundamentals. Moreover, recent evidence shows that geopolitical shocks can propagate through international risk-sharing and network linkages, generating heterogeneous cross-country spillovers (Duong et al., 2024). This mechanism motivates the inclusion of a differential shock for countries bordering Russia and Ukraine in 2022.

[15] During the euro-area sovereign debt crisis, annual Greek five-year CDS spreads surged beyond 1000 bps and remained at extremely elevated levels during the 2010–2015 restructuring episodes (except in 2014), while Portuguese five-year CDS briefly exceeded 1000 basis points in 2011 at the height of market stress.

[16] As in other studies on sovereign risk, lagged fundamentals reduce, but may not fully eliminate, residual endogeneity between CDS spreads and their determinants (e.g., Anyfantaki et al., 2025). The use of annual data further mitigates endogeneity concerns, as aggregation over longer horizons tends to smooth short-term fluctuations and reduces simultaneity bias between regressors and the error term (Hjalmarsson, 2006). Moreover, when the primary objective is forward-looking evaluation rather than causal identification, standard concerns about residual endogeneity are less binding, as emphasized in the related literature (Huang et al., 2019; Luo et al., 2023; Pesaran et al., 2025; Stock & Watson, 2006).

influence of outlying observations, reducing bias from heavy-tailed errors, while maintaining efficiency in the central portion of the distribution (see also Huber & Ronchetti, 2009; Zhou et al., 2018). To assess and compare estimator performances, we report standard in-sample fit measures, including the Root Mean Squared Error (RMSE), Mean Absolute Error (MAE), Median Absolute Error (MdAE), and Mean Absolute Percentage Error (MAPE), each capturing different aspects of accuracy.

5.2. Scenario-conditional projections of sovereign CDS spreads

The estimates obtained from Eq. (3) are utilized to generate conditional, scenario-based projections of five-year sovereign CDS spreads under the NGFS scenarios trajectories. The NGFS scenarios, as discussed in Section 3, provide projections for the macro-financial variables used in our modeling framework, except for the debt-to-GDP ratio, which is addressed separately in Section 5.2.1.

5.2.1. Debt-to-GDP projections under fully and less responsive debt-stabilizing fiscal paths

A straightforward way to derive projections for the debt-to-GDP ratio is to use the standard debt dynamics equation. Accordingly, the evolution of a country's debt-to-GDP ratio over time can be expressed as:

$$\frac{D_t}{Y_t} = \left(\frac{1+r_t}{1+g_t}\right)\frac{D_{t-1}}{Y_{t-1}} - \frac{PB_t}{Y_t} + \frac{SFA_t}{Y_t} \tag{4}$$

where D_t denotes government debt at time t, Y_t is GDP, r_t is the nominal effective interest rate on debt, g_t is the nominal GDP growth rate, PB_t is the primary balance (surplus if positive, deficit if negative), and SFA the stock–flow adjustment (deficit–debt adjustment), which captures all changes in debt not explained by the primary deficit, such as privatizations, re-capitalizations, or statistical revisions. When information on stock–flow adjustments is unavailable, it is common practice to set $SFA = 0$ for projection purposes. This framework underpins most debt sustainability analyses and provides a consistent accounting basis for sovereign debt projections (Escolano, 2010; European Commission, 2024; Economides et al., 2025).

The NGFS scenarios provide projections for key macro-financial variables, including real GDP growth, inflation, and long-term interest rates, which can be directly incorporated into the debt dynamics equation.[17]

A simple way to project the debt-to-GDP ratio using (4) is to impose a debt-stability condition over time, under which the debt ratio remains bounded rather than diverging to unsustainable levels or collapsing. This concept, central to debt sustainability analysis, is rooted in the government budget identity, which links the current debt ratio to its past debt, the primary balance relative to GDP, the nominal interest rate, the nominal GDP growth rate, and other potential adjustment factors (Escolano, 2010; European Commission, 2023).

The assumption of debt stability extends beyond the mechanics of government budget identity. It reflects fiscal credibility and market confidence, implying that fiscal policy is designed to satisfy long-term intertemporal budget constraints and that debt remains on a sustainable trajectory without abrupt future corrections. To illustrate the debt stability conditions, let us consider a steady-state case in which the debt ratio remains constant over time and deficit–debt adjustments are negligible, such that $\Delta\frac{D_t}{Y_t} \approx 0$. Under full debt stabilization, the primary balance adjusts exactly to offset the interest–growth differential. More generally, fiscal authorities may respond only partially to pressures to accumulate debt. Let ϕ denote the *degree of fiscal responsiveness* (stabilization parameter). The primary balance rule is given by:

$$\frac{PB_t}{Y_t} = \phi\,(r_t - g_t)\,\frac{D_{t-1}}{Y_{t-1}}, \tag{5}$$

where $\phi = 1$ implies full debt stabilization; $\phi = 0$ corresponds to the absence of fiscal adjustment, in which case the debt ratio evolves passively; and $0 < \phi < 1$ captures less responsive stabilization, with public debt converging gradually toward a new steady state. Values of $\phi > 1$ imply an over-reaction of the primary balance to the interest–growth differential, leading to faster debt reduction at the cost of very strong fiscal consolidation efforts, which may be politically or macroeconomically demanding.

Substituting this fiscal reaction into the debt dynamics in Eq. (4) yields:

$$\frac{D_t}{Y_t} = \left[\frac{1+r_t}{1+g_t} - \phi(r_t - g_t)\right]\frac{D_{t-1}}{Y_{t-1}} + \frac{SFA_t}{Y_t}. \tag{6}$$

Starting from an initial observed debt ratio and using projected paths for nominal GDP growth (g_t) and the effective interest rate on debt (r_t) from the NGFS scenarios, the debt-to-GDP ratio evolves under different degrees of fiscal responsiveness according to Eq. (6).

In summary, varying ϕ enables us to assess how quickly debt converges toward a sustainable level under alternative assumptions about fiscal responsiveness. Higher values of ϕ correspond to stronger adjustment efforts and faster debt stabilization, whereas lower values imply delayed or weaker fiscal adjustment. This recursive structure provides a transparent framework for translating macro-financial shocks from the NGFS climate scenarios into an assessment of sovereign risk and fiscal sustainability.

[17] Nominal GDP, representing the economy's total output at current prices, is obtained from real GDP by applying the GDP deflator (derived from inflation data) to account for changes in price levels.

5.2.2. Scenario-conditioned paths of sovereign five-year CDS spreads

For the scenario analysis, NGFS supplies country-level, annual, forward-looking climate-conditioned paths for real GDP, inflation, long-term nominal and real interest rates, equity price indices, unemployment rates, and emissions. From these variables, nominal GDP is obtained by combining real GDP with inflation, and stock market performance is computed from the equity price indices.[18] These variables are crucial for assessing the impacts of climate risks on both the economy and the financial system.

Combining the estimates obtained from Eq. (3) with NGFS-consistent projections of macro-financial variables, the model is simulated forward, conditional on each climate pathway, to generate scenario-conditioned projections of 5-year sovereign CDS spreads.

5.3. Contribution of climate risks to sovereign default probabilities

The scenario-conditioned five-year CDS spreads are then converted into risk-neutral default probabilities (e.g., Duffie & Singleton, 1999) to quantify the effect of climate-related shocks on sovereign credit risk, operating through their impact on macro-financial fundamentals. This quantification of climate-induced changes in default risk is directly relevant for climate stress testing and sovereign risk management.

In this framework, CDS spreads are interpreted under the risk-neutral measure, so the implied probability of default reflects both investors' expectations of sovereign default and the compensation they require for bearing systematic credit risk (e.g., Qi et al., 2010). Accordingly, risk-neutral default probabilities typically exceed the corresponding historical (real-world) default probabilities, as they embed investors' risk premia in addition to the actual probability of default.

In applying a simplified closed-form approximation to the general CDS pricing formula, the cumulative risk-neutral probability of default up to maturity T is defined as

$$PD(0,T) = 1 - e^{-\lambda T} \tag{7}$$

where $PD(0,T)$ denotes the risk-neutral cumulative probability of default between time 0 and T, and λ is the (constant) risk-neutral default intensity (hazard rate). Under this reduced-form setup, the intensity λ is approximated from the CDS spread (cds) by equating the present value of the premium and expected loss under continuous compounding,

$$\lambda = \frac{cds}{1 - RR}, \tag{8}$$

assuming a constant default intensity λ over the five-year horizon and a constant recovery rate RR throughout the contract term. Accordingly, combining Eqs. (7) and (8), we can rewrite the cumulative risk-neutral probability of default as:

$$PD(0,T) = 1 - \exp\left(-\frac{cds \times T}{1 - RR}\right) \tag{9}$$

where cds denotes the sovereign CDS spread expressed in decimal form (e.g., 150 basis points = 0.015), $T = 5$ is the associated contractual maturity of our case study, and $RR = 0.4$ the assumed recovery rate, following standard market practice. From Eq. (9), we calculate the deviation of each climate-mitigation scenario s from the Current Policies (CP) baseline as

$$\Delta PD_s = PD_s - PD_{CP}, \tag{10}$$

where $s \in \{\text{NDCs, Net Zero 2050, Delayed Transition}\}$ and the CP scenario represents the case where no additional transition policies are implemented, and thus no transition risk is incorporated.

6. Model estimation results

This section presents the results from OLS and robust estimation of the model in Eq. (3) and evaluates its short-term predictive accuracy through an out-of-time exercise (Section 6.1). Section 6.2 then discusses a set of robustness checks.

Table 1 reports the estimation results for the model in (3), estimated via OLS and two robust alternatives (Gauss and Huber) as discussed in Section 5.1, for all countries listed in Section 4.1.[19]

The high within-adjusted R^2 values (ranging between 0.87 and 0.92) indicate that the model explains a substantial share of the within-country variation in sovereign CDS spreads over time, as expected given the selection of the most relevant drivers of sovereign credit risk.

The estimated coefficients display the expected signs and align closely with the existing literature on the determinants of sovereign credit risk (e.g., Alesina et al., 1992; Beirne & Fratzscher, 2013; Singh et al., 2021). The positive, statistically significant coefficient for the lagged debt-to-GDP ratio confirms that investors perceive higher public indebtedness as a key source of fiscal vulnerability, leading to higher sovereign CDS spreads.

Similarly, changes in the unemployment rate have a strong positive effect on spreads, underscoring how labor-market deterioration undermines fiscal stability and weakens economic resilience (e.g., Balke, 2023). Rising unemployment not only signals

[18] See the NGFS Climate Scenarios Technical Documentation V5.0 for details.

