Are sovereign debts sustainable under energy transition?

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Abstract

We analyze how transitioning to low-carbon energy sources affects sovereign debt sustainability through a data-driven, integrated modeling framework that combines climate change assessment models with stochastic debt sustainability optimization. Using scenarios from the Network for Greening the Financial System (NGFS), we evaluate orderly and disorderly transitions aligned with the Paris Agreement target of limiting global warming below 2°C. Our analysis quantifies both the transition risk premium affecting debt financing costs and the impacts on economic growth, influencing the debt-to-GDP ratio. We find significant increases in sovereign debt for fifteen countries worldwide, starting in the late 2030s. To offset these debt increases, annual fiscal adjustments averaging up to 1.1% of GDP would be necessary, with substantial cross-country differences. Stabilizing heightened debt levels due to the energy transition would require total fiscal adjustments averaging between 1.2% and 1.4% of GDP, depending on climate projections. Additionally, transition risks incentivize debt management toward longer maturities. Achieving green growth of approximately 0.5% from the transition could offset these debt impacts. Recycling carbon tax revenues toward debt repayment could also improve debt sustainability under some conditions.

Keywords: Climate change, integrated assessment models, sovereign debt, scenario analysis, sustainability, tail risk, transition risk.

JEL classification: C61, G15, H63, H68, Q43, Q51, Q54.

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1 Introduction

A complex relationship is emerging between climate policies and sovereign debt (Bolton et al., 2022) amid high COVID-19 debts (Dibley et al., 2021), evidence of priced climate risks in sovereign bond yields (Beirne et al., 2021; Cevik and Tovar-Jalles, 2022), and climate-induced credit downratings (Klusak et al., 2023). The transition to a low-carbon economy requires capital expenditures estimated at 3% of global GDP per annum until 2050 (IPCC, 2018).[1] The strains on public finances from these increasing demands on the public purse and the complex interactions between climate policies and the economy were highlighted in the IPCC Sixth Assessment Report (Pörtner et al., 2022). In this paper, we ask whether transition risk affects the sovereigns' ability to finance their debts sustainably and how countries can stabilize debts that increase with the transition. We document that significant fiscal adjustments are required and ask whether green growth (Porter and van der Linde, 1995) or recycling carbon tax revenues into debt repayment could solve the debt problem.

Investors believe that climate risks in the form of changing regulations on low-carbon transition are already materializing (Krueger et al., 2020) with regulatory risk considered the top climate risk over the next five years (Stroebel and Wurgler, 2021). Non-linearities, risk endogeneity, and inadequate disclosures can cause underpricing of these risks (Campiglio et al., 2023), raising concerns about abrupt repricing (Rebonato, 2023) when market participants recognize the missing risks of climate change (Rising et al., 2022). Using data-driven model-based analysis, we obtain forward-looking quantitative estimates of the transition effects on sovereign debt to provide more transparency and mitigate potential debt mispricing, paying attention to the *deep uncertainty* about climate change (Lempert et al., 2024).

We develop a *transition debt sustainability analysis* model linking forward-looking projections of the energy sectors from integrated assessment models (IAMs, Weyant 2017) with stochastic debt analysis (SDSA, Blanchard 2022). The model optimizes debt financing to trade off financing costs with refinancing risk and project future debt dynamics without or with transition. We calibrate the model for fifteen major global economies and eurozone countries with a wide range of debt levels under two transition policies toward net zero —orderly or disorderly. We show that transition significantly compounds the debts for either transition policy requiring large adjustments to stabilize the current debt levels as increased by transition; see the arrows in Figure 1, with a cross-country average of 1.2-1.4% of GDP per annum. We also show that transition impacts the optimal debt financing strategies towards longer maturities.

To model the transition risk, we obtain projections of shocks to the energy sectors of an economy for two transition scenarios consistent with the Paris Agreement targets using the IAMs from the Network for Greening the Financial System (NGFS, 2020).[2] Orderly transition gradually increases the stringency of climate policies towards net zero, giving a two-thirds chance of limiting global warming to below 2°C. Disorderly implements stringent policies after 2030 for

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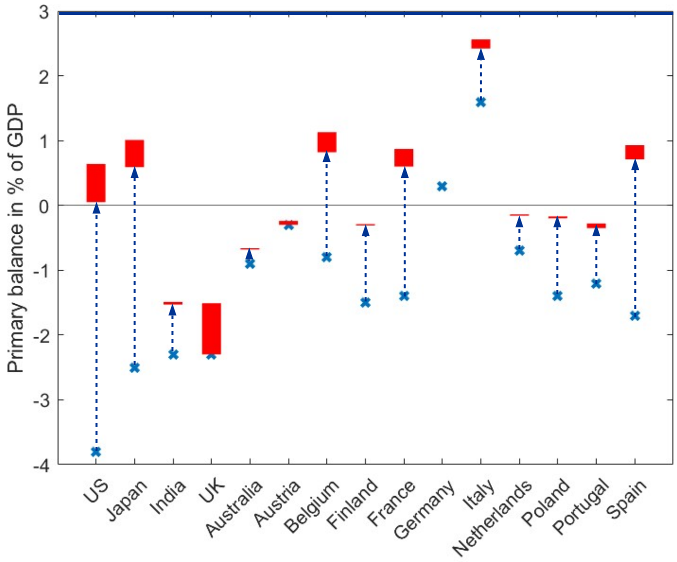
[1] This is the low estimate from the IPCC report and is indicative of estimates such as the European Commission's 2020 Europe's needs of 1.5-1.8% and IMF's 2021 G20 estimate of 2%.

[2] We use Phase IV scenarios from IIASA `https://data.ene.iiasa.ac.at/ngfs/`, `https://www.ngfs.net/en/ngfs-climate-scenarios-phase-iv-november-2023`; accessed Sept. 2023.

Figure 1 – Primary balance to stabilize current and transition debts

This figure displays the average primary balance, per annum, to stabilize the current high debt levels as increased by orderly transition under the REMIND, GCAM, and MESSAGE integrated assessment models. **x** denotes the historical average primary balance, red bars denote the range of estimates under three IAMs, and arrows indicate the required fiscal adjustments. 3% is the threshold primary balance sustained over long periods of historical fiscal adjustment episodes (Eichengreen and Panizza, 2016).



the same goal. These two scenarios are, by design, exposed to medium physical risks. Orderly transition is somewhat less stringent than net zero by 2050, and disorderly is more stringent than the nationally determined contributions. Hence, our analysis keeps physical risk constant while covering a wide range of transition stringency. We use the NGFS projections to link transition-driven changes in the energy sectors to changes in sovereign default probabilities and obtain a forward-looking *transition spread* on sovereign bond yields (Battiston and Monasterolo, 2020). We calibrate this spread to eurozone data spanning the Paris Agreement, uncovering a significant increase post-Paris. This spread adds to the cost of debt financing with a numerator effect on the debt-to-GDP ratio in SDSA. We also consider the denominator effect on the debt ratio using the NiGEM model (Hantzsche et al., 2018) under different IAMs to project real GDP levels and inflation and introduce transition effects on nominal GDP.

The NGFS scenarios are *narratives*, in the sense used by the IPCC (Pirani et al., 2024) and the climate science literature (Climatic Change, 2014), to postulate socio-economic pathways and greenhouse gas concentrations. We use these narrative projections as the expectations on which to build the SDSA model with *aleatory* uncertainties about the financial, economic, and fiscal variables. Aleatory uncertainty is introduced using discrete time- and state-space *scenario trees* with the associated probabilities and a tail risk measure, following Zenios et al. (2021). The expected cost of debt financing carries the transition spread from IAM projections, and the debt ratios incorporate the denominator effects from NiGEM under the different IAMs. A scenario tree of GDP growth and debt financing rates is calibrated to match the mean value projections from the narrative scenarios.

The SDSA model optimizes the maturity of issued debt to trade off financing cost for refinancing risk with sustainability conditions on the stock and flow ratios. It projects debt trajectories under transition for the NGFS narrative scenarios and uses a tail risk measure to assess debt sustainability with a high confidence level. We use the model to estimate two debt-stabilizing fiscal quantities: (i) adjustment to the current primary balance to offset transition debts and (ii) total adjustment to stabilize the current high debt levels as increased by the transition. To increase the acceptance of our findings in the presence of *deep uncertainty* of the narratives from climate models (Berger et al., 2017; Lempert et al., 2024) we follow Howe et al. (2019) and report results with the three NGFS IAMs —REMIND-MAgPIE, GCAM, and MESSAGE-Globiom. A *climate agnostic* version of the model without transition provides baseline reference values to assess the incremental debt effects of transition.

To our knowledge, this is the first study among the literature on climate change and sovereign debt to contribute an analysis of the transition risk effects on debt sustainability to earlier works that consider the effects of under-reporting climate risks on sovereign bonds (Dibley et al., 2021), rising temperatures on credit ratings (Klusak et al., 2023), or internalizing externalities on the optimal debt levels (Kellner and Runkel, 2023). We develop and calibrate the model (Sections 2 and 3) and use it (Section 4) to study the orderly and disorderly transition effects in four steps.

First, we study the cost-risk tradeoff in debt financing and find increasing risks and costs.

Second, we study long-term debt dynamics and find debt increases from the late 2030s. Fiscal adjustments up to 1.1% of GDP per annum (p.a.), with a cross-country average of 0.1-0.3% across IAMs (orderly) or 0.2-0.4% (disorderly), could offset the debt increases, with significant cross-country differences. These adjustments are incremental to what is required to stabilize the currently high debt levels and are indicative of the transition debt problem but not of the total debt problem. Stabilizing the current debt levels as increased by transition requires significantly larger adjustments, as shown by the arrows in Figure 1 (orderly), with a cross-country average of 1.2-1.4%, with slightly higher adjustments of 1.3-1.5% for disorderly transition (not shown). The long-term debt effects of orderly and disorderly transitions differ only slightly in all our tests; under orderly transition, debts start increasing earlier but gradually, whereas, with disorderly, they start later but abruptly, requiring about the same fiscal adjustments on average. The choice between orderly and disorderly transition does not hinge upon debt sustainability. These adjustments are feasible, albeit challenging, compared to the historical fiscal consolidation episodes compiled by Eichengreen and Panizza (2016).

Third, we study the effect of transition on the optimal debt financing strategies. From the shift of the cost-risk tradeoff, it follows that it is not possible to keep debt financing costs constant under transition risk. Maintaining an intermediate stance of cost-risk tradeoff entails a lengthening of the maturities of issued debt.

Fourth, we conduct two robustness tests to deal with deep uncertainty. We consider multiple IAMs and find consistent results with a cross-country average of cross-IAM differences in the fiscal adjustments that offset transition debts of about 0.2% of GDP p.a., although differences are bigger for some countries. We also consider narrative long-term interest rates being relatively high (Pisani-Ferry, 2021) or relatively low (Bylund and Jonsson, 2020) due to the transition and find dampened transition effects under low rates. We also conduct a robustness test on estimates of the elasticities of energy sector profitability.

We go further (Section 5), to ask whether green growth can offset transition debts. Porter and van der Linde (1995) suggest that appropriately crafted climate legislation can trigger innovations that improve productivity. There is some evidence of environmental innovations (Martínez-Zarzoso et al., 2019), but evidence for overall productivity gains is nuanced (van Leeuwen and Mohnen, 2017). We estimate that green growth of about 0.5% p.a. offsets the transition debt increase. Finally (Section 6), we ask whether carbon tax recycling into total debt repayment can solve the problem. Section 7 concludes.

Related literature

Our work contributes to the literature on climate and sovereign debt (Dibley et al., 2021; Kellner and Runkel, 2023; Klusak et al., 2023; Zenios, 2022) with a model of the transition risks to sustainability using IAMs. Accumulating empirical evidence on the effects of climate policy announcements on corporate or sovereign spreads (Bolton and Kacperczyk, 2023; Kölbel et al., 2024; Seltzer et al., 2022) and the municipal bond markets (Goldsmith-Pinkham et al., 2023; Painter, 2020) is supported by structural models (Agliardi and Agliardi, 2021; Le Guenedal and Tankov, 2024; Seghini and Dees, 2024).[3] We document empirically an effect of transition risk on sovereign spreads and uncover an economically large and statistically significant increase after the Paris Agreement, adding to works on the Agreement's impact on corporate debt creditworthiness (Capasso et al., 2020), CDS spreads (Kölbel et al., 2024), and bank loan pricing (Delis et al., 2024). The transition effect on spreads adds to works that documented effects from rising temperatures or climate vulnerabilities (Beirne et al., 2021; Cevik and Tovar-Jalles, 2022). This literature motivates our work to develop projections of sovereign bond spreads using IAMs and link them to debt sustainability analysis.

IAMs provide forward-looking climate and macroeconomic projections. Advances since the seminal DICE reduced-form cost-benefit analysis model of Nordhaus (2019) have motivated, among a vast literature on climate economics, studies on portfolio effects from climate policies (Dietz et al., 2016) and sovereign creditworthiness (Klusak et al., 2023). Among IAMs, a distinction is made between cost-benefit and process-based models (Weyant, 2017). NGFS uses process-based IAMs, which are granular models with sectoral and regional disaggregation that follow specific climate policies within a scenario analysis framework. Process-based models are the analytical engine of the IPCC Working Group III on mitigation (Skea et al., 2021), and we use NGFS projections of the annual energy consumption from different energy sectors under transition narratives. Zenios (2022) had suggested linking IAMs to SDSA to assess the debt effects of climate change. We develop a model of the transition effects on debt, calibrate it for several countries, document the transition effects under orderly and disorderly policies, and assess whether green growth could alleviate the effects. We also assess the effect of recycling part

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[3] For climate change or transition effects on asset prices see Barnett et al. (2020) and the non-overlapping surveys of burgeoning climate finance literature (Campiglio et al., 2023; Giglio et al., 2021).

of the carbon taxes into debt repayments. IAMs are useful “with caveats” (Vaidyanathan, 2021), and we employ all three NGFS models to alleviate concerns that our findings are predicated on a particular IAM.

Current literature finds no significant long-run adverse growth effects from changes in emissions for EU countries (Känzig and Konradt, 2023; Metcalf and Stock, 2023), the US (Goulder et al., 2019), or British Columbia (Bernard and Kichian, 2021), with a small impact documented on EU growth (up to 0.17%) from the nationally declared emission reductions (Vrontisi et al., 2020). The small effects on growth are consistent with the macroeconomic theory that fundamentals, rather than changes in relative prices, drive growth. However, Dees (2020) documents nonlinearities in the identification that cast a shadow on findings obtained using linear regressions on a limited time series. Hence, we also account for the impact of transition on growth using NiGEM but find its marginal effect minor in line with the literature.

Our SDSA model follows the high-realism models of international institutions (Bouabdallah et al., 2017; European Commission, 2020; IMF, 2022) that have been paying increasing attention to climate risks since 2019. A word count on climate change in the annual reports of the IMF, the European Commission, and the ECB since 2015 reveals a couple of innocuous early references, such as “other risks are unlikely to manifest themselves on a significant scale over the next few years (e.g., climate change),” with a surge to 140, 115, and 105 words, respectively, in 2019; IMF (2023) is devoted to climate risks. None of these models links climate change to debt dynamics. We develop an SDSA model to optimize the maturity of issued debt in a trade-off between financing cost and refinancing risk. Calibrating the SDSA on the narrative scenarios, we obtain forward-looking trajectories of the debt stock and flow with their associated probabilities and draw sustainability conclusions with a high confidence level (e.g., 75%).

