Are sovereign debts sustainable under energy transition?

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Abstract

We use stochastic debt sustainability analysis under transition to low-carbon energy sources together with integrated assessment models of climate change to quantify transition risk to sovereign debts. We obtain projections of transition premia and adverse growth effects under the orderly or disorderly transition scenarios of the Network for the Greening of the Financial System and document increasing debt from the mid-2030s for fifteen countries. Cross-country average fiscal adjustments of about 0.30% of GDP per annum can offset the debt increases. However, the stabilization of the currently high debt levels, as increased by the transition, requires adjustments averaging 1.5%, with significant country differences. The effects are muted under low interest rates. Green growth of about 0.5% offsets the transition debts. Recycling carbon taxes into 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

Transition to a low-carbon economy requires capital expenditures estimated at 3% of global GDP per annum until 2050,[1] with the sovereign debt implications of climate-related policies receiving increasing attention (Bolton, Buchheit, Gulati, Panizza, Weder di Mauro, and Zettelmeyer, 2022). A complex relationship between climate and debt is emerging amid high COVID-19 debts (Dibley, Wetzer, and Hepburn, 2021), evidence for a climate spread on sovereign bond yields (Battiston and Monasterolo, 2020; Beirne, Renzhi, and Volz, 2021; Cevik and Tovar-Jalles, 2022), and climate-induced credit downratings (Klusak, Agarwala, Burke, Kraemer, and Mohaddes, 2023).[2] In this paper, we ask whether, and by how much, transition risk changes the level and long-term trend of sovereign debts and if countries can offset any debt increases and stabilize their total debt. Finding significant adverse effects, we then ask whether green growth (Porter and van der Linde, 1995) could solve the debt problem.

Recent surveys find investor beliefs that climate risks are already materializing, especially in the form of changing regulations relating to the low-carbon transition (Krueger, Sautner, and Starks, 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 cast doubts on the efficient pricing of these risks by the markets (Campiglio, Daumas, Monnin, and von Jagow, 2023), raising concerns about abrupt repricing (Rebonato, 2023). This literature motivates our study to provide robust quantitative evidence of transition effects on sovereign debt sustainability and contribute towards alleviating potential risks of abrupt debt repricing.

To answer our research questions, we develop a *transition debt sustainability analysis* (DSA) model linking forward-looking macroeconomic projections from integrated assessment models (IAMs) in the tradition of Nordhaus (2019) with stochastic DSA (Blanchard, 2022). We find large debt increases for a broad sample of developed economies, compounding currently high debt levels and limiting the sovereigns' debt-stabilizing capacity.

[1] This is the low estimate for energy supply and demand investments from the IPCC 2018 report "Global Warming of 1.5°C", available at `https://www.ipcc.ch/sr15/chapter/spm/`, accessed July 2024. It is indicative of estimates from official sources for different groups of countries, such as the European Commission's 2020 Europe's needs of 1.5-1.8% and IMF's 2021 G20 estimate of 2%.

[2] Evidence on climate spreads has also been accumulating for corporate bonds (Bolton and Kacperczyk, 2023; Kölbel, Leippold, Rillaerts, and Wang, 2024; Seltzer, Starks, and Zhu, 2022) and municipalities (Acharya, Johnson, Sundaresan, and Tomunen, 2022; Goldsmith-Pinkham, Gustafson, Lewis, and Schwert, 2023; Painter, 2020).

We take a step further to ask how much green growth is required to offset transition debts and whether carbon tax recycling into debt payment solves the problem.

From the IAMs, we obtain projections of shocks to the climate policy relevant sectors (Battiston, Mandel, Monasterolo, Schütze, and Visentin, 2017) under orderly (below 2°C) or disorderly (delayed below 2°C) transition scenarios, consistent with the Paris Agreement targets, from the Network for Greening the Financial System (NGFS).[3] Following Battiston and Monasterolo (2020), we use these shocks to compute changes in sovereign default probabilities and obtain a forward-looking *transition spread* on sovereign bond yields. 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 which is the numerator of the debt-to-GDP ratio in DSA. We also consider the transition effects on the denominator of the debt-to-GDP. We use the climate module of the National Institute Global Econometric Model (NiGEM, Hantzsche, Lopresto, and Young 2018) to obtain real GDP growth and inflation projections and introduce transition effects on nominal GDP.