[19] The models are estimated using the *feols()* function of the *fixest* R package (Berge et al., 2023). We perform a structural collinearity diagnostic, which searches for linear dependencies among the regressors (including fixed effects) in the estimated model. No collinearity issues are detected.

slower economic activity, consistent with Okun's law (Donayre, 2022; Mussida & Zanin, 2023; Zanin, 2014), but also heightens macroeconomic uncertainty, thereby amplifying investors' perceived sovereign credit risk (see also Boeck et al., 2023).

The positive and highly significant coefficient for long-term interest rates indicates that higher borrowing costs and tighter financial conditions heighten sovereign risk perceptions by increasing debt-servicing burdens and limiting fiscal space (see also Pan et al., 2024). Long-term interest rates and inflation are closely intertwined through the transmission of monetary policy and the formation of inflation expectations. From a policy perspective, when inflation accelerates, central banks typically tighten monetary policy and raise short-term rates to curb price pressures. Over time, this tightening propagates along the yield curve, pushing up long-term interest rates as investors revise expectations of future inflation and policy stance (e.g., Berument & Froyen, 2006). Consequently, movements in long-term yields often reflect shifts in market perceptions of inflation dynamics and monetary credibility, rather than mere mechanical adjustments in nominal benchmarks. This underscores their importance as forward-looking indicators for both macroeconomic surveillance and sovereign credit risk assessment.

Conversely, the coefficient for stock market returns is negative and statistically significant, indicating that stronger equity market performance, often associated with improved growth prospects and investor confidence, reduces sovereign risk premia (see also Pan et al., 2024). Robust equity markets indicate favorable macroeconomic conditions, increased risk appetite, and strengthened private-sector balance sheets, all of which contribute to lower perceived sovereign credit risk and reduced financing costs. These results are consistent with empirical evidence emphasizing that sovereign credit spreads respond not only to domestic fiscal fundamentals but also to broader global financial conditions, including equity and bond market dynamics that shape investors' risk tolerance and the transmission of monetary policy shocks.

Finally, the positive and statistically significant coefficient on the variation in emissions intensity relative to 1990 levels indicates that (de-)carbonization progress is an important conditioning factor for a country's sovereign credit risk. This suggests that investors perceive that decarbonization progress reduces long-run transition risk (policy tightening, stranded assets, litigation) and, ultimately, sovereign credit risk. This implies that slow progress in reducing carbon intensity delivers only a limited reduction in sovereign credit risk, as transition-related vulnerabilities remain largely in place (e.g., Campiglio et al., 2025; Moramarco & Zanin, 2025; Saxena & Singh, 2024).

The included time-fixed effects aim to capture common events that characterize specific years and may affect sovereign risk across Europe. For example, we can mention the launch of the European Central Bank's quantitative easing programme in 2015 (e.g. Lotfi et al., 2024), which entailed large-scale public-sector asset purchases to counter deflationary pressures, compress long-term yields, and restore monetary transmission mechanisms across member states. The country fixed effects, instead, absorb time-invariant characteristics unique to each sovereign, such as structural fiscal capacity, institutional quality, and baseline creditworthiness, which systematically differentiate cross-country risk profiles within the panel.

According to the *p*-value lower than 0.05 of Pesaran's CD test (Pesaran, 2021), the null hypothesis of cross-sectional dependence is rejected, suggesting that the model adequately captures the common components of sovereign CDS dynamics across countries. Overall, the results confirm a strong relationship between sovereign credit risk and key macro-financial fundamentals, and they underscore the need to incorporate transition-risk variables. In other words, models that rely solely on traditional macro-financial drivers risk neglecting the extent to which investors reward progress toward the low-carbon transition, with potentially material implications for future sovereign credit risk (see, e.g., Daki Dominique et al., 2026).

6.1. Predictive accuracy

The lower panel of Table 1 reports the model's predictive performance, distinguishing between in-sample fit and out-of-time forecast accuracy for 2021 and 2022. In line with standard forecast evaluation practice, we use RMSE, MAE, MdAE, and MAPE, as defined in Section 5.1. In-sample fit is very similar across the three estimators, indicating that the choice of estimation method has only a limited impact on overall in-sample performance.

For the out-of-time exercise, the panel model is estimated on data up to 2020, and its predictive ability is then evaluated over the subsequent two years, providing a genuine assessment of performance beyond the estimation period. The corresponding results are shown in Fig. 1 for the Huber estimator, while plots for the other two estimators are qualitatively similar and available upon request. Out-of-time accuracy is also remarkably similar across estimators. Panel Diebold–Mariano tests[20] (Table 2) do not reject the null of equal predictive accuracy for any pair of estimators (OLS vs Gauss, OLS vs Huber, Gauss vs Huber), confirming that out-of-time differences are not statistically significant. Accordingly, the choice among OLS, Gauss, and Huber is guided primarily by robustness and interpretability rather than by forecast performance alone.

Compared with the 2021 forecasts, where, except for Greece, most country observations lie close to the bisector, predictive accuracy deteriorates sharply in 2022, coinciding with the abrupt surge in sovereign CDS spreads following the Russo–Ukrainian conflict. This severe and largely unanticipated geopolitical shock is only imperfectly captured by lagged standard macro-financial factors, particularly for countries bordering Russia and Ukraine. The improvement in forecast performance after excluding these countries reinforces the rationale for including dedicated dummy variables to capture an additional layer of investor sentiment and geopolitical risk not accounted for by macro-fundamentals, as discussed in the previous section and further explored in the robustness analysis.

[20] See Diebold and Mariano (1995) and recent extensions to panel settings in Akgün et al. (2024), as well as related work on panel forecast comparison (Qu, 2024).

Table 1

The models are estimated on panel data with annual frequency and covering the 2010–2022 period. In round parentheses, we report the adjusted standard errors at the country level using the CR2 estimator (Pustejovsky & Tipton, 2018). This adjustment produces cluster-robust standard errors that are unbiased in finite samples. For episodes in which five-year sovereign CDS spreads exceed 1000 basis points, a crisis-dummy variable is introduced, taking the value 1 in the following country-year observations: Greece 2011, Greece 2012, Greece 2014, Greece 2015, and Portugal 2011. The p-values of Pesaran's cross-dependence test are also reported (Pesaran, 2021).

	Dependent variable: log(CDS spread)		
Variables	OLS	Gauss	Huber
$\log(\text{Debt-to-GDP})_{t-1}$	0.433*	0.439***	0.428*
	(0.245)	(0.167)	(0.220)
ΔUnemployment rate$_{t-1}$	3.840	4.038**	4.162*
	(2.705)	(1.836)	(2.288)
Long-term real interest rate$_{t-1}$	4.665***	6.060***	5.379***
	(1.577)	(1.339)	(1.524)
Stock market return$_{t-1}$	−0.449***	−0.366***	−0.424***
	(0.151)	(0.099)	(0.141)
Emissions vs 1990$_{t-1}$	1.616*	1.414**	1.609**
	(0.906)	(0.694)	(0.797)
Year Fixed Effects	YES	YES	YES
Country Fixed Effects	YES	YES	YES
Bordering with Russia–Ukraine (year 2022)	YES	YES	YES
Outliers CDS spreads	YES	YES	YES
N. obs.	287	287	287
R^2 adj.	0.87	0.92	0.88
Pesaran's CD test - p-value	0.02	0.02	0.02
In-sample			
RMSE	60.99	66.80	65.22
MAE	23.56	23.71	23.67
MdAE	7.55	6.73	6.95
MAPE	20.61	20.41	20.51
Out-of-time (2021)			
RMSE	32.17	34.96	34.08
MAE	20.06	22.32	21.53
MdAE	11.19	13.10	11.91
MAPE	30.37	33.09	32.06
Out-of-time (2022)			
RMSE	56.91	56.31	56.35
MAE	34.36	34.80	34.35
MdAE	10.49	11.31	10.21
MAPE	80.82	75.64	76.40
Out-of-time (2022) excluding countries bordering with Russia–Ukraine			
RMSE	15.39	17.63	16.32
MAE	11.71	13.12	12.34
MdAE	8.51	8.68	8.231
MAPE	46.35	43.01	44.73

*** Denote significance at 1% levels, respectively.

** Denote significance at 5% levels, respectively.

* Denote significance at 10% levels, respectively.

Table 2

Panel Diebold–Mariano test: p-values for pairwise comparisons of forecast accuracy across estimators.

	OLS vs Gauss	OLS vs Huber	Gauss vs Huber
p-value	0.558	0.635	0.408

Importantly, our objective is not to produce unconditional long-horizon forecasts of sovereign five-year CDS spreads and related PDs, but to quantify the impact of climate risks on sovereign credit risk under NGFS-consistent scenarios. NGFS scenarios are explicitly designed not as forecasts, but as tools to explore the range of plausible futures of the evolution of climate change, economic, technology and policy dimensions.

War-related energy and risk-premium shocks, such as those observed in 2022, lie outside the NGFS scenarios' narrative and, when relevant, need to be treated separately or incorporated as overlays. The short-horizon out-of-time checks, therefore, serve mainly to evaluate how well macro-financial fundamentals explain sovereign CDS dynamics outside the estimation sample and to complement the estimation results, rather than to validate the model as a stand-alone forecasting model for sovereign CDS spreads up to 2050.