Our paper sheds light on two aspects of deep uncertainty which is prevalent in climate impact studies (Berger et al., 2017; Lempert et al., 2024), and is relevant for our work concerning differences in IAM specifications (Vaidyanathan, 2021) and the climate effects on the natural rate of interest (Mongelli et al., 2024). Following Howe et al. (2019), we provide a range of estimates based on what is currently known. On IAMs, we use projections from the three NGFS models. On interest rates, the sign of climate impact is not a settled issue; some authors expect a lower long-term natural rate of interest (Bylund and Jonsson, 2020) while others suggest a potential increase (Pisani-Ferry, 2021). We conduct our tests using medium levels of interest rates that are broadly in line with US Congressional Budget Office projections (CBO, 2024) and Seghini (2024) but also report results with low rates in line with Blanchard (2022).

The paper most closely related to ours is Klusak et al. (2023), who study rising temperature effects on sovereign creditworthiness. We differ from them in the object of our study and the methodological innovation. We study transition risk, one of the three channels from climate to debt —the others being damages and adaptation— thus studying an important channel not addressed by this earlier work. Methodologically, we look at debt dynamics instead of credit ratings to assess debt sustainability. Our findings of worsening debt sustainability outlook imply down ratings, as they find, but lower ratings do not necessarily imply unsustainable debt. Hence, our work uncovers a mechanism that leads to the phenomenon documented in this reference.

We also contribute a positive outlook to Dibley et al. (2021) that transition risk per se does not imperil the countries' ability to repay debts, but we do corroborate their assertion on climate adverse effects. A related recent work (Seghini, 2024) develops a structural model with carbon budget constraints to estimate debt limit effects of transition in an infinite horizon setting. It finds, like us, a negative impact from the transition to the available fiscal space.

2 Transition debt sustainability analysis

We follow Zenios et al. (2021) to develop an SDSA model with a transition spread on debt financing rates and transition effect on nominal GDP. These effects are predicated on IAM projections under narrative scenarios of orderly or disorderly transitions. We add aleatory uncertainty about the interest rates, growth, and fiscal balance using scenario trees around the narrative mean-value projections. Hence, the model accounts for both aleatory and deep uncertainty. The dynamics of debt stock- and flow-to-GDP ratios are state-dependent on the tree and a tail risk measure is used to formulate the model for optimal debt financing with sustainability constraints.

2.1 Model setup

We consider a sovereign with nominal economic output Y_t at period t, debt stock D_{t-1} with D_0 the legacy debt, and primary balance PB_t. The sovereign's *gross financing needs* (GFN) are given by the *debt flow* variable

$$GFN_t = i_{t-1} D_{t-1} + A_t - PB_t, \tag{1}$$

where i_{t-1} is the *effective nominal interest rate* on debt, and A_t denotes the part of debt stock D_{t-1} which is due. The *debt stock* is given by

$$D_t = (1 + i_{t-1}) D_{t-1} - PB_t. \tag{2}$$

The sovereign issues debt securities of maturities denoted by $j = 1, 2, \ldots, J$, with *financing decisions* $X_t(j)$ denoting the nominal amount of debt with maturity j issued at t. The *debt financing equation* satisfies

$$\sum_{j=1}^{J} X_t(j) = GFN_t. \tag{3}$$

The nominal interest rate on the issued debt is determined by the risk-free interest rate (r_{ft}) plus a premium on the sovereign's debt level (Blanchard et al., 2021). Following Zenios et al. (2021), the interest rate for instrument j issued at t is

$$r_t(j) = r_{ft} + \rho(d_t, j). \tag{4}$$

$d_t = D_t/Y_t$, and $\rho(d_t, j)$ are the premia for the jth instrument maturity given by

$$\rho(d, j) = a_j + \hat{\rho}(d). \tag{5}$$

a_j is the *term premium* and $\hat{\rho}(d)$ is the *risk premium.* $\hat{\rho}(d)$ is a piece-wise linear function with value zero for debt ratios below d_{min} and increasing linearly for higher debt until it hits the ceiling d_{max} when the sovereign loses market access and is financed from multilateral institutions captured by the sigmoid:

$$\hat{\rho}(d) \doteq \hat{\rho}_c \left[\frac{d_{max} - d}{1 + \exp\left(d_{max} - d\right)} - \frac{d_{min} - d}{1 + \exp\left(d_{min} - d\right)} \right]. \tag{6}$$

The constants are estimated from panel regressions on a sample of countries for the eurozone, and for non-eurozone countries, we simplify this with constant historical average spread. $r_t(j)$ determines the *effective interest rate* in (2) as a function of the issued debt through the financing decisions $X_t(j)$.

2.2 The transition-debt channels

2.2.1 Transition spread

We consider the cumulative change in default probability at time t under an energy transition scenario S with projections from integrated assessment model M, $\Delta p_t^{S,M}$. This is the change in default probability from the probability under no transition. The forward-looking *transition spread* $\Phi\left(\Delta p_t^{S,M}\right)$ is a function of this change and is added to the financing rates from (4) under the climate-agnostic business-as-usual policy B,

$$r_t^{S,M}(j) = r_{ft} + \rho(d_t^{S,M}, j) + \Phi\left(\Delta p_t^{S,M}\right), \tag{7}$$

$$\Phi\left(\Delta p_t^{S,M}\right) = \begin{cases} 0 & \text{for } S = B, \\ \beta \cdot \Delta p_t^{S,M} & \text{for } S \neq B. \end{cases} \tag{8}$$

The first two terms in (7) reflect the debt financing rates as determined by the risk-free rate and the idiosyncratic spread for the sovereign under business as usual, and the last term is the spread increase from future changes in the default probability due to transition. We estimate the coefficient β in subsection 3.2, following works that empirically documented the effect of climate policy announcements on sovereign (Shah, 2022) or corporate (Bolton and Kacperczyk, 2023; Kölbel et al., 2024; Seltzer et al., 2022) bond spreads.

To compute $\Delta p_t^{S,M}$, we link the sovereign default probability to changes in the country's energy mix, following Battiston and Monasterolo (2020). Given K sectors in the economy, we assume that a relative change in the share of energy sector k to the gross value added (GVA) of the country implies a proportional relative change in the *net fiscal assets* of the sovereign from sector $k \in K$, A^k. This is the difference between accrued fiscal revenues from the sector and public investments and subsidies granted. Therefore, a transition policy S under model M resulting into a market share shock u^k implies a change $\Delta A^{k,S,M}$ in the net fiscal assets for k equal to

$$\frac{\Delta A^{k,S,M}}{A^k} = u^{k,S,M}\chi^k, \tag{9}$$

where χ^k is the sector's elasticity of profitability to the market share. The change in total fiscal assets is given by

$$\frac{\Delta A^{S,M}}{A} = \sum_{k\in K} \frac{A^k}{A}\frac{\Delta A^{k,S,M}}{A^k} = \sum_{k\in K} \frac{A^k}{A} u^{k,S,M}\chi^k = \sum_{k\in K} c^k u^{k,S,M}\chi^k, \tag{10}$$

where A is the net fiscal assets of the country and c^k is the share of sector k GVA with respect to the total.

The creditworthiness of the issuer is assessed through a default condition on its assets and liabilities. That is, starting from t_0, there is a default at maturity T if the net fiscal assets are below the liabilities (L_T). Assuming an idiosyncratic shock η_T and an independent climate policy shock ξ, the (climate adjusted) default condition is

$$A_T = A_{t_0}(1 + \eta_T + \xi^{S,M}) < L_T. \tag{11}$$

This condition is satisfied if and only if

$$\eta_T < \theta^{S,M},$$

where

$$\theta^{S,M} = \frac{L_T}{A_{t_0}} - 1 - \xi^{S,M} \tag{12}$$

is the default threshold. The probability of default under transition risk is

$$p^{S,M} = \mathbb{P}(\eta_T < \theta^{S,M}) = \int_{\eta_{inf}}^{\theta^{S,M}} \phi^{S,M}(\eta)d\eta, \tag{13}$$

with $\phi^{S,M}(\eta)$ as the probability distribution of the idiosyncratic shock and η_{inf} denoting the lower bound of the distribution support. Assuming that the climate shock on net fiscal assets is proportional to the shock on the GVA of the sectors, we obtain from (10) that $\xi^{S,M} = \sum_{k\in K} c^k u^{k,S,M}\chi^k$. The change in probability of default from the baseline scenario B to the transition scenario S can be approximated by

$$\Delta p^{S,M} \approx -\sum_{k\in K} c^k u^{k,S,M}\chi^k. \tag{14}$$

An interpretation of this result is that ceteris paribus, a shock to the energy sector k impacts the economy GVA in proportion to the contribution (c^k) of this energy sector to the gross value added and the sensitivity of the sector's profitability to the market share (χ^k), hence, having an impact on the net fiscal assets of the issuer and resulting in a shift of creditworthiness. For the full proof see Battiston and Monasterolo (2020).

Out of the K economic sectors, we consider shocks to the market share of primary and secondary energy sectors.[4] $u_t^{k,S,M}$ is the percentage shock at time t to the share of energy sector k in the total country energy mix under transition scenario S and projections from model M. The trajectories of these shocks are obtained from the NGFS scenarios.[5] The contribution of each sector to the total GVA is given by

$$c^k = m^k \, \frac{\text{GVA}^{en}}{\text{GVA}}, \tag{15}$$

where m^k is the energy market share of sector k, adjusted by the relative contribution of the total energy sector GVA^{en} to the country's GVA.

2.2.2 Growth effect

The empirically documented transition effect on growth is insignificant (Bernard and Kichian, 2021; Goulder et al., 2019; Känzig and Konradt, 2023; Metcalf and Stock, 2023) or small (Vrontisi et al., 2020). Still, we include the growth channel in SDSA for completeness, and the model can be used as new information on nonlinearities (Dees, 2020) may become available. We use NiGEM with different IAMs and NGFS scenarios to project real GDP and price level changes.[6]

We first retrieve the real GDP under transition scenarios, given the climate-agnostic baseline GDP without climate change and transition efforts, Y^B. NiGEM provides projections of real GDP proportional change under transition S with model M, $\kappa_t^{S,M}$, and the real GDP dynamics, denoted by subscript r, are

$$Y_{r,t}^{S,M} = (1 + \kappa_t^{S,M}) Y_{r,t}^B. \tag{16}$$

To obtain nominal GDP, denoted by subscript n, we obtain from NiGEM future price levels under transition, $P_t^{S,M}$, in relation to the base year agnostic price level, P_0^B,

$$Y_{n,t}^{S,M} = \frac{P_t^{S,M}}{P_0^B} \, Y_{r,t}^{S,M}. \tag{17}$$

The nominal GDP under transition is obtained from the baseline real GDP as

$$Y_{n,t}^{S,M} = (1 + \kappa_t^{S,M}) \, \frac{P_t^{S,M}}{P_0^B} \, Y_{r,t}^B. \tag{18}$$

2.3 Scenario trees

The NGFS projections are narratives of the best estimates for a given IAM and transition policy. Around these expected values, we introduce financial, economic, and fiscal uncertainty using a discrete-time- and state-space scenario tree of the inputs to the SDSA, namely the risk-free interest rates, growth, and fiscal balance. Figure 2, panel A, illustrates the tree with

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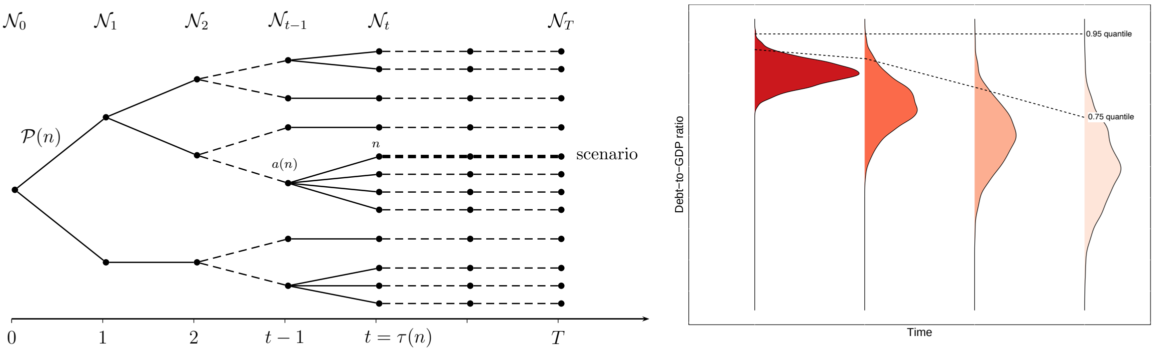
[4] For primary, we consider gas, coal, oil, nuclear, wind, solar, hydro, and geothermal, and for secondary, we use gas, coal, oil, nuclear, wind, solar, hydro, and biomass, including both fossil and renewable sources.

[5] The NGFS IAMs are regional, so each country's us equal the regional values.

[6] We use NiGEM projections consistent with the NGFS Phase IV scenarios with the IAMs from the IIASA database `https://data.ene.iiasa.ac.at/ngfs/`, see `https://www.ngfs.net/en/ngfs-climate-scenarios-phase-iv-november-2023`—data accessed June 2024.

Figure 2 – Scenario tree and stochastic debt dynamics

This figure displays (a) discrete time- and state-space scenario tree, and (b) the distributions of debt-to-GDP ratio at different points in time. Time is denoted by $t = 0, 1, 2, \ldots T$, where T is the risk horizon, and states $\nu \in \mathcal{N}_t$. $\mathcal{P}(\nu)$ denotes the set of states on the unique path from the root state 0 to ν, $a(\nu)$ denotes the unique predecessor of state ν, and $\tau(\nu)$ denotes the time of ν. Each path leading to a terminal state in $\mathcal{N}_T$ is a scenario.


(a) Scenario tree **(b)** Distributions of debt stock

time denoted by $t = 0, 1, 2, \ldots T$, and *states* at t by $\nu \in \mathcal{N}_t$, where T is our risk horizon. The number of states at t is N_t, with a total number of states N. Not all states at t can be reached from every state at $t-1$, and $a(\nu)$ denotes the unique *predecessor* of state ν. $\mathcal{P}(\nu)$ denotes the set of states on the unique *path* from the *root state* 0 to ν, with $\tau(\nu)$ denoting the time of node ν. Each path leading to a terminal state $\nu \in \mathcal{N}_T$ is a *scenario*, with probability $\text{Prob}^{(\nu)}$. For each state ν, all information at states $m \in \mathcal{P}(\nu)$ is known since m precedes ν. Problem data and model variables are state-dependent, indexed by ν, referring to states of a scenario tree calibrated under S and M. For simplicity of notation, we henceforth drop S and M in formulating the state-dependent model. It is understood that $\nu \doteq \nu(S, M)$, and we specify S and M only when using the model and report results.

We calibrate the scenario tree using moment matching (Høyland and Wallace, 2001) to estimate the level of the state variables and the conditional probabilities at each state so that at each period, their mean values, standard deviations, and correlations match input data. The first moments match the projections from the narrative scenarios. Albeit, we have no forward-looking projections of the second moments, and we match historically estimated values of volatilities and correlations. The use of historical estimates is conservative since it assumes that transition policies do not fundamentally alter the correlation structure. In reality, transition uncertainty may increase the volatility and correlations and result in higher impacts. Hence, the findings from our tests can be considered optimistic. The tree need not be binomial or have a fixed number of branches at each period, and the simultaneous estimation of levels and conditional probabilities generates trees that can match the moments with a relatively small number of scenarios. We found that estimating the level of state variables and conditional probabilities of the states of a tree with two branches per state for the first five periods and extended linearly thereafter matches the input moments. Data for the tree calibration are given in subsection 3.1.