The NGFS scenarios are narratives, in the sense used by the IPCC (Pirani, Fuglestvedt, Byers, O'Neill, Riahi, Lee, Marotzke, Rose, Schaeffer, and Tebaldi, 2024) and the climate science literature (Climatic Change, 2014) in postulating socio-economic pathways and greenhouse gas concentrations. They are not discrete realizations of some underlying stochastic process. We use these narrative projections as the mean values on which to build the stochastic DSA model with economic uncertainties. To increase the acceptance of our findings in the presence of *deep uncertainty* of climate models (Lempert, Lawrence, Kopp, Haasnoot, Reisinger, Grubb, and Pasqualino, 2024) we follow Howe, MacInnis, Krosnick, Markowitz, and Socolow (2019) and report results with the three NGFS models —REMIND, GCAM, and MESSAGE.

The transition DSA model is based on Zenios, Consiglio, Athanasopoulou, Moshammer, Gavilan, and Erce (2021). Uncertainty of financial, economic, and fiscal variables is introduced using *scenario trees* to obtain debt stock and flow dynamics with a tail risk measure. The expected cost of debt financing carries the transition spread from IAM projections, and debt stock and flow ratios to GDP account for the denominator effects from NiGEM under the NGFS scenarios. GDP growth and debt financing rates are

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

stochastic around the narrative expected values. They are calibrated on the scenario tree (Høyland and Wallace, 2001) using historical volatilities and correlations, assuming that transition policies do not fundamentally alter the correlation structure. The model optimizes the maturity of issued debt to trade off financing cost for refinancing risk with sustainability conditions on the stock and flow ratios. The *climate agnostic* (no transition) DSA provides the baseline reference values to assess transition debt dynamics.

To the best of our knowledge, this is the first study of transition risk to debt sustainability, contributing to the nascent literature on climate change and sovereign debt (Dibley, Wetzer, and Hepburn, 2021; Kellner and Runkel, 2023; Klusak, Agarwala, Burke, Kraemer, and Mohaddes, 2023; Zenios, 2022). We project fan charts of debt trajectories under transition to assess debt sustainability with a high confidence level and estimate two critical debt-related quantities: (i) fiscal adjustments that offset transition debts and (ii) total adjustments that stabilize the currently high debt levels as increased by transition.

We develop the model in Section 2, calibrate it in Section 3 on five major economies (US, Japan, India, UK, Australia) and ten eurozone countries (Austria, Belgium, Finland, France, Germany, Italy, Netherlands, Poland, Portugal, Spain), and use it in Section 4 to study the effects of orderly and disorderly transitions on the level and trend of debts.

Our use of the model proceeds in three steps. First, we show that the cost-risk tradeoff in sovereign debt financing shifts towards higher risks and costs.

Second, we study long-term debt dynamics and find that most countries' transition debts increase starting from the mid-2030s; Germany is an exception, and so are Finland and France under two IAMs. Fiscal adjustments with cross-country average in the cross-IAM range 0.14-0.30% (orderly) or 0.22-0.37% (disorderly) of GDP per annum (p.a.) offset the transition debts, albeit with significant cross-country differences. These adjustments are incremental to any required to stabilize the current high debt levels; they are indicative of the transition debt problem but not the total debt problem. Stabilizing the current debt levels increased by transition requires the total adjustments shown by the arrows in Figure 1 (orderly). They are relatively large, with a cross-country average of 1.28-1.44%. For disorderly transition, the adjustments are 1.36-1.51% (not shown). Slight differences between orderly and disorderly effects are prevalent in our results. Under orderly transition, debts start increasing earlier but gradually, whereas, with disorderly, they start later but abruptly. Debt accumulates, and the same fiscal adjustment is needed, 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).

[Insert Figure 1 Near Here]

Third, we consider deep uncertainty and find consistent results across IAMs. The cross-country average of cross-IAM differences in the fiscal adjustments that offset transition debts is about 0.16% of GDP p.a. (orderly and disorderly). However, differences are bigger for some countries, and for a few (Austria, Finland, France, Italy), two IAMs suggest stable debts. We also consider narrative uncertainty about long-term interest rates being relatively high (Pisani-Ferry, 2021) or relatively low (Benmir, Jaccard, and Vermandel, 2020; Bylund and Jonsson, 2020) as a result of the transition. We find this uncertainty to be more impactful, with transition effects muted under low rates with four countries (UK, Australia, Austria, Italy) having stable debts. The average total adjustment is reduced from 1.44% to 0.72% (orderly) and from 1.51% to 0.81% (disorderly) under the worst-case IAM projections.[4]

We go further (Section 5), to ask how much green growth is required to offset the transition debts. Porter and van der Linde (1995) argued that appropriately crafted climate legislation can trigger innovations that improve productivity. There is evidence in support of a weak Porter hypothesis (Jaffe and Palmer, 1997) of environmental innovations (Martínez-Zarzoso, Bengochea-Morancho, and Morales-Lage, 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 transition debts. Finally (Section 6), we ask to what extent carbon tax recycling into total debt repayment can solve the problem.