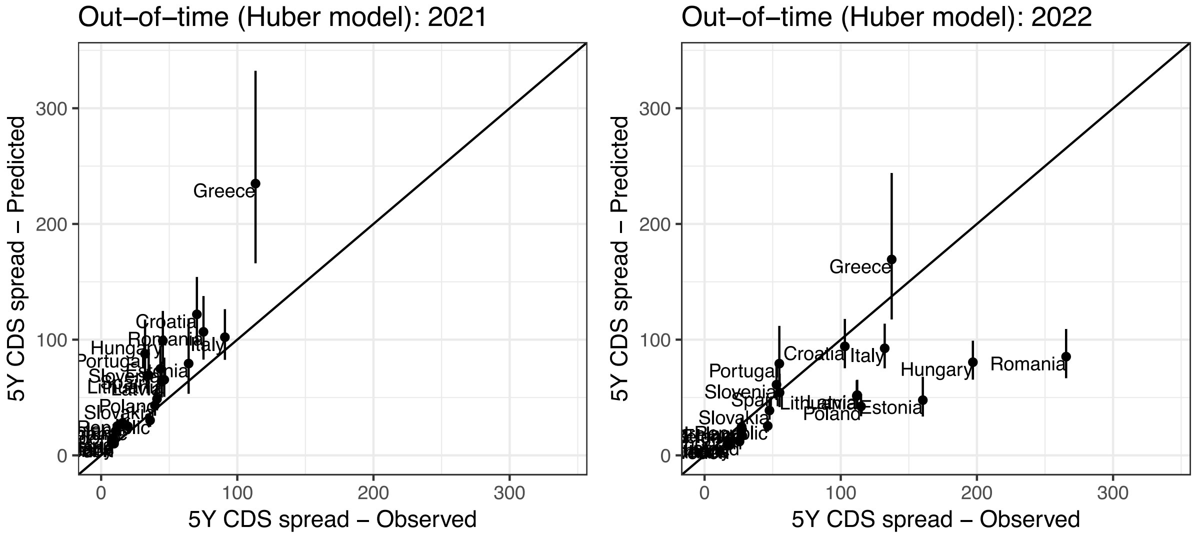

Fig. 1. Plots of the (pseudo-)out-of-time predictive accuracy for 2021 and 2022 by estimating model (3) using the Huber estimator over the 2010–2020 period. The figures also report the 95% vertical confidence interval around the observed value. The asymmetric confidence intervals are constructed by estimating the intervals on the log-transformed scale and then back-transforming them to the original scale.

6.2. Robustness analysis

We conduct an extensive set of robustness checks on the estimated model in Eq. (3). Table A.1 in Appendix A reports the results obtained using the Huber estimator. Results based on OLS and Gaussian M-estimators are qualitatively similar and are available upon request.

First, we re-estimate the model (3) after removing the dummy variables $d_{1,i,t}$ that capture the additional component of sovereign credit risk not explained by lagged macro-fundamentals for countries bordering Russia and Ukraine in 2022, at the onset of the Russia–Ukraine war. As shown in column 2 of Table A.1, the estimated coefficients are not statistically different from those of the baseline model with war dummies (column 1), as the corresponding confidence intervals overlap. However, the MAE, MdAE, and MAPE increase, underscoring the role of these dummies in reducing in-sample prediction errors. As an alternative, one could include an explicit measure of geopolitical risk, such as the index proposed by Caldara and Iacoviello (2022) and used in recent studies (e.g., Demiralay et al., 2024). However, such indicators are not available for all countries in our sample and, more importantly, geopolitical risks are not embedded in the NGFS climate-mitigation narratives. Accordingly, the war dummies are included primarily to prevent the war-related shock from contaminating the estimated effects of macro-financial fundamentals.

Second, we estimate the model excluding the dummy variables $d_{2,i,t}$ that control for extreme outliers in sovereign five-year CDS spreads (column 3). Although the Huber estimator downweights large residuals and is thus more robust than OLS, the sharp increase in RMSE indicates that these extreme observations still exert a non-negligible influence on model fit when not explicitly accounted for.

Third, we exclude Greece from the sample (column 4), as it exhibits the most influential outliers. Despite a slight improvement in the in-sample fit metrics relative to the baseline specification, the estimated coefficients remain largely unchanged, confirming that the main results are not driven by a single country.

As a final robustness check, we augment the specification in Eq. (3) with a lagged dependent variable (column 5). In this dynamic specification, only the lagged CDS term and stock-market returns remain statistically significant. The estimated autoregressive coefficient (0.54) indicates a high degree of persistence in annual sovereign CDS spreads, implying a gradual adjustment toward the long-run level rather than rapid mean reversion.[21]

This degree of persistence is consistent with the behavior of key macro-financial fundamentals. Debt-to-GDP ratios and unemployment typically adjust only gradually to shocks such as crises, fiscal consolidations, or structural reforms (Caporale et al., 2022; Martin-Valmayor et al., 2024). Similarly, decarbonization paths evolve slowly, reflecting inertia in the capital stock, energy mix, and long-term policy frameworks, so transition-risk proxies based on emissions display structural persistence (Molleda et al., 2025).

[21] Because the specification includes a lagged dependent variable with fixed effects, the autoregressive coefficient is subject to the small-sample bias described by Nickell (1981). Given the annual frequency, sample length, and the use of this specification solely as a robustness check, we do not implement bias-corrected dynamic panel estimators.

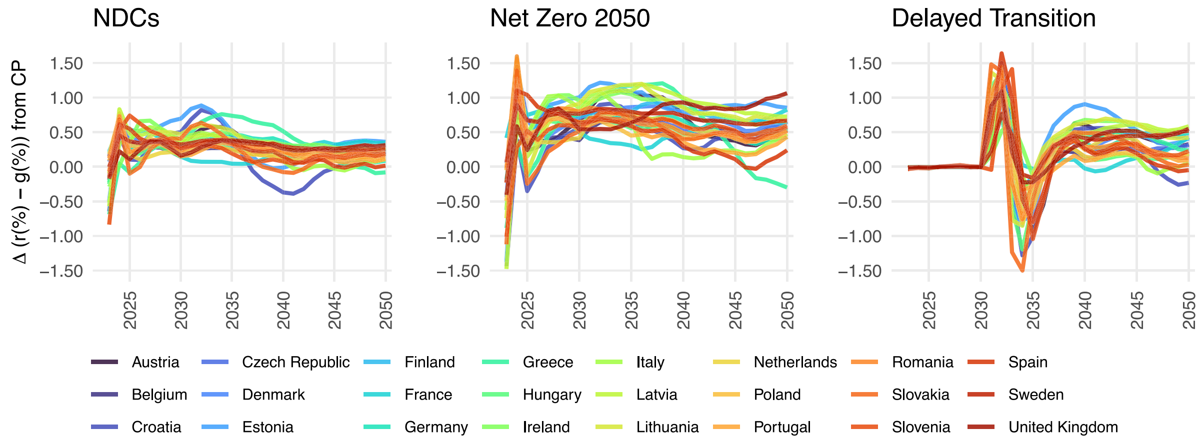

Fig. 2. Projected interest rate–growth differential $(r-g)$ expressed as $\Delta(r-g) = (r-g)^s - (r-g)^{CP}$, where s is the $s-th$ climate mitigation scenario, and CP is the Current Policies scenario.

In the baseline specification, the inclusion of lagged long-term real interest rates captures market perceptions of sovereign creditworthiness and thus embeds a sovereign risk component through the term structure of interest rates. Persistently higher sovereign risk premia are reflected in persistently higher long-term yields, allowing part of the observed persistence in CDS spreads to be captured indirectly via macro-financial fundamentals rather than through an explicit autoregressive CDS term.

For the purposes of this paper, the baseline specification already incorporates dynamic adjustment through lagged macro-financial fundamentals, which capture the gradual transmission of shocks to sovereign credit risk. This structure allows CDS spreads to respond with delay to persistent changes in fiscal conditions, labor-market outcomes, financial variables, and emission trajectories, while preserving a direct link between scenario-implied macro-financial paths and sovereign risk. The dynamic specification with a lagged dependent variable is, therefore, included solely as a robustness check to document the degree of persistence in CDS spreads and does not alter the qualitative conclusions of the analysis.

7. Conditional climate-scenario projections

This section presents projections of the main variables conditional on the NGFS long-term climate scenarios considered. Section 7.1 reports projections of the debt-to-GDP ratio under different NGFS scenarios, assuming both full and less responsive debt-stabilization rules (Sections 7.1.1 and 7.1.2, respectively). Section 7.2 presents projections of sovereign PDs under NGFS climate scenarios, again considering full and less responsive debt-stabilization rules (Sections 7.2.1 and 7.2.2, respectively).

7.1. Projecting the debt-to-GDP ratio under different NGFS long-term scenarios

Before conducting the scenario analysis, we first project the debt-to-GDP ratio as described in Section 5.2.1, accounting for the government's fiscal reaction to public debt as summarized by the debt-responsiveness parameter ϕ in Eq. (6). When $\phi = 1$, the primary balance fully adjusts to stabilize the debt-to-GDP ratio, offsetting the impact of the interest rate–growth differential $(r-g)$ and implying a path consistent with full debt stabilization (Section 7.1.1).[22] However, since NGFS scenarios do not explicitly assume full fiscal stabilization and several transition pathways may imply persistent fiscal imbalances, we also relax this assumption by allowing $0 < \phi < 1$. Specifically, we consider $\phi = 0.25$ and $\phi = 0.5$, corresponding to less responsive fiscal adjustment, whereby the primary balance responds only partially to debt deviations. In this case, interest–growth dynamics play a more prominent role in debt accumulation, and convergence toward a stable level is slower (Section 7.1.2).

Fig. 2 reports the projected interest rate–growth differential $(r-g)$ under the NDCs, Net Zero 2050, and Delayed Transition scenarios, expressed as deviations from the Current Policies scenario, which serves as the benchmark for the projections discussed below.[23]

7.1.1. Assuming full debt stabilization

Fig. 3 shows the percentage deviations of the annual debt-to-GDP ratio under the NDCs, Net Zero 2050, and Delayed Transition scenarios relative to the Current Policies benchmark, under the assumption of full debt stabilization ($\phi = 1$), as implied by Eq. (6).

[22] We take r to be the long-term nominal interest rate on government bonds (approximately ten-year maturity) available in the NGFS climate scenarios. The variable g denotes nominal GDP growth, computed from nominal GDP obtained by combining real GDP with inflation consistent with the climate mitigation scenarios.

[23] As a simplified evaluation strategy, we assume that under each alternative climate scenario and under the Current Policies scenario, the parameter of the degree of fiscal response ϕ is identical.