2.4 Debt dynamics and the risk measure

We can now define state-dependent financing decisions, $X_t^\nu(j)$, to obtain the debt dynamics on the tree. The state-dependent dynamics depend on the transition narrative S under projections from model M through the transition spread in (7) and the growth relation (18). We rewrite (3) as

$$\sum_{j=1}^{J} X_t^\nu(j) = GFN_t^\nu, \tag{19}$$

for $\nu \in \mathcal{N}_t$, and $t = 0, 1, 2, \ldots T$, where $GFN_t^\nu = i_{t-1}^{a(\nu)} D_{t-1}^{a(\nu)} + A_t^\nu - PB_t^\nu$, and $D_t^\nu = (1 + i_{t-1}^{a(\nu)}) D_{t-1}^{a(\nu)} - PB_t^\nu$ are the state-dependent versions of the flow and stock equations (1)-(2), and we obtain i_t^ν from the state-dependent interest on the issued debt financing instruments. The discrete distributions of the flow and debt ratios on the scenario tree are denoted by $gfn_t^\nu = GFN_t^\nu / Y_t^\nu$ and $d_t^\nu = D_t^\nu / Y_t^\nu$, with Y_t^ν the state-dependent GDP.

We use the discrete distributions of the stock and flow ratios to assess debt sustainability. We consider debt sustainable when two conditions are satisfied: (i) refinancing needs are below an (empirically observed) threshold that markets can finance with high probability (Bouabdallah et al., 2017, p. 29), and (ii) stock is on a non-increasing trajectory in the long run with a high probability (Blanchard, 2022). If flows exceed the threshold, the sovereign can face a liquidity crisis, and if the stock keeps increasing, the sovereign will face a solvency crisis. In Figure 2, Panel B, we illustrate an example of temporal debt-to-GDP distributions shifting towards lower values for longer horizons. In this example, the 0.75 percentiles are declining, and therefore, we infer with a high confidence level that debt stock is on a sustainable trajectory.

To quantify the high-confidence requirement, Zenios et al. (2021) introduced a tail risk measure of the gross financing needs, using the coherent *conditional-Value-at-Risk* (CVaR, Artzner et al., 1999), defined as the expected value of financing needs above the right α percentile. If gfn denotes the aggregate gross financing needs stochastic variable over all periods, the CVaR of flow is given by

$$\Psi(gfn) \doteq \mathbb{E}\left(gfn \mid gfn \geq gfn^\diamond\right), \tag{20}$$

where $gfn^\diamond$ is the Value-at-Risk. It is the right α-percentile of the gross financing needs, i.e., the lowest value of gfn such that the probability of gross financing needs less or equal to $gfn^\diamond$ is greater or equal to α. If $\Psi(gfn)$ is bounded by the refinancing threshold, then debt can be refinanced with probability α and refinancing risk is low.

2.5 Optimal debt financing with sustainability conditions

Equipped with a risk measure of the flow dynamics, we formulate a Pareto model of optimal debt financing to minimize the expected *net interest payment* (NIP) subject to acceptable levels of refinancing risk, and assess the sustainability of debt stock dynamics.

Interest payments on state ν of the tree consist of interest on legacy debt, denoted by I_t^ν, plus service payments on the debt created endogenously by the financing decisions. To calculate the endogenous service payments on a path leading to ν, we introduce $CF_t^\nu(j, m)$ to denote the nominal amount of interest payment at state ν of period t, per unit of debt $X^m_{\tau(m)}(j)$ issued at state m of an earlier period $\tau(m)$ on path $\mathcal{P}(\nu)$. Both the interest on legacy debt and the endogenous debt service payment are computed from scenarios of the term structure of interest rates. The legacy interest rate can be scenario-independent if the legacy debt is fixed-interest, whereas the endogenously issued debt carries the risk premium (7) and the term premia for the maturities of the issued debt.

The state-dependent net interest payment, which is what the issuing sovereign controls through the financing decisions, is given by

$$\text{NIP}^\nu_t = I^\nu_t + \sum_{m \in \mathcal{P}(\nu)} \sum_{j=1}^{J} X^m_{\tau(m)}(j)\, CF^\nu_t(j,m). \tag{21}$$

Recall that $\nu \doteq \nu(S, M)$ and the SDSA variables are conditional on transition narratives through transition spreads (7) or growth (18). Hence, the transition SDSA minimizes the expected cost of debt subject to a flow risk constraint

$$\underset{X}{\text{Minimize}} \qquad \sum_{\substack{\nu \in \mathcal{N}_t, \\ t=0,1,2,\ldots T.}} \text{Prob}^{(\nu)}\, \text{NIP}^\nu_t \tag{22}$$

$$\text{s.t.} \qquad \Psi(gfn) \leq \omega. \tag{23}$$

Varying the parameter ω, we trade financing cost with refinancing risk. For ω, below the empirically observed threshold, we ascertain, with high confidence, that debt financing needs can be met (first sustainability condition). However, debt stock increases for lower ω, and there is a tension between stock and flow. We can impose a stock sustainability constraint on the CVaR of the inter-temporal rate of stock change (second sustainability condition), $\Psi\left(\frac{\Delta d^\nu}{\Delta t}\right) \leq 0$. However, if debts are not sustainable, as our research question seeks to answer, the model with flow and stock constraints will have no feasible solution. Instead, we solve for the minimum cost for values of ω below the threshold and check, ex-post, if the stock trajectories are non-increasing with high probability.

If debt stock is on an increasing trajectory, we use a model extension (Zenios et al., 2021, section 6) to optimize fiscal adjustments to stabilize debt in the long run with high probability. Specifically, we find the minimum adjustments to the historical primary balance that satisfy the debt stock constraint. Using a decision variable z_t to denote adjustments as a proportion of GDP, we write debt financing (19) as

$$\sum_{j=1}^{J} X^\nu_t(j) + z_t Y^\nu_t \geq GFN^\nu_t. \tag{24}$$

$z_t Y^\nu_t$ is the part of gross financing that is not financed by issuing debt. This is the required fiscal adjustment to increase primary balance and repay debt. To obtain the minimum adjustments to satisfy the target refinancing risk with non-increasing stock, we add a penalty term $M \sum_{t=0}^{T} z_t$ to (22), where M is a large constant.

We compute the temporal average of the estimated fiscal adjustment over the periods for which such an adjustment is warranted and increase the country's long-term primary balance by this amount to stabilize debt. This is the *debt-stabilizing primary balance* (denoted by pb* as a fraction of GDP) and provides an aggregate measure of the debt effects of different transition scenarios. If the debt-stabilizing primary balance is considered practically feasible, e.g., compared to the historical experiences compiled by Eichengreen and Panizza (2016), we conclude that sovereign debts are sustainable under transition.

We use the transformation $w_t^\nu(j) = \frac{X_t^\nu(j)}{GFN_t^\nu}$, with $\sum_{j=1}^J w_t^\nu(j) = 1$, for three debt financing strategies: (i) a *fixed-mixed strategy* with simple *rules* whereby the weights are time-invariant $w(j)$ for all periods; (ii) an *adaptive fixed-mix strategy* that adapts with time but is identical for all states at each period with weights $w_t(j)$; (iii) a *dynamic strategy* with state-contingent weights $w_t^\nu(j)$. A dynamic strategy can be more efficient than adaptive, which is more efficient than fixed-mix. To isolate the transition effects on debt from changes in debt financing strategy we use fixed-mix as the default; see Section 4.3 for the transition effects on optimal financing. The model formulation with linearization of the risk measure follows (Zenios et al., 2021, Appendix).

3 Model calibration

We now describe the data for the scenario tree calibration and estimate the transition spread. We start in December 2023 with a horizon to 2070 that extends well beyond the target of current transition policies, such as the EU 2050 goal for achieving neutrality and the COP28 pledge for a significant increase in renewable power capacity by 2030.[7] Our sample of countries includes major global economies (US, Japan, India, UK, Australia) and eurozone countries (Austria, Belgium, Finland, France, Germany, Italy, Netherlands, Poland, Portugal, and Spain). They were chosen for their geographical diversity, large dispersion of current debt levels, and diverse energy mix.

3.1 Data and scenario trees

The sources for country data for the legacy debt term structure, the transition risk variables, and the data to calibrate the scenario trees —yield curves on government bonds, economic growth, fiscal balance— are given in online Appendix Table A.1.

Sovereign debt. The term structure of the legacy tradeable debt is from Eikon-Refinitiv. We consider bonds issued in the home currency, which covers 95% to 99.7% of the total debt, with an average of 97.5%. We correct for any mismatch between the initial debt-to-GDP ratio from the Eikon-Refinitiv data compared to the country's debt ratio from various official sources by scaling our estimates to obtain identical initial values.[8] The average scaling across countries is ±6% with a net of zero.

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[7] See `https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32021R1119` and `https://www.carbonbrief.org/cop28-key-outcomes-agreed-at-the-un-climate-talks-in-dubai/`.

[8] The sources include IMF/WorldBank for US, the treasuries of Finland and the Netherlands, Istat for Italy, Office for National Statistics for the UK, Statistics Austria for Austria, Statista for Japan, and Trading Economics for the remaining countries.

Energy sector contribution to gross value added (m^k). This is computed from each sector's share of the country's energy mix from Our World in Data. The share of energy to the countries' gross value added is from the sources of Table A.1.

Interest rates. We use five-year forward rates as the risk-free rate. For EU countries, we compute the forward rates from the yield curve of AAA-rated bonds from the European Central Bank. For the US, UK, and Japan, we use yield curves from FRED, the Bank of England, and Refinitiv. We select yield curves for medium interest rates with long-term spot rates of about 2.5%; see Appendix Figure A.1, Panel A. We also perform robustness tests with low yields starting near the zero lower bound and increasing to about 1% in the long run; see Figure A.1, Panel B.

Risk premia over the risk-free rate are computed for the eurozone countries according to (6), with $\hat{\rho}_c = 3.25$ (Zenios et al., 2021), within the range 2-4 from Blanchard et al. (2021). $d_{min} = 60$ and $d_{max} = 160$ are set to the historically observed limits for eurozone countries; spreads have been virtually zero for countries within the 60% stability and growth pact criterion and for debt ratios above 160% the countries lost market access. For India and Australia, we use the US yield curve with risk premia computed as the historical average of spreads over the US spot rate, respectively 500 and 100 basis points. There are no risk premia over their yield curves for the US, UK, and Japan. The term premia are computed from historical averages of 2001-2020; see Figure A.1, Panel C.

GDP growth. For eurozone countries, we obtain real GDP growth and HICP until 2070 from the 2024 European Commission Ageing Report. For non-eurozone countries, we use nominal projections from the 2023 IMF World Economic Outlook until 2028 to match the first moment on the tree for the first five periods and past that the long-term scenarios converge linearly to the 1995-2020 historical averages; see Appendix Table A.2, Panel A. For the transition effects on growth, we use the NiGEM-NGFS coefficients $\kappa^{S,M}$; their temporal average until 2070 is in the range 0.998–1.012 for all countries, with a minimum of 0.985 and maximum of 1.028. The transition effects on growth are small.

Primary balance. We use the 2023 IMF World Economic Outlook projections, in % of GDP, over the period 2024-2028 with long-term projections as the historical averages over the period 1995-2020; see Table A.2, Panel B. The first moment of the tree matches the IMF projections for the first five periods and past that it converges linearly to the long-term average.

Standard deviations and correlations. We estimate the standard deviations and correlations to calibrate the scenario trees from historical data going back twenty years before 2020 to avoid potential regime changes during the pandemic. The standard deviations are in the tables above, and correlations are available from the authors.

Scenario trees. We calibrate scenario trees for each country using the moment matching method of Høyland and Wallace (2001) so that the first moments of the state variables match the projections of interest rates, GDP growth, and primary balance described above. We also match the standard deviations and correlations above.

Carbon taxes. We obtain aggregate revenues accrued from carbon taxes to each sovereign as projected by NGFS until 2070 under orderly and disorderly transitions using REMIND. The data are in 2010 dollars and the relative contribution of the carbon tax as % of GDP is adjusted by 2010 US GDP.

3.2 Transition spread and the Paris Agreement

To compute the transition spread (cf. eqn. 8) we first obtain the default probability changes from (14)-(15) using IAM projections under the transition scenarios. We use elasticities $\chi^k = 1$ for all sectors (Battiston and Monasterolo, 2020), but we also run robustness tests with lower values. See online Appendix Figure A.2 for the default probabilities of our sample of major economies. We then estimate the βs from a panel regression of the spreads on changes of default probability with country and global control variables using a generalized linear mixed model (Breslow and Clayton, 1993) on a balanced panel of the eurozone countries spanning 2001-2022. The model uses random effects to account for intra-cluster correlations and we include a structural break for the Paris Agreement.

We regress the most liquid 10-year sovereign bond yield spreads (s) over the German bund. To account for the impact of the change in default probabilities on spreads, we compute the temporal change in the implied probability of defaults (p), computed at the end of the year, and use a dummy variable D, taking value zero before the Paris Agreement and one otherwise, controlling for spread determinants from the literature (Afonso et al., 2012; Delatte et al., 2017; Gabriele et al., 2017). We use nominal debt-to-GDP ratio (d), changes in the debt-to-GDP ratio (Change), the country's primary balance as a fraction of GDP (pb), and a high-debt dummy (H) taking value one for high-debt countries, taken to be those with a debt ratio above the EU stability and growth pact threshold of 60%, and zero otherwise, for government controls, and real GDP growth (Real) for macroeconomic controls. For global controls, we use the US 10-year yield (YieldUS), market volatility (VIX) as a proxy for risk appetite (Longstaff et al., 2011), world real GDP growth (World), the rate of change of the HICP (ΔHICP). X is the matrix of interaction terms of D with the regressors excluding Δp, with coefficients vector Γ

$$\begin{aligned} s_{i,t} = \alpha_0 + \alpha_1 d_{i,t-1} + \alpha_2 \Delta p_{i,t-1} + \alpha_3 D_{i,t-1} \times \Delta p_{i,t-1} + \alpha_4 \mathrm{H}_{i,t-1} + \alpha_5 \mathrm{Real}_{i,t-1} + \\ + \alpha_6 \mathrm{Change}_{i,t-1} + \alpha_7 \mathrm{YieldUS}_{i,t-1} + \alpha_8 \mathrm{VIX}_{i,t-1} + \alpha_9 \mathrm{World}_{i,t-1} + \\ + \alpha_{10} \Delta \mathrm{HICP}_{i,t-1} + \alpha_{11} \mathrm{pb}_{i,t-1} + \Gamma X_{t-1} + \epsilon_{i,t}. \end{aligned} \tag{25}$$

The independent variables are lagged to alleviate endogeneity issues. The Variance Inflation Factor for the Δp regressor has a value of 1.10, alleviating multicollinearity concerns.

Table 1 summarizes our results.[9] The Chow test shows a statistically significant effect of the Paris Agreement on the spreads. The coefficients of Δp and the interaction of Δp with the structural break are statistically significant at the 0.01 level. The total effect on spreads of a unit change in default probabilities is $\hat{\alpha}_2 + \hat{\alpha}_3 = 0.60$ after the Paris Agreement and $\hat{\alpha}_2 = 0.19$

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[9] We also used country fixed effects with robust standard errors (Newey and West, 1987) and found consistent results (available from the authors).