Related literature

Our work contributes to the literature on climate and sovereign debt (Dibley, Wetzer, and Hepburn, 2021; Kellner and Runkel, 2023; Klusak, Agarwala, Burke, Kraemer, and Mohaddes, 2023; Zenios, 2022) a model to quantify transition risks to debt sustainability using IAMs. IAMs providing forward-looking macroeconomic and climate projections (Nordhaus, 2019) have motivated, among a vast literature on climate economics, studies on portfolio effects from climate policies (Battiston, Jakubik, Monasterolo, Riahi, and Ruijven, 2019; Dietz, Bowen, Dixon, and Gradwell, 2016) and sovereign creditworthiness

[4]These adjustments are the sums of the agnostic (Tables 2-5) and transition (Tables 4-6) tests using REMIND worst-case projections.

(Klusak, Agarwala, Burke, Kraemer, and Mohaddes, 2023). We obtain projections of shocks to climate policy-relevant sectors under orderly and disorderly transitions to estimate bond yield changes. IAMs have proponents (Nordhaus and Moffat, 2017) and critics (Pindyck, 2017) and are useful "with caveats" (Vaidyanathan, 2021), and we employ the three NGFS models to alleviate concerns that our findings are predicated on a particular IAM.

Going beyond the IAMs, there is accumulating empirical evidence of climate policy announcement —as opposed to climate change— effects on corporate (Bolton and Kacperczyk, 2023; Kölbel, Leippold, Rillaerts, and Wang, 2024; Seltzer, Starks, and Zhu, 2022) or sovereign (Battiston and Monasterolo, 2020) bond yields, supported by structural models (Agliardi and Agliardi, 2021; Le Guenedal and Tankov, 2024; Seghini and Dees, 2024).[5] This literature motivates our work. We contribute an empirical estimation of sovereign bond yields' response to transition risk in line with Battiston and Monasterolo (2020), and uncover an economically large and statistically significant increase after the Paris Agreement, adding to works on the Agreement's impact on, e.g., bank loan pricing (Delis, Greiff, Iosifidi, and Ongena, 2024), corporate debt creditworthiness (Capasso, Gianfrate, and Spinelli, 2020), and firm leverage (Ginglinger and Moreau, 2023). We add to earlier works that document the bond yields effects from rising temperatures (Beirne, Renzhi, and Volz, 2021), climate vulnerabilities (Cevik and Tovar-Jalles, 2022) or GDP damages (Klusak, Agarwala, Burke, Kraemer, and Mohaddes, 2023), the effect from transition.

We also account for potential transition effects on growth. We do this for completeness, although Metcalf and Stock (2023) find no long-run growth effects from EU carbon taxes, consistent with the macroeconomic theory that it is fundamentals, and not changes in relative prices, that drive growth. Känzig and Konradt (2023) find similar results on the panel of EU emissions trading system members with a significant GDP drop of about 0.5% only for countries in the second quartile of GDP per capita. Vrontisi, Fragkiadakis, Kannavou, and Capros (2020) estimate a small impact on EU growth (up to 0.17%) from the nationally declared emission reductions. The growth effects are low or not significant. However, Dees (2020) documents nonlinearities and thresholds in the identification, and we introduce a growth effect using NiGEM.[6]

[5]For climate change or transition effects on asset prices see Barnett, Brock, and Hansen (2020) and the non-overlapping surveys of burgeoning climate finance literature (Battiston, Dafermos, and Monasterolo, 2021; Campiglio, Daumas, Monnin, and von Jagow, 2023; Giglio, Kelly, and Stroebel, 2021; Zenios, 2024).

[6]Seghini (2024) developed a model of debt limits under GDP damages from carbon budget constraints.