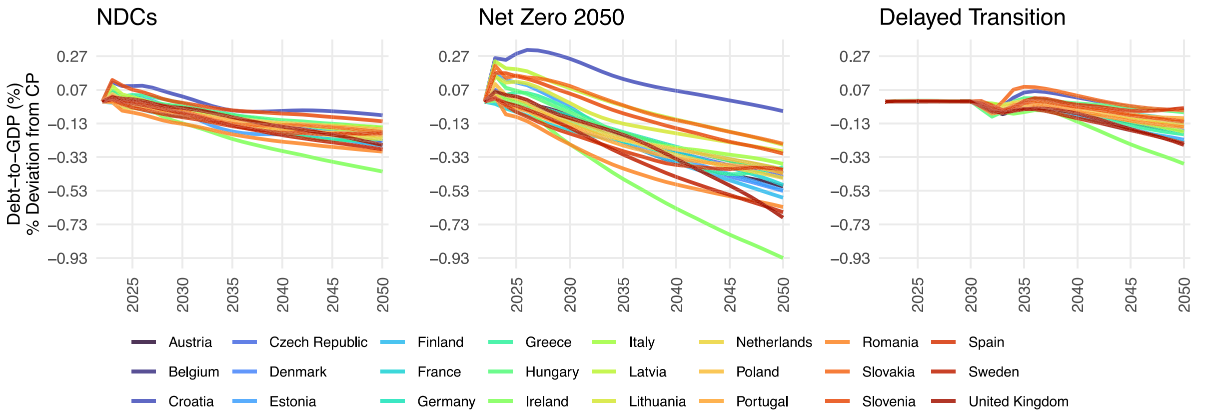

Fig. 3. Percentage deviations of the debt-to-GDP ratio from the Current Policies scenario under the assumption of full debt stabilization ($\phi = 1$) obtained by applying Eq. (6).

Comparing the projected deviations across scenarios, a modest but gradually widening negative gap relative to Current Policies emerges over the projection horizon, with the largest deviation observed under the Net Zero 2050 pathway. This pattern arises despite the application of a primary balance rule designed to stabilize the debt ratio. The reason is that identical fiscal reaction parameters operate in different macro-financial environments across scenarios: mitigation pathways affect nominal growth and interest rates, so that even small differences in the interest rate–growth differential $(r - g)$ and in the required primary balances accumulate over time into increasingly larger gaps in the debt-to-GDP ratio relative to the Current Policies scenario.

In the Delayed Transition scenario, in which climate policies are postponed until after 2030, the interest rate–growth differential is higher than under the Current Policies baseline (Fig. 2), indicating a less favorable environment for debt dynamics. For most countries, $r - g > 0$, implying that sustained primary surpluses are required to prevent debt from drifting upward. Under the assumption of full debt stabilization ($\phi = 1$), the primary balance therefore reacts more strongly to debt in the delayed scenario, generating larger and more persistent primary surpluses than under Current Policies. These adjustments more than offset the less favorable $r - g$, resulting in a debt ratio that falls below the Current Policies path. The resulting differential in the debt-to-GDP ratio relative to Current Policies can be interpreted as an additional macro-financial cost associated with delaying climate action. In several cases, this differential exceeds that observed at the early stages of the Net Zero 2050 and NDCs scenarios.

Under the fiscal rule, the deterioration in $r - g$ following the eventual implementation of climate policies in the Delayed Transition scenario may require a stronger and more persistent primary adjustment to preserve debt stability. To avoid abrupt future fiscal corrections, a front-loaded consolidation strategy may be necessary, with the primary balance responding earlier and more forcefully to rising debt levels.

A tighter fiscal policy would eventually constrain the country's fiscal space, leaving less room for discretionary spending, particularly for climate-related expenditures, as a larger share of revenues would need to be devoted to interest payments and debt stabilization. Over the longer horizon, as transition-related shocks are gradually absorbed, the debt differential relative to the Current Policies scenario stabilizes, indicating a normalization of debt dynamics after the initial adjustment phase.

7.1.2. Assuming less responsive debt stabilization

Governments may react only partially to the projected interest rate–growth differential $(r - g)$, allowing the primary balance to adjust below the level required to completely stabilize public debt under the fiscal rule. In this case, the fiscal reaction coefficient satisfies $0 < \phi < 1$. We consider two values, $\phi = 0.25$ and $\phi = 0.5$, implying a less responsive adjustment of the primary balance to rising debt. For a given increase in the debt-to-GDP ratio, the primary balance adjusts by only one quarter and one-half, respectively, of the amount implied under full stabilization. Such less responsive fiscal behavior allows debt to deviate further and for longer from its stabilization path, resulting in slower convergence and greater vulnerability of debt dynamics to adverse $r - g$ developments and macroeconomic shocks. This setting is consistent with limited willingness or capacity to implement large and persistent fiscal consolidations.

Figs. 4 and 5 report the percentage deviations of the debt-to-GDP ratio from the Current Policies benchmark under less responsive debt stabilization, illustrated for $\phi = 0.25$ and $\phi = 0.5$, respectively, using Eq. (6). In contrast to the full stabilization case (Fig. 3), the projected paths under both assumptions exhibit a persistent positive deviation of the debt-to-GDP ratio relative to Current Policies over the long run, particularly under the Net Zero 2050 scenario. This pattern mainly reflects stronger transition-related fiscal pressures combined with less responsive fiscal adjustment, which keeps primary balances insufficiently tight while the interest rate–growth differential does not improve enough to offset the additional debt accumulation.

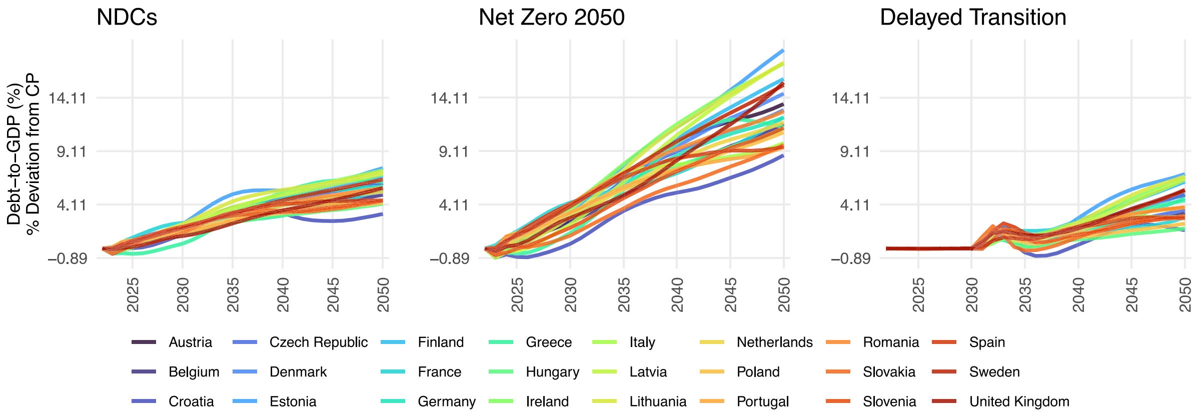

Fig. 4. Percentage deviations of the debt-to-GDP ratio from the Current Policies scenario under the assumption of less responsive debt stabilization ($\phi = 0.25$) obtained by applying Eq. (6).

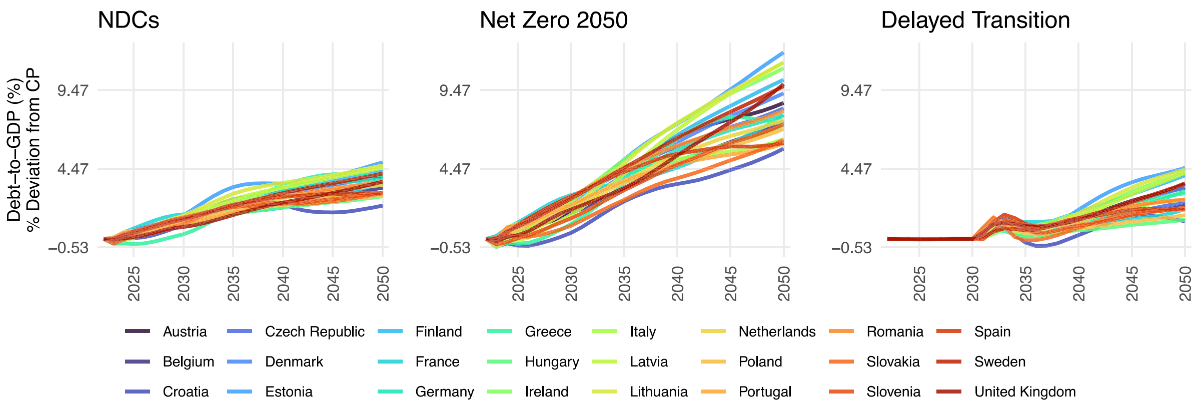

Fig. 5. Percentage deviations of the debt-to-GDP ratio from the Current Policies scenario under the assumption of less responsive debt stabilization ($\phi = 0.5$) obtained by applying Eq. (6).

7.2. Projecting the impacts of climate risks on sovereign PD

In line with the recent literature on climate and sovereign risk, we view climate policy as generating both risks and opportunities for sovereigns. More ambitious and credible transition paths entail short- and medium-term adjustment costs but, by lowering emissions and strengthening macro-financial fundamentals over the long run, they can ultimately reduce sovereign risk premia relative to a business-as-usual scenario. Figs. B.1 in Appendix B and Section 7.1 report the scenario-specific trajectories of the predictor variables used in model (3) up to 2050, expressed as deviations from the Current Policies scenario, thereby illustrating the materiality of climate risks for the macro-financial fundamentals of interest. These trajectories show similar dynamics across countries, particularly during the early phases of climate-policy implementation. Nonetheless, cross-country heterogeneity becomes evident over time, most notably in the evolution of emissions intensity relative to 1990 levels. While the transition signal is common, countries follow different decarbonization paths and thus face different transition risks and opportunities. In our setting, faster and more credible decarbonization not only reduces exposure to transition and physical risks but can also be rewarded by investors through lower sovereign risk premia, insofar as it supports stronger and more resilient macro-financial fundamentals. The observed divergence in emissions intensity relative to 1990 levels reflects differences in countries' initial conditions and in the impact of policy stringency, technological progress, and sectoral composition, all of which shape the transmission of climate policy to sovereign credit risk. Pathways featuring faster reductions in emissions intensity, capturing both cleaner energy production and more efficient energy use, can mitigate exposure to physical risks over time and strengthen fiscal and growth foundations, with potential benefits for sovereign risk.

To quantify the impact of climate risks on sovereign PDs, the analysis proceeds in three steps. First, the Huber estimates for model (3), reported in Table 1, are used to project five-year sovereign CDS spreads up to 2050 under the NGFS climate scenarios.[24] Second,

[24] The results from the two alternative estimation approaches (OLS and GAUSS) are qualitatively similar and thus omitted for brevity, but are available upon request. Huber preserves the interpretability of OLS coefficients while providing additional resilience to extreme CDS spikes.