Table 1 – Estimation of transmission coefficient β

This table displays the coefficients estimated of (25) on the change in default probability Δp, with control variables including the debt-to-GDP ratio (d), a dummy for high debt (H) taking value 1 for debt ratios above 60% and 0 otherwise, real GDP growth (Real), changes in the debt-to-GDP ratio (Change), the US 10-year yield (YieldUS), market volatility (VIX), world real GDP growth (World), rate of change of the HICP (ΔHICP), and the primary balance (pb). D takes a value of zero before the Paris Agreement and one otherwise. ***, **, and * denote statistical significance at the 1%, 5%, and 10% levels, respectively. The sample spans sixteen eurozone countries with yearly observations from 2001 to 2022.

Variable	Coefficient	p-value
Intercept	-4.03***	0.01
d	0.065***	0.01
Δp	0.19***	0.01
$D \cdot \Delta p$	0.41***	0.01
H	-1.34***	0.01
Real	-0.07*	0.08
Change	0.04***	0.01
YieldUS	-0.17	0.14
VIX	0.05***	0.01
World	0.41***	0.01
ΔHICP	0.11**	0.04
pb	-0.02	0.52
D	1.74	0.23
$D \cdot d$	-0.029***	0.01
$D\cdot$ H	1.15**	0.01
$D\cdot$ Real	0.015	0.86
$D\cdot$ Change	-0.04	0.13
$D\cdot$ YieldUS	0.19	0.57
$D\cdot$ VIX	-0.02	0.63
$D\cdot$ World	-0.26*	0.06
$D \cdot \Delta$HICP	-0.036	0.76
$D\cdot$ pb	0.07	0.40
Chow test (F)	7.41***	0.01

before. The post-Paris increase is in line with effects documented for corporate debt spreads (Capasso et al., 2020; Kölbel et al., 2024) and bank loan pricing (Delis et al., 2024).

Alternatively, and as a robustness test, we estimate β directly from the linear relation

$$p = \frac{s}{1-R}, \tag{26}$$

where R is the recovery rate. Hence, $\frac{\Delta s}{\Delta p} = (1-R)$, which is the loss-given-default (LGD) so that β=LGD measures the spread sensitivity to a change in p. Using the ISDA constant recovery rate for senior bonds of developed countries also gives $\beta = 0.60$.[10]

4 Transition effects on sovereign debt

We put the model to work on our broad sample of fifteen developed economies. We take the flow threshold to be 20% as set in (Bouabdallah et al., 2017, p. 29), set $\alpha = 0.95$ for the flow tail risk, optimize over 3-, 5-, 10-, and 30-year debt financing bonds, and examine the 0.75 percentile

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[10] See `https://www.cdsmodel.com/fee-computations.html?`.

Table 2 – Fiscal adjustments to stabilize current debts

This table displays the climate-agnostic fiscal adjustments (Adj) required to stabilize current debts in the long run and the resulting long-term debt-stabilizing primary balance (pb*), in % of GDP p.a. The results are obtained using the climate-agnostic SDSA. The German debt is stable, and no adjustment is required from the historical primary balance of 0.3% of GDP, but we estimate that it remains stable with a primary balance of -0.6%, albeit at a higher level.

	Adj	pb*
US	3.3	-0.5
Japan	3.1	0.6
India	0.5	-1.8
UK	0.0	-2.3
Australia	0.1	-0.8
Austria	0.0	-0.3
Belgium	1.6	0.8
Finland	1.2	-0.3
France	2.0	0.6
Germany	0.0	0.3
Italy	0.5	2.1
Netherlands	0.4	-0.3
Poland	1.0	-0.5
Portugal	0.9	-0.4
Spain	2.3	0.6
Average	1.1	-0.1

of debt stock for sustainability. We implement the model in MATLAB using FMINCON for constrained optimization, solving the resulting nonlinear programs on an HP with an i5-7200U CPU and 16 GB of memory.

To test for the transition effects, we first generate climate-agnostic reference debt projections using the original SDSA model and compare them with medium-term projections from the IMF Article IV reports. The corresponding projections are remarkably close for most countries; see Appendix Figure B.1. Small differences are explained by the fact that Article IV data are from 2021 or 2022, just after the COVID-19 lockdowns, preceding our analysis by at least one year, and the sources of financial, economic, and fiscal data available to us are not those of the IMF. The initial differences are small, averaging 6.85 percentage points (p.p.), and the reference projections can be considered reliable.

For a consistent cross-country comparison of the transition effects, we first adjust for the fact that some countries have precarious debt positions while others can borrow more. Specifically, we estimate fiscal adjustments that stabilize long-run debt under climate agnostic SDSA to obtain the debt-stabilizing primary balance pb*; see Table 2. Negative pb* implies that a country can have sustainable debt running a deficit and positive indicates a need for surplus. We notice that an average adjustment of 1.1% of GDP can stabilize current debts, corresponding to an average long-term deficit of -0.1%.

We obtain a threshold of how much primary surplus may be feasible from Eichengreen and Panizza (2016), who discuss episodes of fiscal adjustments to estimate for how long countries have been able to run surpluses and by how much. Primary surpluses averaging 3% of GDP for up to five years have been possible, albeit under solid growth and high debt ratios, making the adjustment urgent. The adjustments in Table 2 can be considered feasible but challenging and with significant differences among countries. We also benchmark pb* against the historical maximum primary surplus from IMF data, following Seghini (2024). The historical cross-country average maximum is about 4.7%, with most countries' maxima higher than 3%; India and Poland are the only exceptions, with respective maxima of 2.3% and 1.3%. The pb* estimates are always below the historical maxima, but the maxima are excessively optimistic since they are one-off.

Our estimates are roughly aligned with those by Darvas et al. (2024) of the minimum structural adjustments required by eurozone countries to satisfy the EU new fiscal framework; see Appendix Table B.1. The EU fiscal framework has a shorter horizon of 4- or 7-years with more stringent sustainability criteria, including a deficit rule and debt safeguards, so their results are not directly comparable with our long-run debt stabilizing balances pb* that are lower. When comparing their results for a 7-year horizon with our primary balance at year seven (denoted by pb(7*)), our estimates are, on average, 0.97 times theirs.

Overall, the comparisons with the IMF Article IV reports and Darvas et al. offer some reassurance that the numbers from our SDSA are in a reasonable range.[11]

We perform the main tests after applying the stabilizing primary balance adjustments to estimate the *additional fiscal effort* that offsets the debt increases due to transition. Thus, we assume that countries first put their public finances in order to disentangle the transition effects from the current debt problems. An assessment of total debt sustainability requires the joint consideration of adjustments to stabilize current debts plus the fiscal effort to offset transition debt. In the figures, we illustrate the effects of transition on stabilized current debts. In the tables, we report both adjustments for completeness.

4.1 Cost-risk tradeoff

Our first test is on the tradeoff in debt financing under the agnostic SDSA and orderly and disorderly transitions for the major economies; see Figure 3. The x-axis is the refinancing risk, and the y-axis is the expected cost of debt financing. The blue frontiers are agnostic, and fan charts cover the frontiers with the three IAMs under orderly (green) and disorderly (red) transition, with the solid frontiers denoting the mean values.

We observe a shift toward higher cost and risk under transition. All frontiers start at values near or below the 20% threshold, and flow financing is sustainable. However, we will see in the next test that debt stock shifts into unsustainable trajectories. Disorderly transition is more impactful than orderly, but differences are relatively small and not uniform across countries. Orderly transition is preferable for the US, Japan, and UK; for India and Australia, the differences are marginal.

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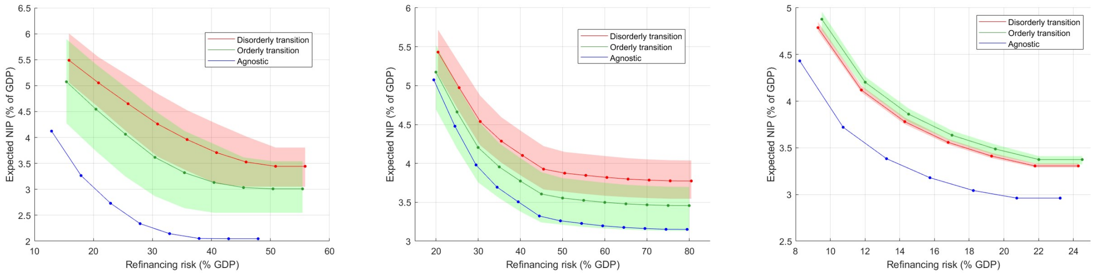
[11] The agnostic model was used for Italy, UK, Finland, Netherlands, Cyprus, and Japan; we consider these analyses reliable with results published in academic journals (Alberola et al., 2023; Consiglio et al., 2023; Zenios et al., 2021).

Figure 3 – The cost-risk tradeoff under transition risk

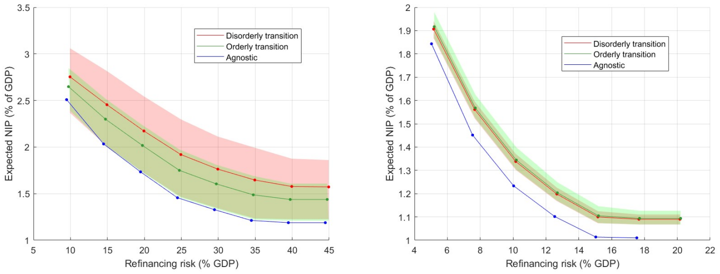
This figure shows the tradeoff between the expected cost of debt financing and refinancing risk under the agnostic SDSA (blue line) and for orderly (green fan charts) and disorderly (red fan charts) transition scenarios for the REMIND, GCAM, and MESSAGE models. The solid line is the average, and fans denote the cross-IAM range.



US

Japan

India



UK

Australia

4.2 Debt sustainability

We zoom in on frontier points with refinancing risk at the 20% threshold and examine the debt stock trajectories; see Figure 4. We display the fan charts for the five major economies using REMIND for orderly (column A, green) and disorderly (column B, red) transitions, overlaying on the agnostic SDSA (blue). The median and 0.75 percentile shift upwards under transition starting from the late 2030s. The direction and timing of the shift align with the finding of Klusak et al. (2023) on sovereign creditworthiness changes from rising temperatures. Orderly transition has marginally less impact on debt stock than disorderly; under orderly transition, debts start increasing earlier but gradually, whereas, with disorderly, they increase later but more abruptly. Debts shift towards non-sustainable trajectories but with heterogeneous impact across countries.[12]

We report in Table 3 the debt increase at 2070 over the stabilized debt for all countries. We give the median and 0.75 percentile under orderly (Panel A) and disorderly (Panel B) transitions with the three IAMs. The 0.75 percentile debt increase under orderly transition exhibits significant transition effects with cross-country average increases of 4 to 17p.p. for the three IAMs, with substantial differences among countries. Under REMIND, nine countries have long-term debt

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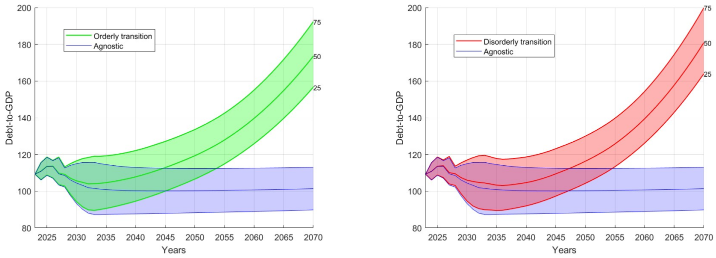
[12] We also run a test with only the growth effects of transition and find that the marginal effect is minor, in line with the current empirical literature. The effect on nominal growth can be positive or negative, depending on inflation, with an average debt change until 2070 for Italy of -3% (orderly) or -7% (disorderly), and for the US of 0.4% (orderly) or -1.6% (disorderly).

Figure 4 – Transition effects on debt dynamics

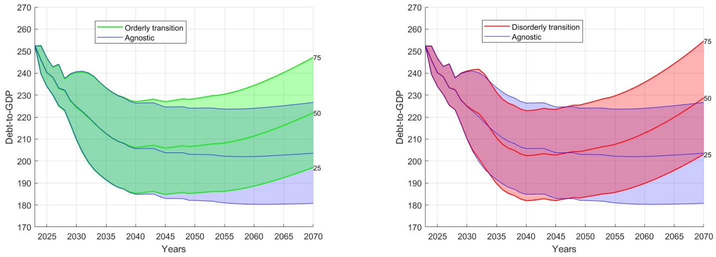
This figure shows debt stock dynamics fan charts with transition risk under (a) orderly (green) and (b) disorderly (red) transitions, using REMIND. The fan charts are overlayed on the charts of stabilized debt with the climate agnostic SDSA (blue). The solid lines display 0.25, 0.50, and 0.75 percentiles.

(a) Orderly (b) Disorderly

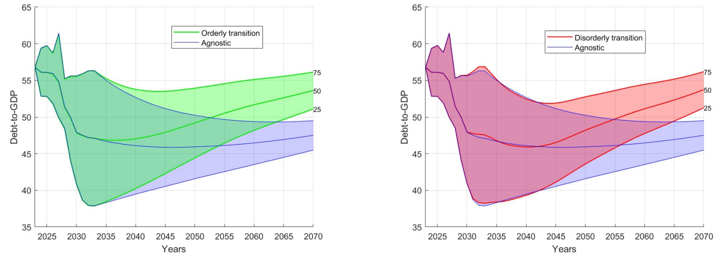
US



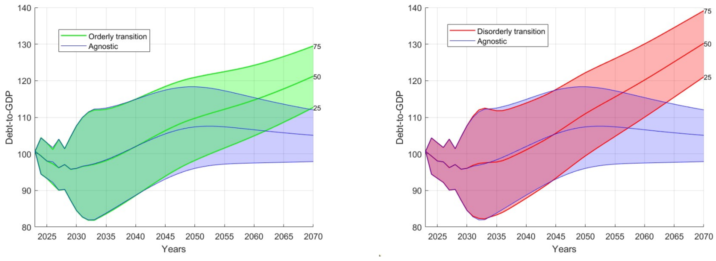
Japan



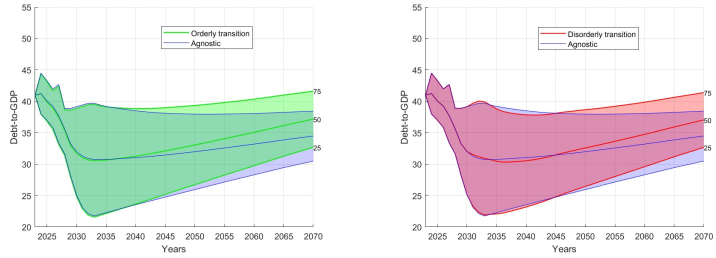
India



UK



Australia



increases of 10p.p. or less, three have increased up to 20p.p., and two go above 40p.p. Under MESSAGE, five countries experience small debt decreases, six have increases below 10p.p., and four have up to 27p.p. The debt increases are somewhat larger under disorderly transition. [13]

A policy implication of the cross-country differences is that international collaboration may be required to curb transition effects, corroborating Bolton et al. (2024) on the need for financial support "at scale" for some countries to replace coal with renewable energy.