Our DSA model follows the tradition of high-realism models by the international institutions; see Bouabdallah, Checherita-Westphal, Warmedinger, Stefani, Drudi, Setzer, and Westphal (2017) for ECB, European Commission (2020), IMF (2022), Zenios, Consiglio, Athanasopoulou, Moshammer, Gavilan, and Erce (2021) for ESM. The institutions 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, and IMF (2023) is devoted to climate risks. None of these models links climate change to debt dynamics.[7]

The institutions' DSA models represent uncertainty typically through ex-post fan charts. Still, Ben Bernanke criticized fan charts in his recent review of the Bank of England forecasting methods.[8] Zenios et al. (2021) introduced ex-ante scenarios and a coherent tail risk measure (Artzner, Delbaen, Eber, and Heath, 1999) on debt stock and flow. We follow the scenario approach to develop a transition DSA model.

To deal with problems of deep uncertainty, which are common in climate impact studies, we examine two sources, namely differences in IAM specifications (Vaidyanathan, 2021) and uncertainty about the climate effects on interest rates (Mongelli, Pointner, and van den End, 2024). We follow Howe, MacInnis, Krosnick, Markowitz, and Socolow (2019) and provide a range of estimates based on what is known from currently available science. On IAMs, we use projections from the three NGFS models. On interest rates, some authors expect lower long-term natural rate of interest resulting from climate change (Benmir, Jaccard, and Vermandel, 2020; Bylund and Jonsson, 2020) while others suggest a potential increase (Pisani-Ferry, 2021); the direction of change is not a settled issue. We conduct our main tests using medium levels of interest rates but also report results with low rates. Our paper sheds light on some aspects of deep uncertainty.

The paper most closely related to ours is Klusak, Agarwala, Burke, Kraemer, and Mohaddes (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

[7]For a large literature on structural debt models, without climate change effects, see among many others, Bocola and Dovis (2019); Conesa and Kehoe (2017); D'Erasmo, Mendoza, and Zhang (2016).

[8]See `https://www.bankofengland.co.uk/independent-evaluation-office/forecasting-for-monetary-policy-making-and-communication-at-the-bank-of-england-a-review`.

damages and adaptation— thus covering an important channel not addressed by earlier works. 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. We also contribute a positive outlook to Dibley, Wetzer, and Hepburn (2021) that transition risk per se does not imperil the countries' ability to repay debts but do not overturn their main assertion on aggregate climate adverse effects. Our tests on carbon tax recycling find results consistent with Darracq, Dees, De Gaye, Parisi, and Sun (2023).

2 Transition debt sustainability analysis

We develop the DSA model based on Zenios et al. (2021), with a transition spread on the debt financing rates and a transition effect on nominal GDP, predicated on narrative scenarios using IAM projections for orderly or disorderly transitions. We add interest rates, growth, and fiscal balance uncertainty using scenario trees around the narrative scenario mean-value projections. The dynamics of debt stock- and flow-to-GDP ratios are state-dependent on the tree, and we specify a tail risk measure 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* are given by the *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 interest rate on AAA-rated sovereign bonds, taken as the risk-free rate (r_{ft}) plus a risk premium on the sovereign. The risk premium depends on the debt level (Blanchard, Leandro, and Zettelmeyer, 2021) and Zenios et al. (2021) modeled it as a function of the debt stock-to-GDP ratio, $d_t = D_t/Y_t$, with *term premia* for debt of different maturities. The interest rate for instrument j issued at t is given by

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

$\rho(d, j)$ 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 risk premium as a function of debt stock. $\hat{\rho}(d)$ 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. This is approximated by the smooth sigmoid:

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

$r_t(j)$ 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, $\Delta p_t^{S,M}$. The *transition spread* $\Phi\left(\Delta p_t^{S,M}\right)$ is a function of this change in default probability conditional on the transition scenario and model projections. This is a forward-looking spread added to the financing rates under the baseline agnostic policy B from (4),

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

where

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

Changes in default probability induced by a given transition policy affect interest rates through the coefficient β. The effect of transition policy announcements on bond spreads has been documented empirically for corporate (Bolton and Kacperczyk, 2023; Kölbel et al., 2024; Seltzer et al., 2022) or sovereign (Battiston and Monasterolo, 2020) bonds, and we estimate β in subsection 3.2.