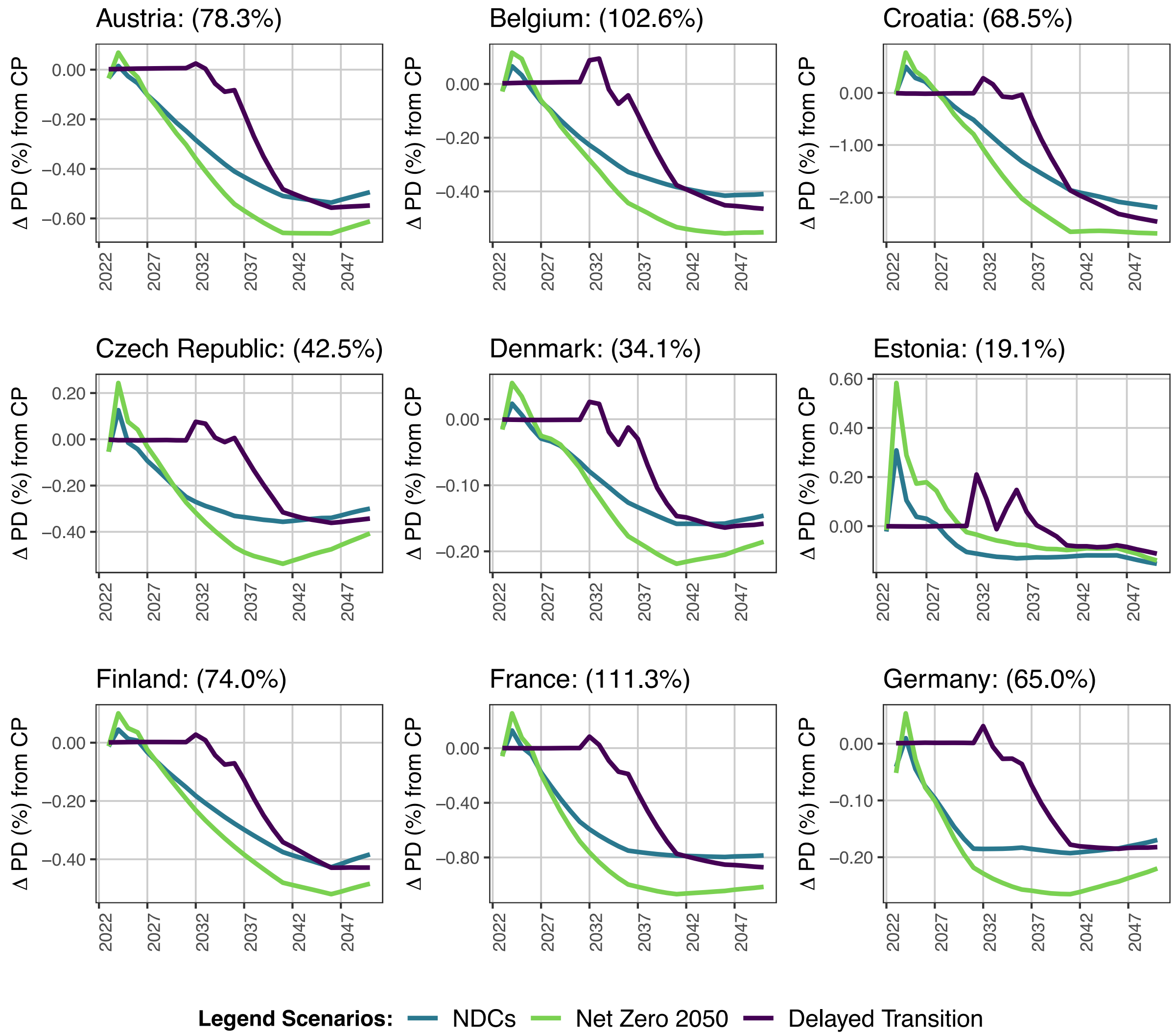

Fig. 6. Projected materiality of climate risks on sovereign five-year default probabilities (ΔPD) under alternative climate mitigation scenarios, expressed as deviations from the Current Policies (CP) scenario. Assumes full debt stabilization ($\phi = 1$). The observed debt-to-GDP ratio for 2022, according to the IMF, is reported in parentheses.

the projected CDS spreads are mapped into risk-neutral sovereign PDs, as outlined in Section 5.3. This use of risk-neutral PDs allows forward-looking information on sovereign credit risk to be extracted directly from market prices, specifically, CDS spreads, rather than from historical default realizations, with the inferred PDs reflecting both the expected PD and the compensation investors require for bearing sovereign credit risk.[25] Finally, the materiality of climate transition risk for sovereign credit risk is assessed by applying Equation (10), which links changes in risk-neutral PDs to the underlying climate scenarios with respect to the CP scenario.

In the next two subsections, we report the impact of climate risks on sovereign PDs under alternative assumptions about the debt-to-GDP trajectory, which differ in the degree of fiscal responsiveness as described in Section 7.1.

7.2.1. Assuming full debt stabilization

Projections of sovereign credit risk for the European countries considered are conditioned on the NGFS climate scenarios, Current Policies, NDCs, Net Zero 2050, and Delayed Transition. For the debt-to-GDP trajectory, we adopt the path implied by full debt stabilization, as described in Section 7.1.1, whereby governments respond to the projected interest rate, growth differential $(r - g)$ by adjusting the primary balance so as to ensure debt sustainability. Figs. 6–8 report the projected climate-risk materiality for five-year

[25] In this framework, investors are assumed to be risk-neutral, valuing securities as if they have no risk preferences. Consequently, the estimated PD reflects both the expected default probability and the risk premium investors demand for holding sovereign credit risk (e.g., Qi et al., 2010).

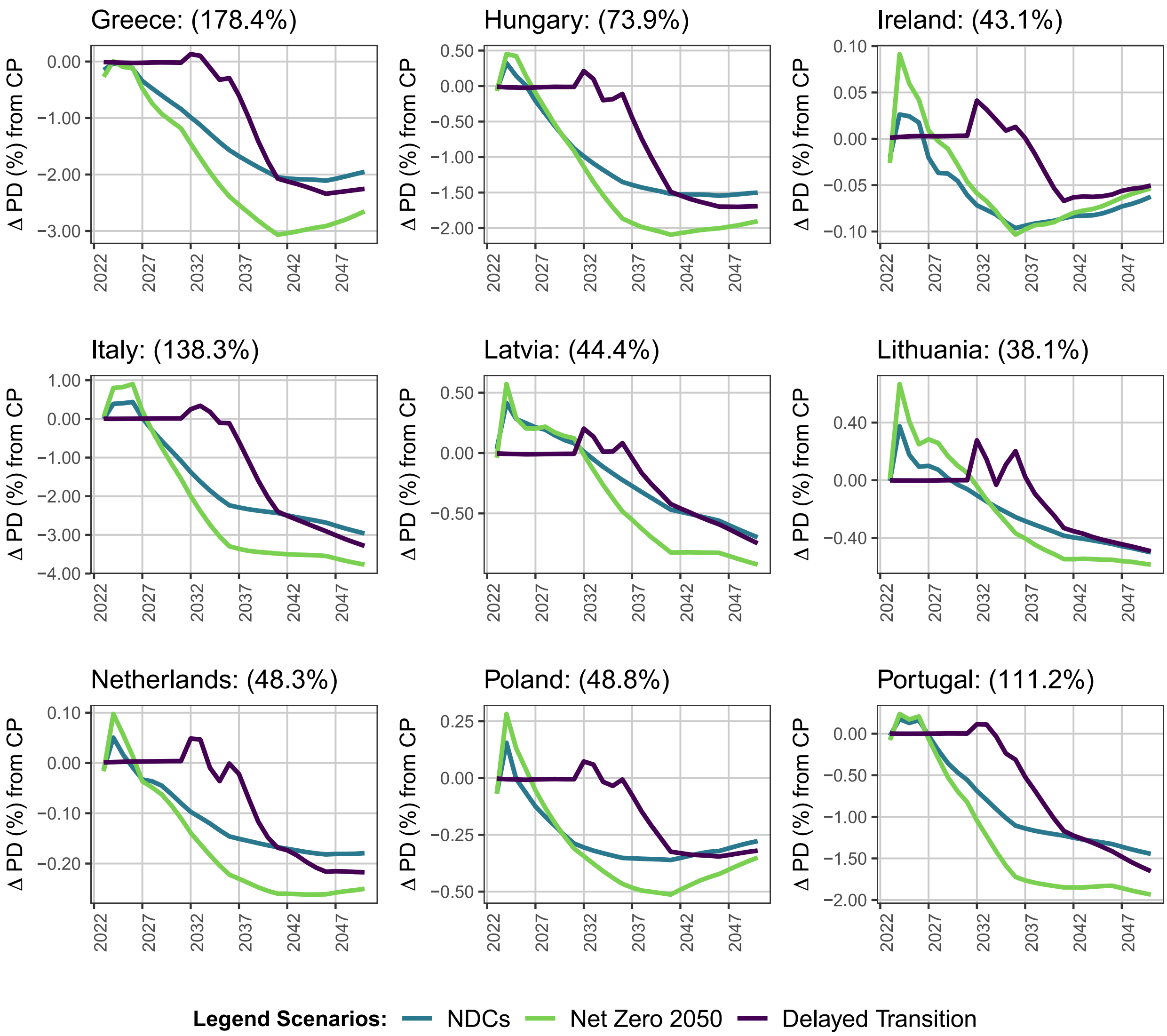

Fig. 7. Projected materiality of climate risks on sovereign five-year default probabilities (ΔPD) under alternative climate mitigation scenarios, expressed as deviations from the Current Policies (CP) scenario. Assumes full debt stabilization ($\phi = 1$). The observed debt-to-GDP ratio for 2022, according to the IMF, is reported in parentheses.

sovereign risk-neutral default probabilities through 2050. Specifically, we plot ΔPD (10) under the alternative climate-mitigation scenarios, by country, relative to the baseline scenario.

The comparison of results across scenarios highlights the sovereign credit risk implications of how European countries progress in the low-carbon transition, relative to a scenario in which they fail to adopt ambitious climate policies. In this way, the analysis isolates and quantifies the specific contribution of climate risks to sovereign credit risk, which is the focus of our analysis.

Under the Net Zero 2050 scenario, changes in sovereign default probability (ΔPD) are shaped by the country's economic structure, regarding the relative importance of high- versus low-carbon sectors in gross value added and GDP, as well as fiscal and financial conditions and progress in decarbonization relative to 1990 levels. The scenario assumes an orderly transition in which stringent mitigation policies are introduced early and become progressively tighter to achieve the 1.5 °C global temperature target. Our scenario-conditioned projections suggest that ΔPD initially increases, reflecting near-term adjustment costs associated with implementing climate policies, but subsequently declines as economies transition toward a more resilient and sustainable structure. This pattern implies a persistent reduction in sovereign credit risk over the medium term, with particularly pronounced improvements in Hungary, Italy, France, Portugal, Romania, Slovenia, and Spain.