In the map of Figure 5, we display the 2070 debt increases over the no-transition stabilized

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[13] The increases are larger if countries run historical primary balances without stabilizing current debts; see Appendix Table B.2.

Table 3 – Debt increases under transition risk

This table displays the debt increase at 2070 under (a) orderly and (b) disorderly transitions for REMIND, GCAM, and MESSAGE. Increases are in p.p. over the stabilized 2070 debts with countries running debt-stabilizing primary balances pb* from Table 2 without energy transition, for the 0.50 and 0.75 percentiles.

	REMIND		GCAM		MESSAGE		Cross-IAM dif.	
	0.50	0.75	0.50	0.75	0.50	0.75	0.50	0.75
(a) Orderly								
US	73	79	43	48	24	27	49	52
Japan	18	21	10	11	-7	-6	25	27
India	6	7	8	9	8	9	2	3
UK	16	17	11	12	0	0	16	17
Australia	3	3	2	2	2	2	1	1
Austria	6	10	4	6	-13	-11	19	21
Belgium	11	15	0	0	7	10	11	15
Finland	1	2	-2	-1	-6	-4	7	6
France	5	8	-3	-2	-4	-2	9	10
Germany	5	5	3	3	3	3	2	3
Italy	27	47	22	40	5	10	22	37
Netherlands	4	5	3	3	3	4	1	2
Poland	8	10	6	8	8	10	2	2
Portugal	3	5	1	1	0	0	4	5
Spain	14	24	4	6	6	12	10	18
Average	13	17	8	10	2	4	12	15
(a) Disorderly								
US	80	86	49	51	64	69	31	35
Japan	25	28	17	19	8	9	17	19
India	6	7	7	8	7	8	0	1
UK	25	27	16	18	1	1	24	26
Australia	3	3	2	2	2	2	1	1
Austria	9	14	7	10	-14	-12	23	26
Belgium	13	18	8	11	7	10	6	8
Finland	2	2	0	0	-6	-5	8	7
France	5	8	1	1	-4	-3	9	11
Germany	5	6	4	4	3	3	2	3
Italy	35	58	30	52	3	9	32	49
Netherlands	5	7	4	5	3	4	2	3
Poland	9	12	8	10	7	9	2	3
Portugal	6	10	4	5	0	0	7	10
Spain	21	37	11	20	7	12	14	25
Average	17	23	11	14	6	8	12	15

debts. The transition debt effects under stabilized debt (Panel A) are moderate to large for most countries and very large for the US. In Panel B, we show the total debt increase if the debt is not stabilized, and we add transition risk. Debt increases exceed 100% of GDP for the US, Japan, and most of Central and Southern Europe. The increase is also very large for Finland, but this is mainly due to projected large deficits and not transition risks; the transition debt increase for Finland is only 2% of GDP under REMIND, with GCAM and MESSAGE projecting debt decreases of up to -4% of GDP, see Table 3.

We ask whether countries can offset the transition debt increases by computing incremental fiscal effort to offset the increases with a high probability; see Table 4. Under orderly transition, countries need up to 1.1% of GDP (US) additional fiscal effort average p.a. until 2070 to stabilize debt under REMIND; the cross-country average is 0.3%. Under disorderly transition, the range goes up to 1.3% with an average of 0.4%. The number of years of persistent effort (column "Yrs") is, in general, slightly lower than the 47-year horizon by one to four years, allowing some space for countries to stabilize current debts. Estimates are lower with GCAM and MESSAGE, with Austria, Finland, France, and Germany having stable transition debts. Across IAMs, the total effort to stabilize transition debt over the horizon has a cross-country average of 4.3-10.8% of GDP (orderly) and 7.1-13.6% (disorderly).[14]

Adding these adjustments to the agnostic pb* we obtain primary balances within the 3% threshold from Eichengreen and Panizza (2016), and although prolonged, they can be cyclically adjusted and offset the transition debt increases. Hence, it is feasible to offset transition debts.

Given the current high debt levels, we take another step and compute the total fiscal effort to stabilize current plus transition debts. The net primary balance for all countries under all IAMs is shown in Figure 1 (red bars) for orderly transition together with the historical average primary balance (**x**) and the required adjustments (arrows). The total adjustments have cross-country averages of 1.2-1.4%, with marginally higher adjustments for disorderly transition (1.3-1.5%, not shown). Still, the stabilizing primary balance is below 3% for all countries.

Overall, stabilizing current and transition debts can be considered feasible, albeit the adjustments are relatively large and can be challenging. While the effects of a disorderly transition are somewhat higher than those of an orderly transition, the differences are small. The required adjustments are heterogeneous among countries, suggesting that international cooperation may be needed for an orderly transition.

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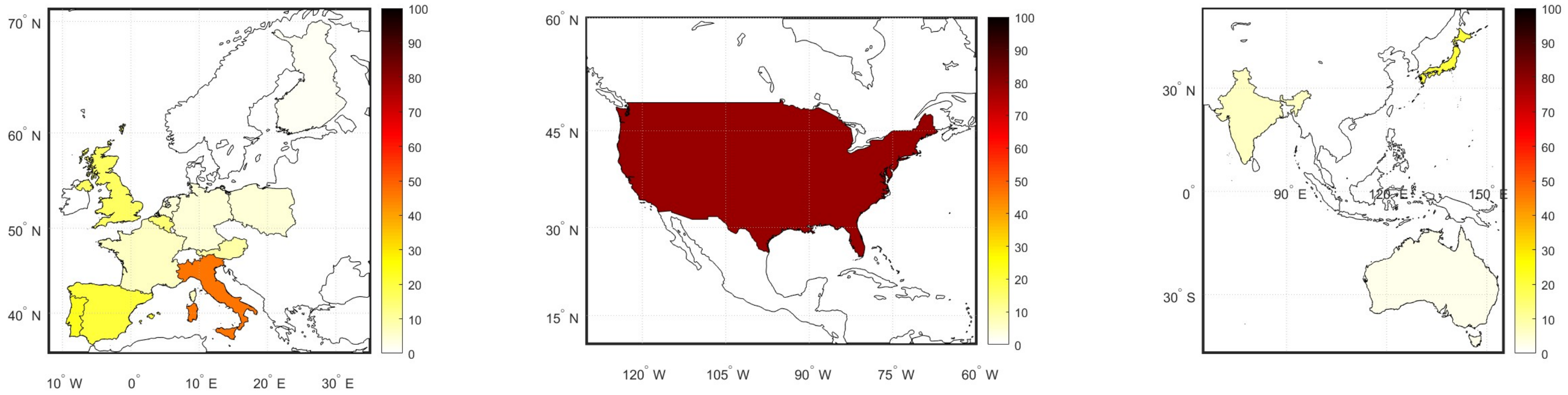
[14] We also performed this test with the energy mix of only fossil fuels and found, as expected, that the required fiscal effort would have been higher. Results are available from the authors.

Figure 5 – Sovereign debt increases from transition risk at 2070

This figure displays the increases in debt-to-GDP ratios (in p.p.) from an orderly transition compared to the agnostic. Panel A shows the debt increases, assuming that the countries first stabilize their current high debt levels. Panel B shows the debt increases if the countries do not stabilize their current debt levels. Black denotes increases beyond 100p.p.

(a) Debt increase after stabilizing current debt levels



(b) Debt increase without stabilizing current debt levels

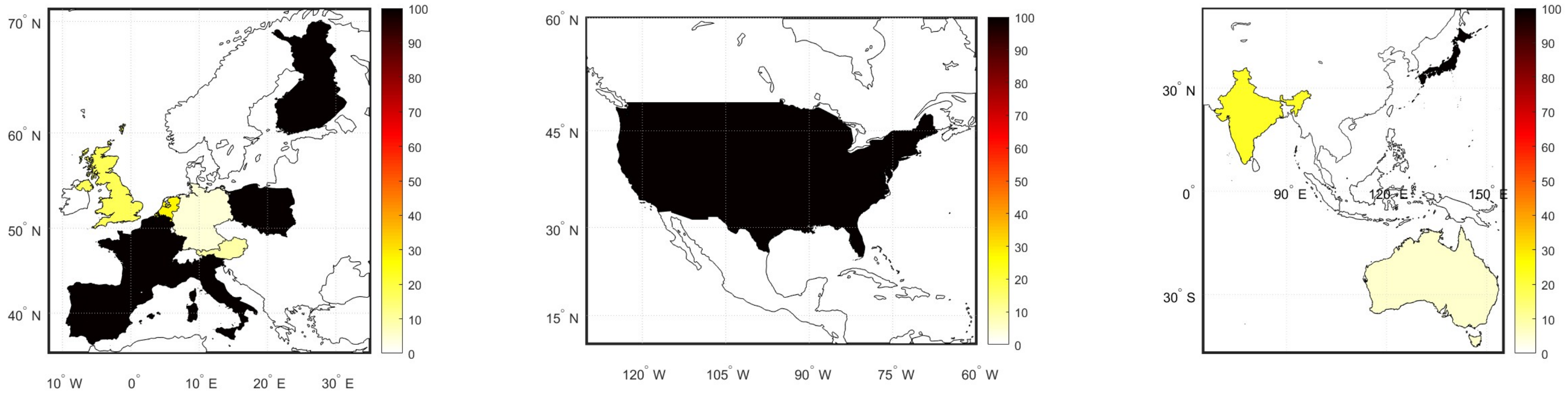


Table 4 – Fiscal adjustments to offset transition debts

This table displays the fiscal adjustments required to offset the debt increases from (a) orderly and (b) disorderly transitions, using the REMIND, GCAM, and MESSAGE integrated assessment models. It displays the average (Avg) adjustment over the years required (Yrs) and the total effort until 2070 in % GDP. pb* is the long-term debt-stabilizing primary balance of the current debts from Table 2.

	Agnostic	REMIND			GCAM			MESSAGE			Cross-IAM
	pb*	Avg	Yrs	Total	Avg	Yrs	Total	Avg	Yrs	Total	difference
(a) Orderly											
US	-0.5	1.1	45	50.2	0.8	45	33.8	0.5	44	23.3	0.6
Japan	0.6	0.4	47	19.7	0.3	47	15.0	0.0	-	0.0	0.4
India	-1.8	0.2	47	10.8	0.3	47	12.2	0.3	47	12.7	0.1
UK	-2.3	0.8	44	34.8	0.7	44	29.9	0.0	-	0.0	0.8
Australia	-0.8	0.1	43	5.2	0.1	43	4.3	0.1	43	4.1	0.0
Austria	-0.3	0.1	43	2.4	0.0	-	0.0	0.0	-	0.0	0.1
Belgium	0.8	0.3	8	2.5	0.0	-	0.0	0.2	9	1.6	0.3
Finland	-0.3	0.0	43	0.9	0.0	-	0.0	0.0	-	0.0	0.0
France	0.6	0.3	6	1.6	0.0	-	0.0	0.0	-	0.0	0.3
Germany	0.3	0.0	-	0.0	0.0	-	0.0	0.0	-	0.0	0.0
Italy	2.1	0.5	10	4.8	0.5	8	3.8	0.3	3	1.0	0.2
Netherlands	-0.3	0.2	47	7.0	0.1	47	6.1	0.1	47	6.3	0.1
Poland	-0.5	0.3	47	13.1	0.3	47	11.8	0.3	47	12.9	0.0
Portugal	-0.4	0.1	47	3.5	0.0	-	0.0	0.0	-	0.0	0.1
Spain	0.6	0.1	47	6.1	0.4	8	2.8	0.4	9	3.2	0.3
Average	-0.1	0.3	35	10.8	0.2	22	8.0	0.1	17	4.3	0.2
(b) Disorderly											
US	-0.5	1.3	44	56.8	0.8	45	37.4	1.1	45	48.2	0.5
Japan	0.6	0.7	47	30.6	0.5	47	21.6	0.4	47	16.9	0.3
India	-1.8	0.2	47	11.3	0.2	47	11.3	0.3	47	11.6	0.1
UK	-2.3	0.9	44	40.5	0.8	44	34.8	0.0	-	0.0	0.9
Australia	-0.8	0.1	43	5.6	0.1	43	4.3	0.1	43	4.1	0.0
Austria	-0.3	0.1	47	4.2	0.1	47	2.4	0.0	-	0.0	0.1
Belgium	0.8	0.4	9	3.8	0.3	8	2.2	0.3	8	2.0	0.1
Finland	-0.3	0.0	43	1.6	0.0	-	0.0	0.0	-	0.0	0.0
France	0.6	0.3	6	2.0	0.3	1	0.3	0.0	-	0.0	0.3
Germany	0.3	0.0	-	0.0	0.0	-	0.0	0.0	-	0.0	0.0
Italy	2.1	0.5	15	7.4	0.5	12	5.8	0.5	2	0.9	0.0
Netherlands	-0.3	0.2	47	8.5	0.2	47	7.1	0.1	47	6.6	0.1
Poland	-0.5	0.3	47	13.9	0.3	47	12.9	0.3	47	12.7	0.0
Portugal	-0.4	0.1	47	6.1	0.1	47	3.8	0.0	-	0.0	0.1
Spain	0.6	0.2	47	11.3	0.1	47	5.2	0.4	9	3.5	0.3
Average	-0.1	0.4	36	13.6	0.3	32	9.9	0.2	20	7.1	0.2

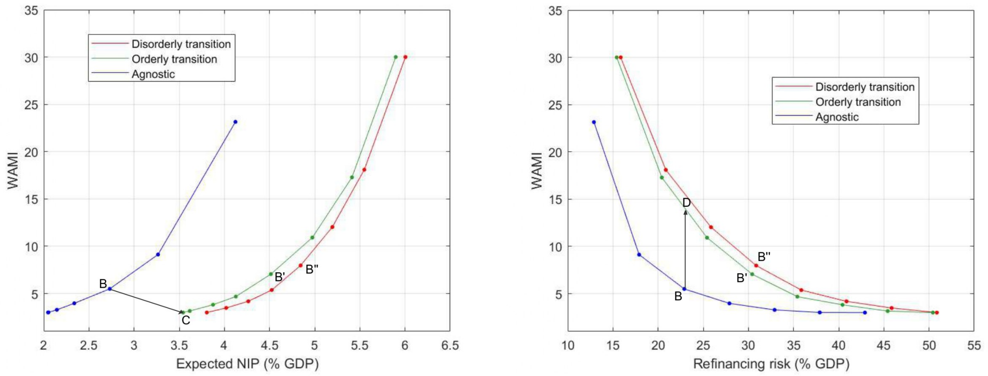
4.3 Debt management

Extracting further information from Figure 3 we study the effect of transition on the optimal debt financing strategies. We show in Figure 6 the weighted average maturity at issuance (WAMI) against the expected cost of debt financing (Panel A) and refinancing risk (Panel B) under climate agnostic, orderly, and disorderly transitions for the US under REMIND. The minimum cost strategy has the shortest WAMI, and the minimum risk strategy has the longest WAMI but for intermediate points on the frontiers, the optimal financing strategy changes.

From Panel A, we observe that starting from intermediate strategy B on the agnostic frontier

Figure 6 – Debt management under transition risk

This figure shows the weighted average maturity at issuance (WAMI) at different points of the efficient frontier under the climate agnostic SDSA (blue) and for orderly (green) and disorderly (red) transition. It displays the WAMI vs (a) expected cost of debt financing and (b) refinancing risk. Points B, $B^{'}$ and $B^{''}$ denote intermediate cost-risk debt financing strategies. Point C is the minimum cost strategy under orderly transition. Point D indicates the orderly transition strategy with the same refinancing risk as the intermediate agnostic strategy. This example is for the US under REMIND.