Under the NDCs scenario, the long-term co-benefits are less pronounced than in the Net Zero 2050 scenario. The more gradual and fragmented pace of emissions reduction, aligned with national commitments, implies weaker and delayed policy

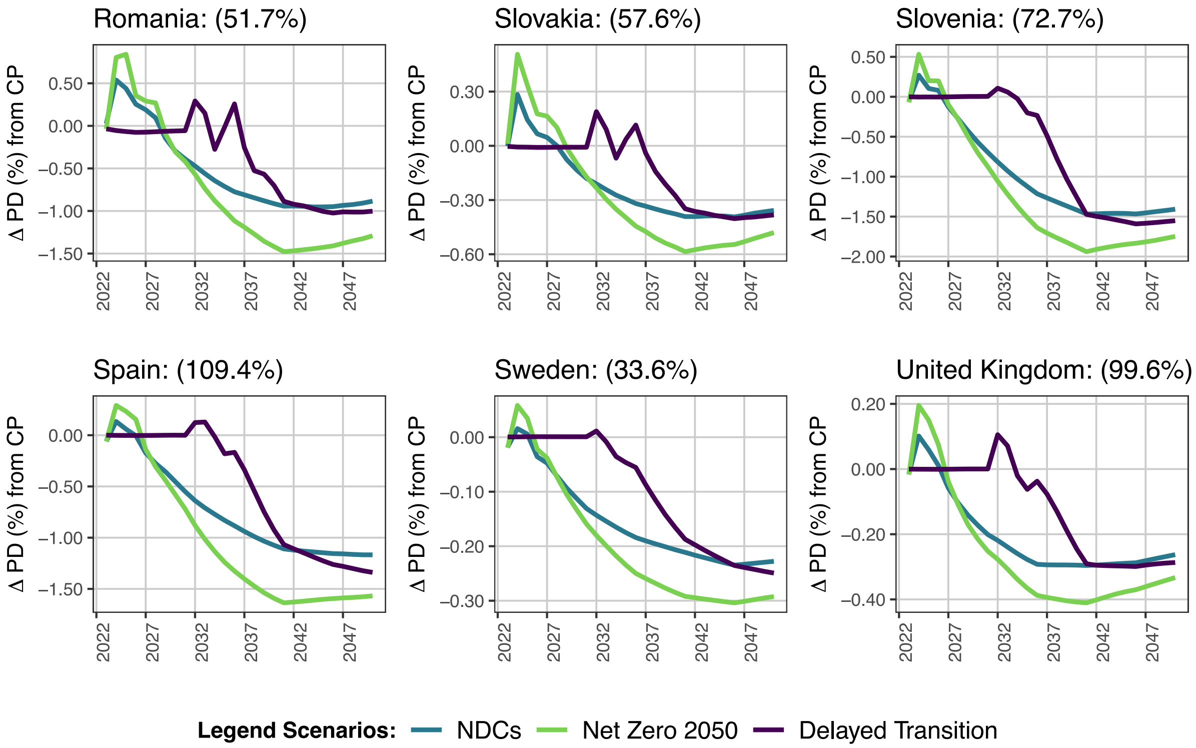

Fig. 8. Projected materiality of climate risks on sovereign five-year default probabilities (ΔPD) under alternative climate mitigation scenarios, expressed as deviations from the Current Policies (CP) scenario. Assumes full debt stabilization ($\phi = 1$). The observed debt-to-GDP ratio for 2022, according to the IMF, is reported in parentheses.

implementation. Consequently, transition risks persist longer, as reflected in higher fiscal imbalances, weaker investor confidence, and slower diversification away from carbon-intensive sectors. The resulting decline in sovereign ΔPD is therefore more moderate, and the overall improvement in credit quality remains limited, particularly in economies already characterized by structural fiscal vulnerabilities.

When climate policy measures are postponed and enacted only after 2030, as in the delayed transition scenario, projections show an initial surge in sovereign default probabilities, driven by the abrupt enforcement of delayed mitigation policies. Although subsequent structural adjustments and decarbonization efforts gradually reduce risk, sovereign credit performance remains weaker than under Net Zero 2050 by the end of the projection horizon. This underperformance reflects the cumulative macro-financial costs of delayed action and the compressed timeframe for achieving deep emission reductions. The oscillations observed in some countries mirror the temporal variability in unemployment changes implied by the NGFS delayed-transition assumptions, highlighting how short-term labor-market shocks and uncertainty can further amplify sovereign risk.

7.2.2. *Assuming less responsive debt stabilization*

We relax the assumption of full debt stabilization by introducing less responsive fiscal adjustment to movements in the interest rate–growth differential $(r-g)$. In this specification, the debt-stabilization coefficient is set to $\phi = 0.25$ and 0.5, so that governments counteract only one quarter or half of the change in $(r-g)$ through primary balance adjustments.

Relative to the full-stabilization benchmark in Section 7.2.1, these configurations imply a weaker automatic adjustment mechanism, such that debt-to-GDP ratios adjust more slowly and may cumulate over time following adverse macro-financial shocks. Figs. 9–11 report the projected materiality of climate risks for five-year sovereign default probabilities, measured by ΔPD (10) under the alternative NGFS mitigation scenarios, conditional on less responsive debt stabilization.

Overall, the long-run credit-risk gains from either an early or a delayed transition (relative to Current Policies) are smaller under weaker fiscal responsiveness to $(r-g)$ than under a fiscal rule that fully stabilizes the debt ratio. Within the weak fiscal-responsiveness regime, two patterns emerge. First, in countries such as Estonia and Ireland, the transition does not generate persistent long-run co-benefits for sovereign credit risk; ΔPD does not become persistently more favorable, particularly under the Net Zero 2050 scenario. Second, in countries such as Austria, Italy, and Portugal, long-run outcomes in ΔPD (relative to Current Policies) are broadly similar across fiscal-responsiveness regimes: while weaker fiscal responsiveness leads to higher debt-to-GDP ratios and thus tends to increase

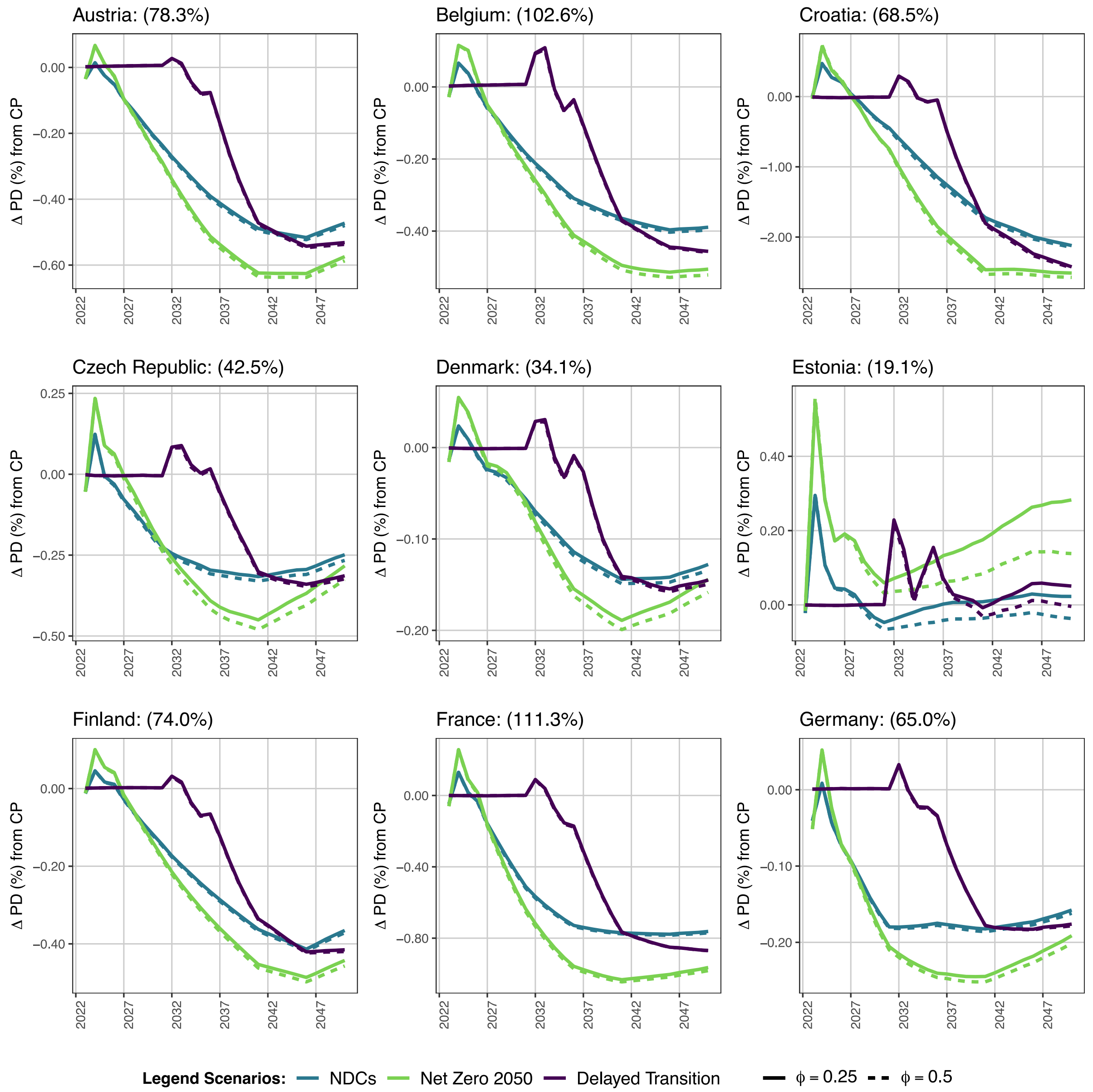

Fig. 9. Projected materiality of climate risks on sovereign five-year default probabilities (ΔPD) under alternative climate mitigation scenarios, expressed as deviations from the Current Policies (CP) scenario. Assumes less responsive debt stabilization with $\phi = 0.25$ (solid lines) and $\phi = 0.5$ (dashed lines). The observed debt-to-GDP ratio for 2022, according to the IMF, is in parentheses.

CDS-implied risk-neutral PDs, this adverse debt channel is largely offset by benefits of stronger projected reductions in emissions intensity (relative to 1990) than those for Estonia and Ireland, thereby limiting the cross-regime widening in ΔPD.[26]

Taken together, the comparison between full ($\phi = 1.0$) and less responsive ($\phi = 0.25$ and $\phi = 0.5$) debt stabilization highlights the role of credible fiscal policy adjustments in mitigating the financial implications of climate transition risks. The results suggest

[26] Estonia and Ireland recorded substantial reductions in emissions intensity by 2022 compared with 1990 levels, with both countries among the EU members showing the largest cuts (greater than 80%). In the Net Zero 2050 scenario, by the end of the projection horizon, this reduction is only marginally larger than under the Current Policies scenario, with a differential of around 3 percentage points. By contrast, in Austria, Italy, and Portugal, emissions reductions in 2022 relative to 1990 levels were more moderate, at around 45% for Austria and Italy and about 35% for Portugal. Under the Net Zero 2050 scenario, the projected emissions reductions for these countries exceed those under the Current Policies scenario by more than 40 percentage points at the end of the horizon, placing them among the largest differentials in the sample of countries analyzed (see also Fig. B.1 in Appendix B).

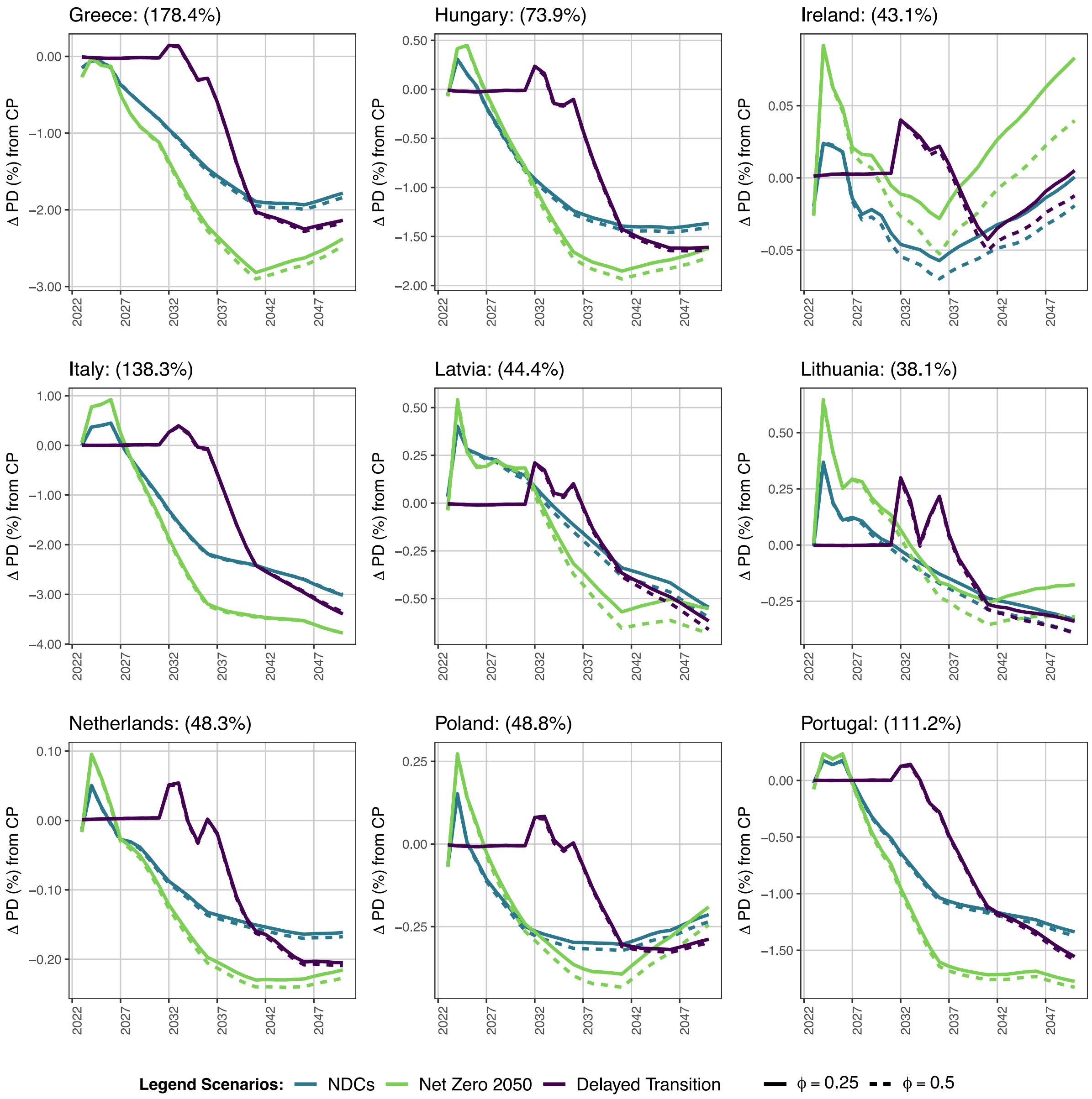

Fig. 10. Projected materiality of climate risks on sovereign five-year default probabilities (ΔPD) under alternative climate mitigation scenarios, expressed as deviations from the Current Policies (CP) scenario. Assumes less responsive debt stabilization with $\phi = 0.25$ (solid lines) and $\phi = 0.5$ (dashed lines). The observed debt-to-GDP ratio for 2022, according to the IMF, is in parentheses.

that countries with limited fiscal space or weaker policy responsiveness are more exposed to increases in sovereign vulnerability under delayed low-carbon transition scenarios.

8. Conclusions

We provide an analysis of the implications of climate transition scenarios on sovereign financial stability in Europe, thus complementing the wealth of research on climate risks for private financial institutions. We develop a panel-data model estimated using annual data for 24 European countries from 2010 to 2022 to examine the interaction between countries' climate transition risk exposure and their fiscal and financial fundamentals. The model is then used to project sovereign credit risk up to 2050 under the supervisory long-term climate scenarios developed by the Network for Greening the Financial System (NGFS).

Across climate transition scenarios, European countries with more carbon-intensive economies are likely to experience short-term increases in sovereign credit risk, reflecting macroeconomic and financial adjustments associated with decarbonization policies.

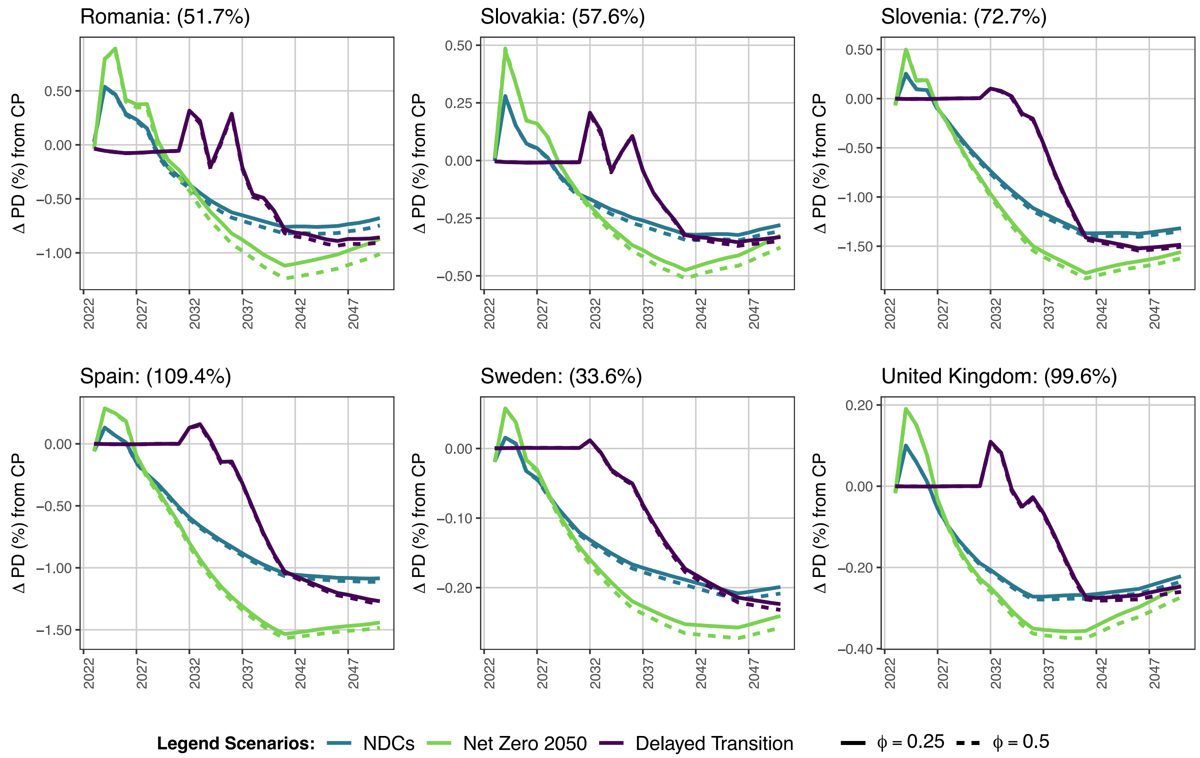

Fig. 11. Projected materiality of climate risks on sovereign five-year default probabilities (ΔPD) under alternative climate mitigation scenarios, expressed as deviations from the Current Policies (CP) scenario. Assumes less responsive debt stabilization with $\phi = 0.25$ (solid lines) and $\phi = 0.5$ (dashed lines). The observed debt-to-GDP ratio for 2022, according to the IMF, is in parentheses.

Cross-country heterogeneity is substantial and is largely explained by differences in fiscal capacity, financial conditions, and economic specialization. Climate-related sovereign vulnerabilities are particularly pronounced in economies reliant on traditional high-carbon sectors, directly or indirectly linked to fossil fuels, which are more exposed to stranded-asset risks. Nevertheless, over longer horizons, an orderly and credible transition consistent with Net Zero 2050 can generate co-benefits relative to the Current Policies baseline, leading to lower sovereign credit risk than under a delayed transition pathway.