(a) WAMI vs. cost of debt financing (b) WAMI vs. refinancing risk

(blue curve), we get the smallest possible cost increase of about 0.8% of GDP under orderly transition by moving to C; this entails a shortening of WAMI from 5.5 to 3 years. To pursue, instead, an intermediate financing strategy under orderly ($B^{'}$, green curve) or disorderly ($B^{''}$, red curve) transition, the WAMI increases, respectively, from 5.5 to 7 and 8 years with corresponding expected costs increases by 1.8-2.1% of GDP.

Panel B shows that it is possible to keep the refinancing risk of B unchanged under the transition by increasing WAMI from 5 to about 14 years (strategy D). However, maintaining the intermediate strategy entails a move from B to $B^{'}$ (orderly) and $B^{''}$ (disorderly). The WAMI increases from 5 to about 8-9 years, and refinancing risk increases from about 22% of GDP, which is near the threshold, to about 30%, violating the threshold.

Overall, the transition to a low-carbon economy suggests a shift of optimal debt financing towards longer maturities. This has a policy implication that sovereigns should pay due care in selecting their debt financing strategy in managing the transition.

4.4 Robustness tests for deep uncertainty

To increase the "public acceptance" of our findings (Howe et al., 2019), we acknowledge the impact of deep uncertainty stemming from the IAMs, long-term interest rate projections, and the elasticities of energy sector profitability. These sources of uncertainty are "deep" (Berger et al., 2017; Lempert et al., 2024) in that IAMs are subject to non-linearities, interest rates respond to many factors, including the climate policies to be adopted and the state of policy implementation, and elasticities change due to climate policies that shift energy demand and technological advances. Hence, we can not know the probabilities to aggregate differences as statistical errors and we report a range of results given the available information. We discuss here the results from the robustness tests that show our conclusions to be qualitatively robust even if the quantitative estimates may change; the tables are relegated to online Appendix B.

4.4.1 IAM projections

The deep uncertainty surrounding IAMs is manifested in Figure 3 with the cross-IAM dispersion of cost-risk tradeoffs and the cross-IAM debt differences in Table 3 with the concomitant fiscal adjustments of Table 4. While the average debt difference is a modest 15p.p. (orderly and disorderly), there are significant differences among countries. For some countries, there is no consensus among the IAMs on whether the transition to a low-carbon economy will increase or decrease debt. For Japan and Austria, one of the models (MESSAGE) predicts small debt decreases. For Finland and France, only one model (REMIND) predicts a debt increase. Consistent cross-IAM differences are noticed in the additional fiscal efforts to offset transition debts in Table 4 of 0.2p.p. for orderly and disorderly transitions. Under GCAM and MESSAGE, four countries (Austria, Finland, France, Portugal) have stable transition debts.

IAM uncertainty does not qualitatively alter our findings of (i) impact on debt financing tradeoffs; (ii) debt increases for most countries starting from the late 2030s; (iii) the need for modest but persistent fiscal effort to offset transition debts; and (iv) significant debt increases if countries do not stabilize their current high debts. However, some IAMs suggest that some eurozone countries can weather the transition without increasing debt.

4.4.2 Interest rates

We repeat the tests of Tables 2 and 4 for low interest rates (see Appendix Figure A.1, Panel B) and find that more countries (India, UK, Australia, Austria, Italy, Netherlands) have stable debts, with the rest requiring lower fiscal effort than under medium rates. The required debt-stabilizing fiscal adjustments are reported in Appendix Table B.3.[15]

We perform SDSA under transition using REMIND and estimate the fiscal effort to offset the debt increase —see Appendix Figure B.2 for the fan charts and Appendix Table B.4 for debt stabilizing primary balance. The fiscal effort to offset transition debts is significantly reduced under low interest rates from the corresponding results under medium rates from Tables 3-4 and is zero for the UK, Australia, Austria, and Italy. Offsetting transition debts is much easier under low rates, as expected. Although transition still puts upward pressure on debt, most countries in our sample require fiscal adjustments below 0.1p.p.

4.4.3 Elasticities

We estimate the fiscal adjustments required to offset the transition debt increase for values of χ's in the empirically observed range 0.2-0.6 (Battiston and Monasterolo, 2020), using REMIND for the major economies. The results are reported in online Appendix Table B.5, together with the agnostic pb* and the fiscal adjustment estimates from our main tests with $\chi = 1$, As

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[15] The results of this test are optimistic; comparing our agnostic SDSA debt projections with the IMF Article IV, we find ours below the IMF's which are based on higher medium-term rates.

expected, the fiscal adjustments to offset transition debts are dampened for lower elasticities. Still, they remain significant for all countries and add about 0.2% of GDP, in the best case, to the primary balance required to stabilize the current large debts. Our main findings remain qualitatively the same but with smaller magnitudes.

5 Green growth effects

We test whether green growth (Porter and van der Linde, 1995) can offset transition debts. Following the Paris Agreement goals of reaching net zero by 2050, we assume that the transition will be completed by 2050 with significant changes noticeable from 2030. Hence, we consider growth increasing linearly due to greening by 2050 from its steady state by GDP_G^+ and estimate the increase that would stabilize debt; see Table 5.

We observe that under medium rates, cross-country average green growth increase by 0.5% (orderly) and 0.6% (disorderly) could offset transition debts, but with significant differences among countries. The US requires up to 1.9% and Australia 0.4%. The required average green growth under low rates is 0.4% (orderly) to 0.5% (disorderly). Australia, Austria, Germany, and Italy can deal with transition debts without relying on green growth at low rates, and the UK needs green growth only under a disorderly transition. Overall, modest green growth can offset transition debts, but whether the transition to a low-carbon economy will deliver this growth remains an open question.

Table 5 – How much green growth to offset transition debts?

This table shows the green growth required to offset the debt effects of transition (GDP_G^+) under the orderly and disorderly transitions using REMIND. Results are displayed for medium and low interest rates.

	Medium rates		Low rates	
	Orderly	Disorderly	Orderly	Disorderly
US	1.6	1.9	1.6	1.9
Japan	0.3	0.4	0.2	0.4
India	0.8	0.9	0.7	0.8
UK	0.6	0.9	0.0	0.9
Australia	0.3	0.4	0.0	0.0
Austria	0.5	0.7	0.0	0.0
Belgium	0.4	0.5	0.4	0.5
Finland	0.2	0.3	0.2	0.2
France	0.4	0.4	0.3	0.4
Germany	0.0	0.0	0.0	0.0
Itay	0.7	0.8	0.0	0.0
Netherlands	0.5	0.7	0.5	0.6
Poland	0.7	0.8	0.7	0.8
Portugal	0.3	0.4	0.3	0.4
Spain	0.7	0.9	0.6	0.8
Average	0.5	0.6	0.4	0.5

6 Carbon tax recycling

We take a step further to study the effect of recycling carbon tax revenues into debt repayment. We consider disorderly transition for which the NGFS scenarios are tax neutral, i.e., carbon taxes are offset with tax reductions for the private sector; for an orderly transition, the NGFS scenarios assume recycling of one-half of the carbon taxes. Our estimation of transition spreads was obtained from a shock to the energy sectors which changes the contribution of each sector to the gross value added, and taxes did not enter directly into the data we used. Still, we can not rule out that carbon tax recycling effects creep into our analysis for those NGFS scenarios that use them. Therefore, we test the carbon tax recycling effects only for disorderly transition.

Darracq et al. (2023) studied the impact of tax recycling on GDP and here we consider its debt impact. Instead of introducing transition risk through the pricing channel, we consider recycling (part of) the carbon taxes to repay debt while financing (part of) the transition and determine sustainability based on the fundamentals.

We obtain carbon taxes from REMIND and use our model to account for the government's carbon tax revenues and transition spending. We assume that the government pays one-third of the 3% GDP p.a. transition investments until 2050 while recycling 50% of the carbon taxes into debt. This is blended finance of the transition, where the public sector's share was estimated to be in the range 25-40% (Seghini and Dees, 2024) or 25-50% (Bolton et al., 2024) by 2050. REMIND accounts for the effects of carbon taxes on real GDP and inflation but not for recycling effects. Still, we follow (Darracq et al., 2023, Chart 10) who find that recycling all carbon taxes into debt repayment has a marginal effect on GDP —real GDP decreases by about -1.5% by 2050 and inflation increases by 0.15p.p.— and abstract from tax recycling effects on growth.

We display the results in Figure 7 and observe that they align with our main findings. Debts increase for all major economies by 2070. India is the only exception, with the carbon revenues to the government reducing debts even after the government invests in transition, whereas, for all other countries, this investment exceeds the carbon revenues in the long run. The long-term debts are in line with those from Section 4.2, although not the same given the different assumptions underlying the two approaches. Under 50% tax recycling and no transition investments, debt decreases initially but again follows an upward trajectory in the long run (Appendix Figure B.3). Overall, carbon tax recycling into debt can improve sustainability but is offset by government financing of transition; the balance between the two is delicate.

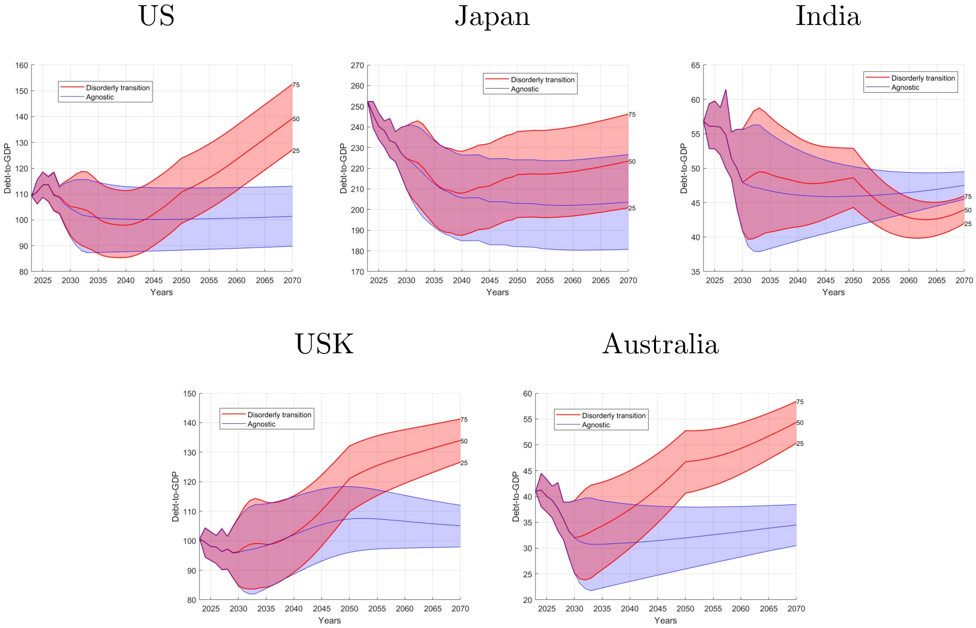
7 Conclusions

We add the transition risk channel to the literature on climate change effects on sovereign debt. We develop a debt sustainability analysis model and study the effects of orderly or disorderly transition to a low-carbon economy for a sample of developed economies.

Transition has a significant impact on debt financing tradeoffs and puts upward pressure on debt stock with increases starting from the late 2030s for most countries. It can lead to unsustainable debt dynamics. Modest but persistent fiscal adjustments can offset the debt increases without

Figure 7 – Transition effects on debt dynamics with carbon tax recycling

This figure shows debt stock fan charts under disorderly transition, using REMIND, with 50% of carbon taxes recycled to pay debt and 1% of GDP transition financing costs. It also displays the fan charts of stabilized debt with the agnostic SDSA (blue). The solid lines display 0.25, 0.50, and 0.75 percentiles.



significant differences between orderly and disorderly transitions. The problem is exacerbated by the current high debt levels, with relatively large adjustments required under transition. Our findings are consistent under three IAMs, although two IAMs find that some eurozone countries can weather the transition risk without a debt increase. Our findings remain qualitatively the same but are quantitatively dampened if low interest rates result from the transition.

The requirement of modest efforts holds on the average and for most countries in our sample, but with cross-country divergences driven by country differences in the energy mix. This calls for policy intervention to harmonize efforts at the international level to curb the effects of transition. We also find that the optimal debt financing strategies shift towards longer maturities under transition, which has a policy implication for public debt management offices during transition.

Modest green growth can offset the transition debts. Also, government expenditures on transition financing offset the positive impact of carbon tax recycling on debt sustainability. Striking the right balance requires further work on the growth effects of recycling policies, opening an avenue for further research.

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Online Appendix

Are sovereign debts sustainable under energy transition?

A Data

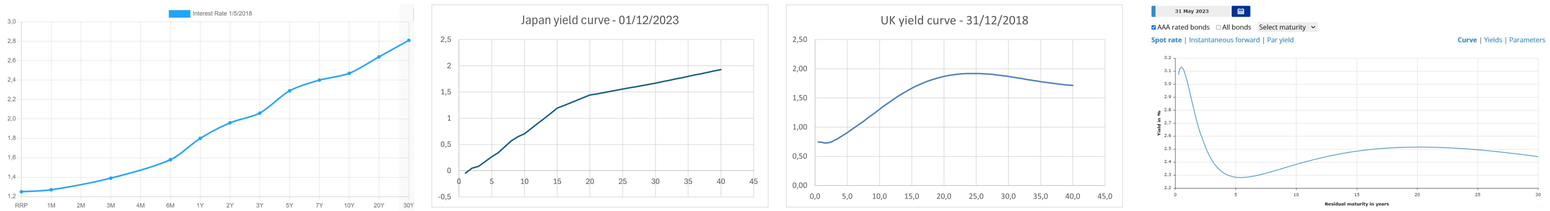
Table A.1 – Sources of input data

Variable	Source
Country debt	Eikon-Refinitiv
US spot yield curve	Federal Reserve Economic Data (FRED)
EU spot yield curve	European Central Bank
UK spot yield curve	Bank of England
Japan spot yield curve	Refinitiv
Primary balance	IMF Fiscal Monitor 2023
EU GDP growth	European Commission Ageing Report 2024
	`https://economy-finance.ec.europa.eu/publications_en`
Non-EU GDP growth	IMF World Economic Outlook 2023
CPRS shocks	Network for Greening the Financial System database
	`https://data.ene.iiasa.ac.at/ngfs/`
CPRS energy share	Our World in Data
	`https://ourworldindata.org/`
Transition effect on GDP	Network for Greening the Financial System database
Carbon taxes	Network for Greening the Financial System database
Share of energy sector to total country Gross Value Added	
US	EIA
EU	Eurostat
IN	Statista
UK	UK Government National Statistics
AU	Government of Australia
JP	Cabinet Office Japan

Figure A.1 – Yield curves

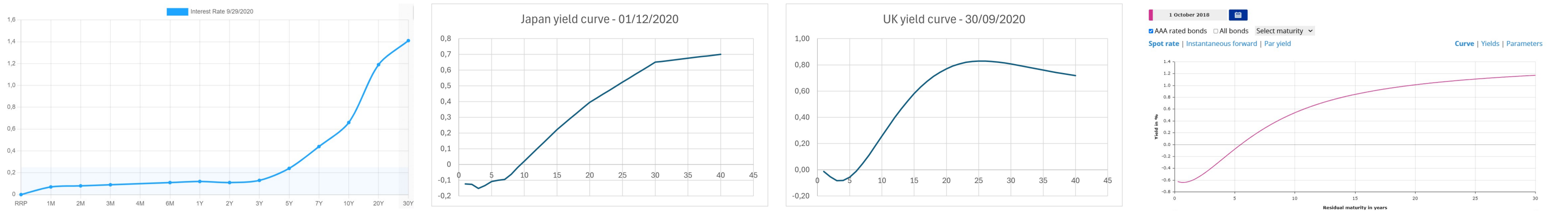
This figure displays the (a) medium and (b) low yield curves environments in % over time in years, together with (c) the term premia with reference to the 5-year bond in basis points.