These findings provide relevant insights for European governments and finance ministries in a global political context characterized by growing uncertainty and heterogeneity in climate policy implementation. Because sovereign credit risk responds to macro-financial fundamentals as well as to decarbonization progress, climate-policy credibility and timing enter debt-sustainability conditions rather than remaining an "external" environmental add-on. While fiscal policy is often designed with a short time horizon, our results highlight the importance of integrating the long-term dimension of transition risk into current fiscal frameworks and public investment decisions. In practice, credible early climate policies, together with the integration of NGFS-style scenarios into medium-term fiscal planning and debt management strategies, can help anticipate periods of elevated refinancing risk, support smoother adjustment paths, and preserve fiscal space for investment and adaptation.

Our analysis also underscores the importance for supervisors and investors to integrate climate scenarios into sovereign risk assessment and monitoring. For institutions engaged in fiscal surveillance (e.g., the European Stability Mechanism) and for central banks, embedding climate scenarios into debt-sustainability analysis can improve the assessment of mid- to long-term vulnerabilities. For investors and risk managers, the key message is that sovereign climate risk is forward-looking and state-dependent with respect to the transition path: similar initial fiscal positions can map into materially different risk trajectories depending on the transition pathway and its macro-financial repercussions. By translating scenario-conditioned CDS projections into risk-neutral default probabilities, our framework supports comparative scenario analysis rather than point forecasting, helps identify and motivate the use of climate-policy credibility and decarbonization progress as complements to standard fiscal indicators in sovereign surveillance.

Importantly, these implications operate through the same channels priced in sovereign CDS, debt dynamics, labor-market conditions, financing costs, and decarbonization progress. As a result, the long-run co-benefits of an orderly transition reflect improvements in scenario-consistent fundamentals rather than an assumed 'green premium'. Since our exercise is scenario-conditional (not a forecast), the main policy value is comparative: identifying where delayed action is most likely to amplify refinancing risk and constrain fiscal space.

As a potential limitation, our projections may underestimate the overall impacts of climate risks due to inherent limitations in the NGFS long-term scenarios. These scenarios quantify only a subset of physical risks and assess their effects primarily through GDP, using an external macroeconomic framework. This approach constrains the assessment of transmission channels from physical shocks to broader macro-financial variables, including capital markets and sovereign balance sheets. Furthermore, the NGFS framework currently overlooks compounding effects among physical hazards and fails to account for climatic tipping points, such as ice-sheet collapse or major disruptions to ocean circulation, which could substantially amplify systemic climate risk. On the other hand, regarding transition risk, the scenarios do not account for the role of finance and expectations, which are crucial for investment decisions and could significantly influence whether transition scenarios are met or missed (Battiston, Monasterolo, et al., 2021).

Despite these recognized limitations, the NGFS scenarios provide a common analytical foundation for assessing the impact of climate risks on the economy and financial system, including sovereign credit risk.

Future research should not only aim to further refine NGFS scenario frameworks, but also integrate potential cross-border spillover effects, which are presently only partially proxied by stock market dynamics, into sovereign risk modeling (Buchholz & Tonzer, 2016). Additionally, explicitly incorporating geopolitical risks into model specifications and projections would allow for a more comprehensive modeling of the interconnected channels driving systemic vulnerability. Such an integrative approach would facilitate a holistic assessment of the complex interactions between climate transition policies, financial contagion, and geopolitical tensions, thus better capturing the multifaceted nature of risks facing sovereign credit in an era of accelerating climate and policy shocks.

CRediT authorship contribution statement

Luca De Angelis: Conceptualization, Funding acquisition, Methodology, Data curation, Writing – original draft, Writing – review & editing. **Irene Monasterolo:** Conceptualization, Funding acquisition, Writing – original draft, Writing – review & editing. **Luca Zanin:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Software, Visualization, Writing – original draft, Writing – review & editing.

Declaration of competing interest

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

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Appendix A. Robustness checks

See Table A.1.

Appendix B. Climate-mitigation scenario for predictors

See Fig. B.1.

Appendix C. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.iref.2026.105057.

Data availability

The authors do not have permission to share data.

Table A.1
The models are estimated on panel data with annual frequency and covering the 2010–2022 period. In round parentheses, we report the adjusted standard errors at the country level using the CR2 estimator (Pustejovsky & Tipton, 2018). This adjustment produces cluster-robust standard errors that are unbiased in finite samples. For episodes in which five-year sovereign CDS spreads exceed 1000 basis points, a crisis-dummy variable is introduced, taking the value 1 in the following country-year observations: Greece 2011, Greece 2012, Greece 2014, Greece 2015, and Portugal 2011. The p-values of Pesaran's cross-dependence test are also reported (Pesaran, 2021).

	Dependent variable: log(CDS spread)				
	(1)	(2)	(3)	(4)	(5)
log(CDS spread)$_{t-1}$					0.540***
					(0.066)
log(Debt-to-GDP)$_{t-1}$	0.428*	0.557**	0.402*	0.423**	0.007
	(0.220)	(0.263)	(0.205)	(0.207)	(0.236)
Δ Unemployment rate$_{t-1}$	4.162*	4.510**	7.101***	5.427***	0.713
	(2.288)	(2.235)	(2.204)	(2.064)	(2.133)
Long-term real interest rate$_{t-1}$	5.379***	4.553***	4.845***	6.060***	1.627
	(1.524)	(1.473)	(1.586)	(2.137)	(1.184)
Stock market return$_{t-1}$	−0.424***	−0.452***	−0.491***	−0.351**	−0.260**
	(0.141)	(0.138)	(0.157)	(0.142)	(0.116)
Emissions intensity vs 1990$_{t-1}$	1.609**	1.774**	1.482*	1.748**	0.523
	(0.797)	(0.856)	(0.770)	(0.756)	(0.727)
Year Fixed Effects	YES	YES	YES	YES	YES
Country Fixed Effects	YES	YES	YES	YES	YES
Bordering with Russia–Ukraine (year 2022)	YES	NO	YES	YES	YES
Outliers CDS spreads	YES	YES	NO	YES	YES
Exclusion Greece	NO	NO	NO	YES	NO
N. Obs.	287	287	287	287	287
R2 adj.	0.88	0.87	0.85	0.87	0.92
Pesaran's CD test - p-value	0.02	0.02	0.03	0.02	0.02
In-sample					
RMSE	65.22	61.99	390.38	43.59	63.13
MAE	23.67	25.44	59.66	18.87	20.35
MdAE	6.95	7.90	7.77	6.73	6.01
MAPE	20.51	22.22	22.39	19.78	16.79

*** Denote significance at 1% levels, respectively.

** Denote significance at 5% levels, respectively.

* Denote significance at 10% levels, respectively.

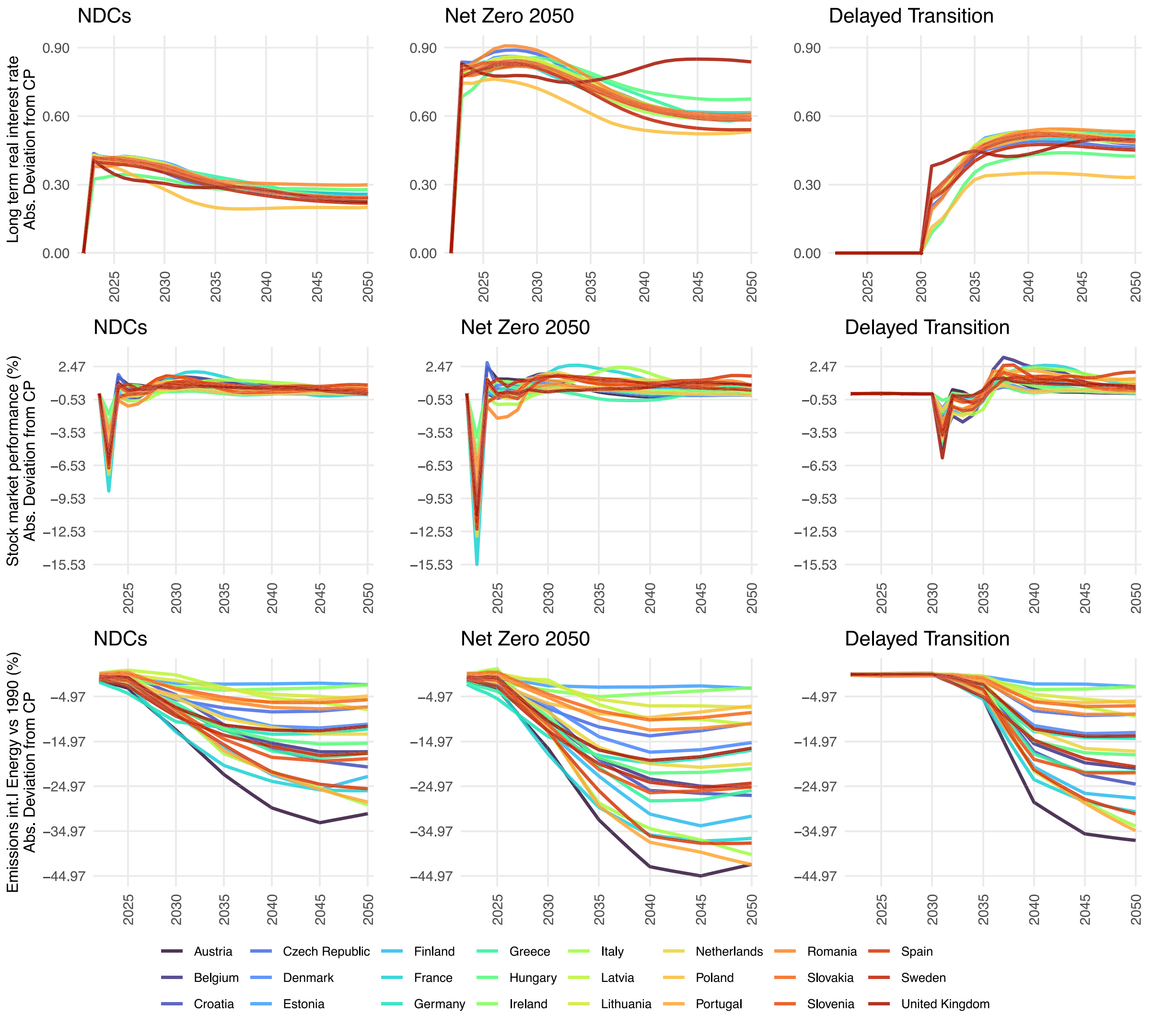

Fig. B.1. Trajectories of macro-financial variables in our modeling framework under different NGFS climate mitigation scenarios are shown as deviations from the Current Policies scenario.

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