(a) Medium yields



US Japan UK Eurozone

(b) Low yields



US Japan UK Eurozone

(c) Term premia

Country.	3-year	5-year	10-year	30-year
US	-45	0	67	136
JP	-11	0	41	121
UK	-32	0	52	90
EU	-26	0	59	108

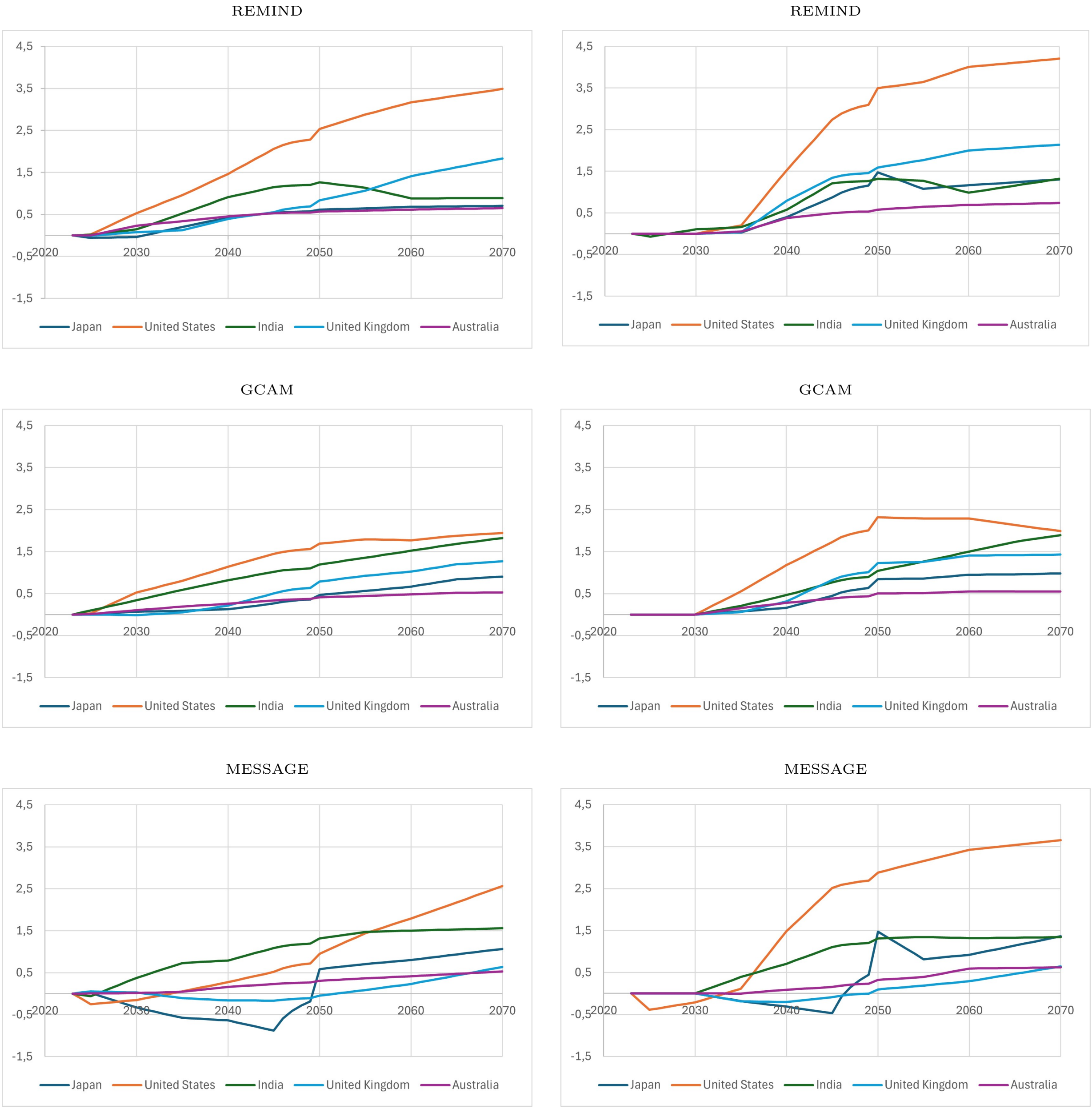
Table A.2 – Growth and primary balance projections

This table displays (a) economic growth rates and (b) primary balance projections in % of GDP). The projections until 2028 are from the 2023 IMF World Economic Outlook report; the long-term projections are from authors' calculations of the historical averages. GDP growth projections for the Eurozone countries are obtained on a yearly basis until 2070 from the 2024 European Commission Ageing Report of Table A.1.

	2024	2025	2026	2027	2028	Long-term	StDev
			(a) Growth rate				
US	3.8	3.9	4.0	4.0	4.0	3.7	2.2
Japan	4.2	2.9	2.2	2.1	2.2	2.6	2.1
India	10.7	10.7	10.7	10.6	10.5	11.8	4.5
UK	4.1	4.0	4.2	3.8	3.6	3.8	2.6
Australia	1.9	5.2	5.2	4.9	5.0	5.8	2.9
			(b) Primary balance				
US	-4.3	-4.2	-3.5	-3.0	-3.1	-3.8	3.6
Japan	-6.4	-3.0	-2.7	-2.8	-2.8	-2.5	2.3
India	-2.9	-2.5	-2.3	-2.2	-2.2	-2.3	1.8
UK	-1.9	-1.5	-1.4	-1.6	-1.8	-2.3	3.4
Australia	-0.7	-0.3	0.1	0.2	0.5	-0.9	2.7
Austria	-0.8	-0.5	-0.2	-0.1	-0.1	-0.3	1.9
Belgium	-3.0	-2.8	-3.0	-3.1	-3.0	-0.8	3.2
Finland	-1.8	-2.4	-2.5	-2.5	-2.6	-1.5	3.4
France	-2.7	-2.0	-1.5	-1.1	-0.9	-1.4	2.0
Germany	-0.7	-0.4	0.0	0.2	0.4	0.3	2.1
Italy	0.8	1.8	2.2	2.7	3.2	1.6	2.2
Netherlands	-1.7	-1.5	-1.2	-1.3	-1.3	-0.7	2.5
Poland	-2.1	-2.0	-2.1	-1.7	-1.3	-1.4	1.8
Portugal	2.3	2.2	2.2	2.2	2.2	-1.2	2.6
Spain	-1.3	-1.4	-1.5	-1.5	-1.5	-1.7	4.0

Figure A.2 – Default probabilities under orderly and disorderly transition

This figure displays the changes in default probabilities for the sample of major economies under (a) orderly and (b) disorderly transitions, using projections from the REMIND, GCAM, and MESSAGE integrated assessment models until 2070.



(a) Orderly

(b) Disorderly

REMIND

GCAM

MESSAGE

B Supplementary results

Table B.1 – Comparison for fiscal adjustments to stabilize current debts

This table displays the long-term debt-stabilizing primary balance (pb*) in % of GDP p.a. under the climate-agnostic SDSA, the stabilizing primary balance at the end of the first seven years (pb*(7)), and the minimum structural primary balance (SPB) at the end of a 7-year adjustment period satisfying the sustainability requirements of the EU new fiscal framework discussed in (Darvas et al., 2024, Table 1, column 5). pb* is obtained with an upper bound at each time period to align with the methodology of Darvas et al. and may differ from those of Table 2 for some countries. Our estimate for France deviates from that of the reference due to the nonlinear increase of debt past the 7-year horizon, as seen from the comparison of the agnostic SDSA with the Article IV projections in Figure B.1; this increase is captured by the long-horizon SDSA even in the early years, including year 7, but is missed from the analysis with a seven-year horizon.

	pb*	pb*(7)	SPB
Belgium	0.5	0.8	1.1
Finland	-0.3	0.8	1.0
France	0.6	2.0	0.8
Italy	2.1	3.3	3.0
Netherlands	-0.6	-0.7	-0.6
Poland	-0.4	0.8	0.8
Portugal	-0.4	2.4	2.3
Spain	0.4	2.5	2.8

Table B.2 – Debt increases under transition risk for non-stabilized debt dynamics

This table displays the debt increases at 2070 (in p.p.) under (a) orderly and (b) disorderly transitions, using REMIND, GCAM, and MESSAGE. The increases are over the non-stabilized 2070 debts with countries running their long-term historical primary balances. The table displays the 0.50 and 0.75 percentiles.

	REMIND		GCAM		MESSAGE		Cross-IAM dif.	
	0.50	0.75	0.50	0.75	0.50	0.75	0.50	0.75
(a) Orderly								
US	104	108	63	65	32	33	72	75
Japan	29	32	17	18	0	0	29	32
India	8	9	11	12	11	12	3	3
UK	16	17	11	12	0	0	16	17
Australia	3	3	2	2	2	2	1	1
Austria	6	10	4	6	-13	-11	19	21
Belgium	18	21	3	4	12	14	15	17
Finland	2	2	-8	-6	-23	-18	25	20
France	13	15	-5	-5	-10	-9	23	24
Germany	5	5	3	3	3	3	2	2
Italy	30	36	26	30	9	11	21	25
Netherlands	7	10	4	7	5	8	3	3
Poland	26	37	19	26	26	37	7	11
Portugal	6	8	-1	0	-4	-3	10	11
Spain	33	39	10	13	16	19	23	26
Average	20	24	11	13	4	7	18	19
(b) Disorderly								
US	120	125	69	72	94	97	51	53
Japan	43	46	29	31	21	22	22	24
India	9	9	10	10	10	10	1	1
UK	25	27	16	18	1	1	24	26
Australia	3	3	2	2	2	2	1	1
Austria	9	14	7	10	-14	-12	23	26
Belgium	22	27	13	16	12	14	10	13
Finland	3	3	-2	-1	-26	-21	29	24
France	14	17	2	2	-12	-11	26	27
Germany	5	6	4	4	3	3	2	3
Italy	36	36	33	40	7	9	29	31
Netherlands	9	14	7	11	6	9	3	5
Poland	26	35	22	30	21	30	5	5
Portugal	12	15	6	8	-5	-3	17	18
Spain	52	62	27	32	16	19	36	43
Average	26	29	16	19	9	11	19	20

Table B.3 – Fiscal adjustments to stabilize current debts (low rates)

This table displays the climate-agnostic fiscal adjustments (Adj) required to stabilize current debts in the long run and the resulting long-term debt-stabilizing primary balance pb*, in % of GDP p.a., for low interest rates. It also compares the results with medium rates from Table 2. The results are obtained using the climate-agnostic SDSA.

	Medium rates		Low rates	
	Adj	pb*	Adj	pb*
US	3.3	-0.5	2.2	-1.6
Japan	3.1	0.6	1.0	-1.5
India	0.5	-1.8	0.0	-2.3
UK	0.0	-2.3	0.0	-2.3
Australia	0.1	-0.8	0.0	-0.9
Austria	0.0	-0.3	0.0	-0.3
Belgium	1.6	0.8	0.7	-0.1
Finland	1.2	-0.3	0.9	-0.6
France	2.0	0.6	1.3	-0.1
Germany	0.0	0.3	0.0	0.3
Italy	0.5	2.1	0.0	1.6
Netherlands	0.4	-0.3	0.0	-0.7
Poland	0.9	-0.5	0.6	-0.8
Portugal	0.9	-0.4	0.4	-0.9
Spain	2.3	0.6	1.5	-0.2
Average	1.1	-0.1	0.6	-0.7

Table B.4 – Fiscal adjustments to offset transition debts (low rates)

This table displays the fiscal adjustments required to offset the debt increases from (a) orderly and (b) disorderly transitions, using REMIND under low rates and, for comparison, the corresponding results with medium rates. It displays the average (Avg) adjustment over the years required (Yrs) and the total adjustment until 2070. pb* is the long-term debt-stabilizing primary balance of the current debts from Table B.3.

	Medium rates				Low rates			
	pb*	Avg	Yrs	Total	pb*	Avg	Yrs	Total
(a) Orderly								
US	-0.5	1.1	45	50.2	-1.6	1.1	44	47.5
Japan	0.6	0.4	47	19.7	-1.5	0.4	47	18.3
India	-1.8	0.2	47	10.8	-2.3	0.2	47	8.0
UK	-2.3	0.8	44	34.8	-2.30	0.0	-	0.0
Australia	-0.8	0.1	43	5.2	-0.9	0.0	-	0.0
Austria	-0.3	0.1	43	2.4	-0.3	0.0	-	0.0
Belgium	0.8	0.3	8	2.5	-0.1	0.1	47	4.7
Finland	-0.3	0.0	43	0.9	-0.6	0.0	43	0.7
France	0.6	0.3	6	1.6	-0.1	0.1	47	2.9
Germany	0.3	0.0	-	0.0	0.3	0.0	-	0.0
Italy	2.1	0.5	10	4.8	1.6	0.0	-	0.0
Netherlands	-0.3	0.2	47	7.1	-0.7	0.1	47	4.0
Poland	-0.5	0.3	47	13.1	-0.8	0.2	47	10.8
Portugal	-0.4	0.1	47	3.5	-0.9	0.1	47	3.9
Spain	0.6	0.1	47	6.1	-0.2	0.2	47	8.0
Average	-0.1	0.3	35	10.8	-0.7	0.2	31	7.3
(b) Disorderly								
US	-0.5	1.3	44	56.8	-1.6	1.2	44	54.6
Japan	0.6	0.7	47	30.6	-1.5	0.6	47	30.1
India	-1.8	0.2	47	11.3	-2.3	0.2	47	10.3
UK	-2.3	0.9	44	40.5	-2.3	0.4	44	16.7
Australia	-0.8	0.1	43	5.6	-0.9	0.0	-	0.0
Austria	-0.3	0.1	47	4.2	-0.3	0.0	-	0.0
Belgium	0.8	0.4	9	3.8	-0.1	0.2	47	8.0
Finland	-0.3	0.0	43	1.6	-0.6	0.0	43	1.5
France	0.6	0.3	6	2.0	-0.1	0.1	47	3.8
Germany	0.3	0.0	-	0.0	0.3	0.0	-	0.0
Italy	2.1	0.5	15	7.4	1.6	0.0	-	0.0
Netherlands	-0.3	0.2	47	8.5	-0.7	0.1	47	5.6
Poland	-0.5	0.3	47	13.9	-0.8	0.3	47	11.8
Portugal	-0.4	0.1	47	6.1	-0.9	0.2	47	7.1
Spain	0.6	0.2	47	11.3	-0.2	0.3	47	13.6
Average	-0.1	0.4	36	13.6	-0.7	0.2	34	10.9

Table B.5 – Fiscal adjustments to offset transition debts (different elasticities)

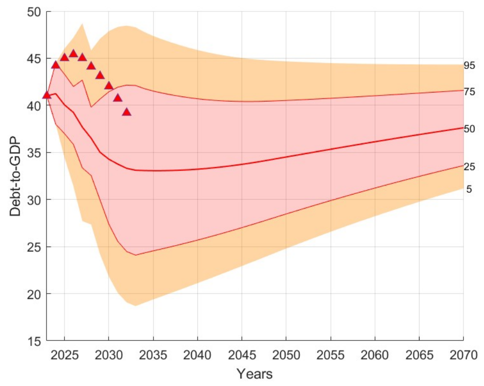
This table displays the fiscal adjustments required to offset the debt increases of the five major economies from (a) orderly and (b) disorderly transitions, using the REMIND integrated assessment model for different values of the elasticity of sectors' profitability. It displays the average adjustment in % GDP for $\chi = 1$, 0.6, and 0.2, and pb* is the long-term debt-stabilizing primary balance of the current debts from Table 2.

	Agnostic pb*	Elasticity $\chi = 1$	$\chi = 0.6$	$\chi = 0.2$
		(a) Orderly		
US	-0.5	1.1	0.7	0.3
Japan	0.6	0.4	0.2	0.1
India	-1.8	0.2	0.2	0.1
UK	-2.3	0.8	0.7	0.5
Australia	-0.8	0.1	0.1	0.1
Average	-1.0	0.5	0.4	0.2
		(b) Disorderly		
US	-0.5	1.3	0.8	0.4
Japan	0.6	0.7	0.4	0.2
India	-1.8	0.2	0.2	0.1
UK	-2.3	0.9	0.8	0.5
Australia	-0.8	0.1	0.1	0.1
Average	-1.0	0.6	0.5	0.3

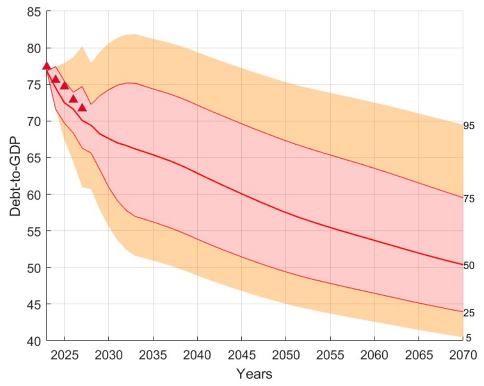
Figure B.1 – Consistency of agnostic SDSA with IMF Article IV

This figure shows the debt-to-GDP ratio fan charts for our sample of countries with the agnostic SDSA and compares them with the medium-term projections from the latest IMF Article IV consultation reports, denoted by the red triangles. Reports are from 2022 for Australia, Belgium, Germany*, India, Italy, Portugal*, the UK*, and the US*, and 2021 for Austria, Finland*, France, Netherlands, and Spain. For the * countries, the starting IMF debt ratio is scaled to match the 2023 starting ratio from the sources of our analysis with average scaling ±5%.

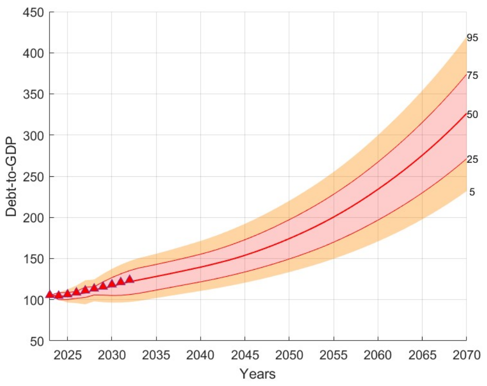
Australia



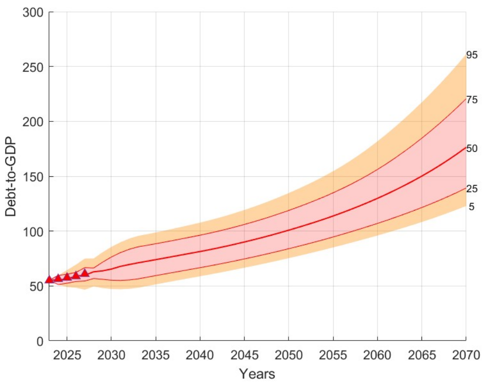
Austria



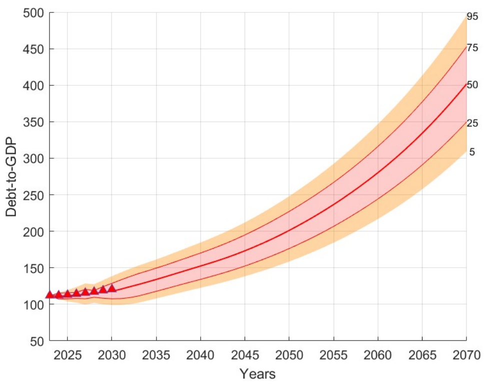
Belgium



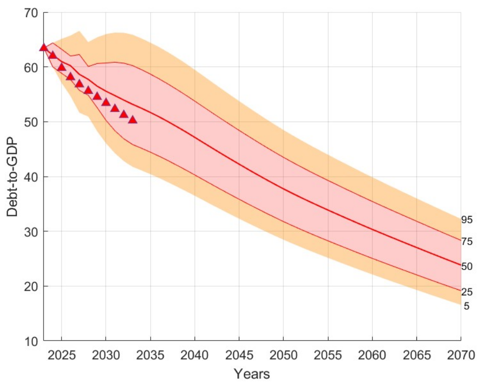
Finland



France



Germany



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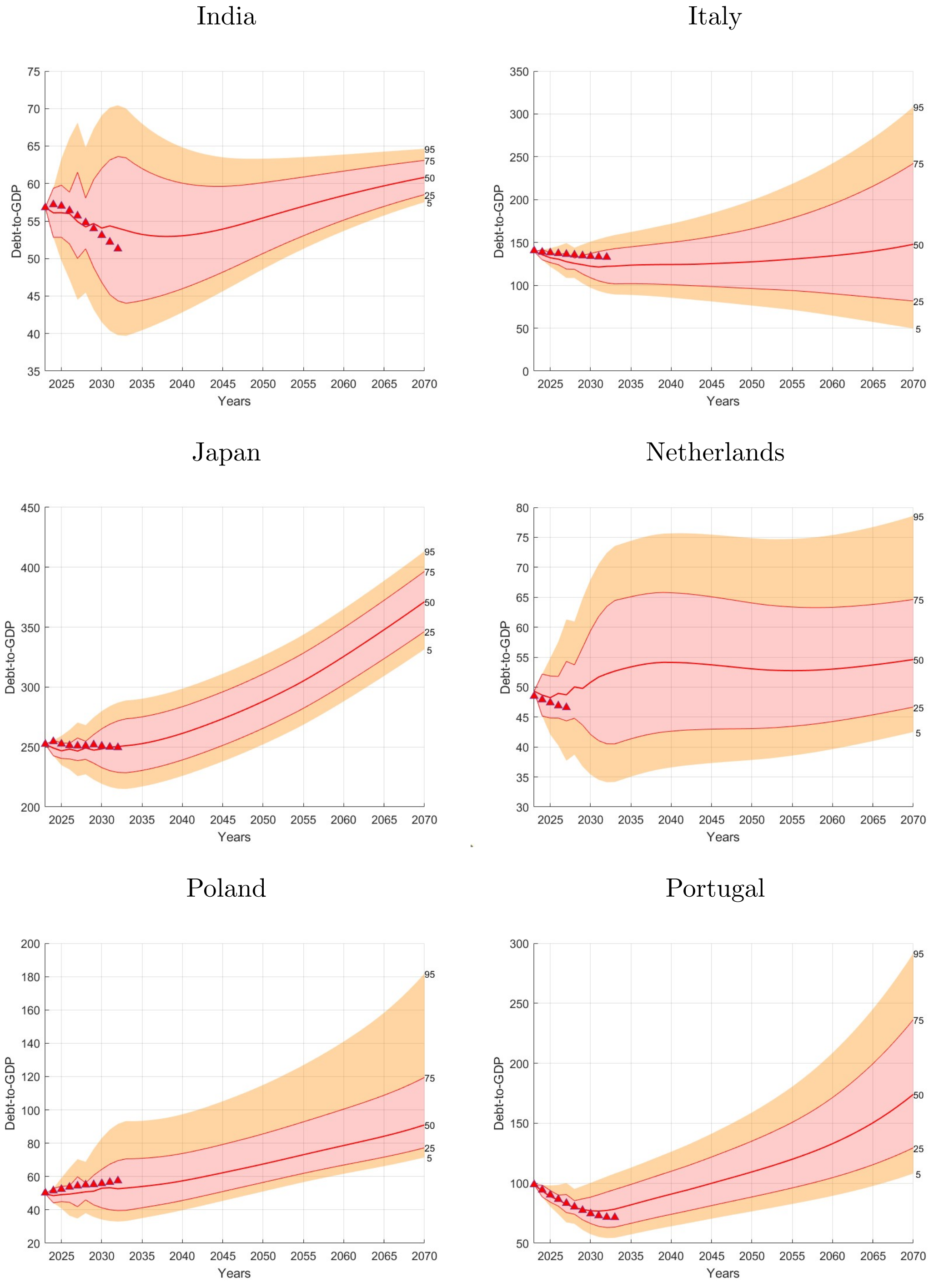
India
Italy
Japan
Netherlands
Poland
Portugal
Debt-to-GDP
Years
2025
2030
2035
2040
2045
2050
2055
2060
2065
2070
95
75
50
25
5
35
40
45
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55
60
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80
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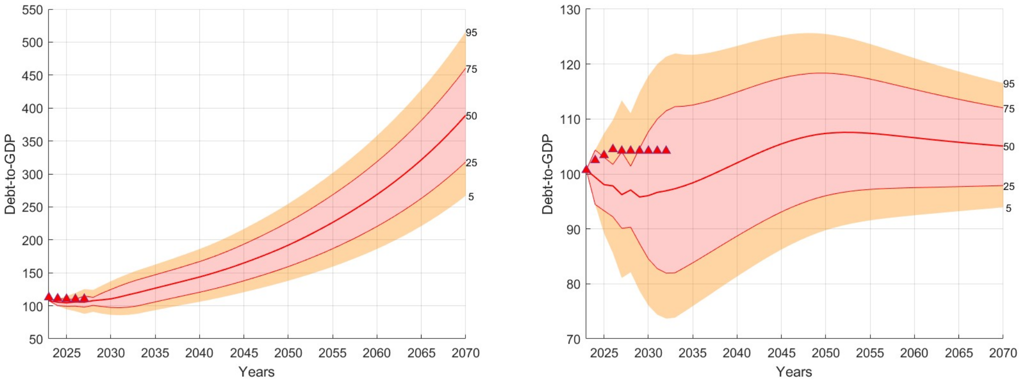
140
160
180

(continued)



Spain

UK

US

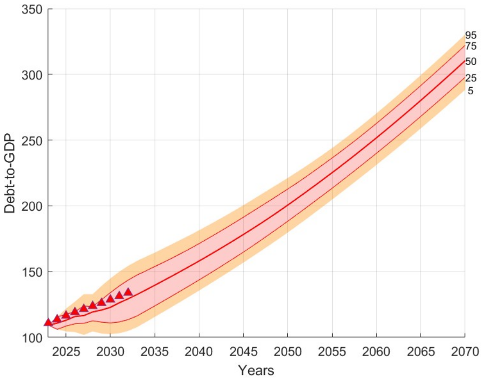
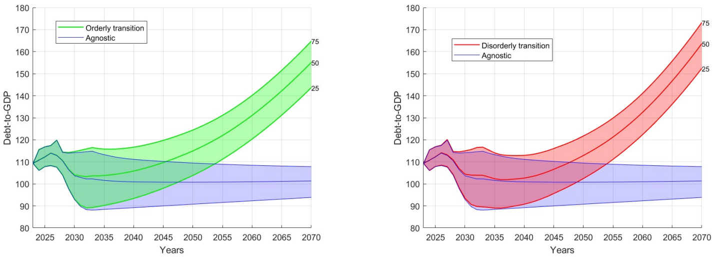


Figure B.2 – Transition risk effects on debt dynamics for low rates

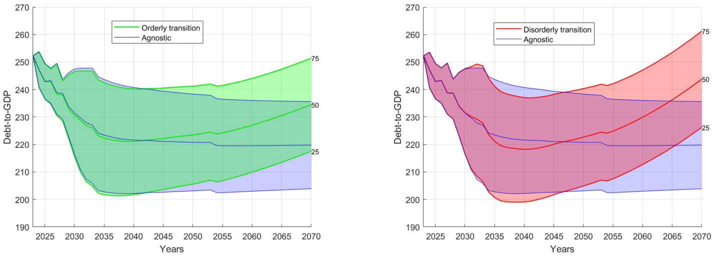
This figure shows the debt stock fan charts with transition risk under (a) orderly and (b) disorderly transition scenarios, using REMIND under low interest rates. The fan charts are overlayed on the debt dynamics without transition risk (blue). The solid lines display 0.25, 0.50, and 0.75 percentiles.

(a) Orderly (b) Disorderly

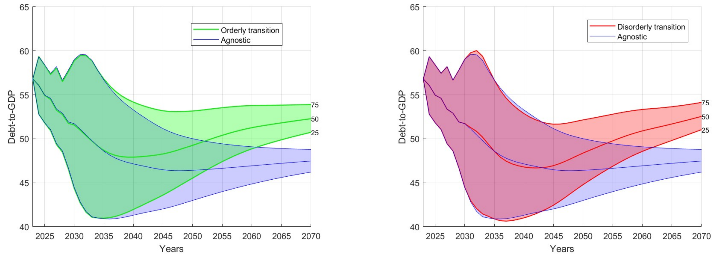
US



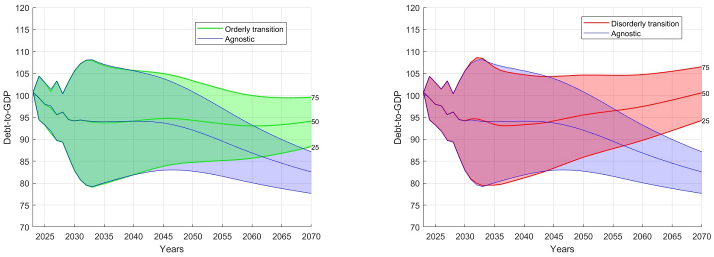
Japan



India



UK



Australia

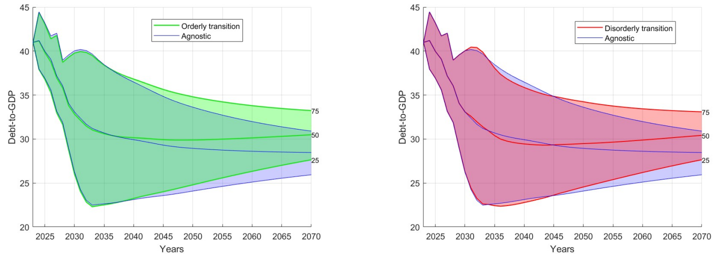


Figure B.3 – Transition effects on debt with 50% carbon tax recycling

This figure shows the debt stock fan charts with transition risk under disorderly transition scenarios, using REMIND when 50% of the carbon taxes are recycled to pay the debt. The fan charts are overlayed on the debt dynamics without transition risk (blue). The solid lines display 0.25, 0.50, and 0.75 percentiles.