Following Battiston and Monasterolo (2020) (henceforth, Battiston-Monasterolo), we compute $\Delta p_t^{S,M}$ from the shocks in the climate policy relevant sectors (CPRS, Battiston et al. 2017). The CPRS shocks are the changes in the sectors' market share when the country follows a transition scenario. The probability change depends on the exposure of the sovereign to the CPRS and the relative sector profitability (Battiston and Monasterolo, 2020, Proposition 1)

$$\Delta p_t^{S,M} = \sum_{k \in K} w^k \, u^{k,S,M} \, \chi^k. \tag{9}$$

w^k denotes the contribution of sector k to the sovereign's total Gross Value Added (GVA), considering primary and secondary energy sectors from fossil and renewable sources.[9] $u^{k,S,M}$ is the percentage shock to the market share of sector k in the total country energy mix when following transition scenario S under projections from model M.[10] χ^k is the relative profitability of k, and following the reference, is set at 1.

The contribution of each sector to GVA is given by

$$w^k = m^k \, \frac{\text{GVA}^{en}}{\text{GVA}}, \tag{10}$$

where m^k is the market share of CPRS in the country's energy sector and is adjusted by

[9]For the primary sector, we consider gas, coal, oil, nuclear, wind, solar, hydro, and geothermal; for the secondary, we use gas, coal, oil, nuclear, wind, solar, hydro, and biomass.

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

the relative contribution of the energy sector GVA^{en} to the country's total GVA.

2.2.2 Transition growth effect

Although the transition effects on growth are insignificant (Känzig and Konradt, 2023; Metcalf and Stock, 2023) or small (Vrontisi et al., 2020), we include the growth channel for completeness, so the transition DSA model can be applied as new information on nonlinearities and tipping points (Dees, 2020) become available. We use the NiGEM projections of real GDP and price level changes with different models M under the NGFS scenarios.[11] We use subscripts r and n to denote real and nominal values, respectively.

We first retrieve the real GDP under the transition scenarios, given the agnostic baseline GDP. NiGEM provides projections of real GDP proportional change under transition S with model M, $\kappa_t^{S,M}$, and we obtain the transition real GDP from the baseline as

$$Y_{r,t}^{S,M} = (1 + \kappa_t^{S,M}) Y_{r,t}^{B}. \tag{11}$$

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

$$Y_{n,t}^{S,M} = \frac{P_t^{S,M}}{P_0^B} Y_{r,t}^{S,M}. \tag{12}$$

The nominal GDP is obtained from the baseline real GDP as

$$Y_{n,t}^{S,M} = (1 + \kappa_t^{S,M}) \frac{P_t^{S,M}}{P_0^B} Y_{r,t}^{B}. \tag{13}$$

2.3 Scenario trees

The NGFS projections are narrative scenarios 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 DSA, namely the risk-free interest rates, growth, and fiscal balance. Figure 2, panel A, illustrates the tree with time denoted by $t = 0, 1, 2, \dots T$, 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.

[11] We use NiGEM projections consistent with the NGFS Phase IV scenarios with the three 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.

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. We build the tree using moment matching so that the first moments of the state variables match the projections from the narrative scenarios and the second moments match historically estimated values of volatilities and correlations.

[Insert Figure 2 Near Here]

2.4 Debt dynamics and the risk measure

We now define state-dependent financing decisions, $X_t^\nu(j)$, to obtain the state-dependent debt dynamics equations on the tree. All state-dependent variables, except the primary balance, also depend on the transition narrative S under projections from model M, through the transition spread in (7) or the growth relation (13). For simplicity of notation, we do not use superscripts S and M in defining the state-dependent transition DSA model. The state-dependent debt dynamics we give next are understood to apply to a scenario tree with mean values generated under S and M.

The debt financing equation (3) on the tree becomes

$$\sum_{j=1}^{J} X_t^\nu(j) = GFN_t^\nu, \tag{14}$$

for $\nu \in \mathcal{N}_t$, and $t = 0, 1, 2, \ldots T$, where $GFN_t^\nu = i_{t-1}^{a(\nu)} D_{t-1}^{a(\nu)} + A_t - PB_t^\nu$, and D_{t-1}^ν is obtained from the state-dependent stock equation

$$D_t^\nu = (1 + i_{t-1}^{a(\nu)}) D_{t-1}^{a(\nu)} - PB_t^\nu. \tag{15}$$

Debt stock and flow, as a ratio to GDP, are given by $d_t^\nu = D_t^\nu / Y_t^\nu$ and $gfn_t^\nu = GFN_t^\nu / Y_t^\nu$. i_t^ν is obtained from the state-dependent interest on the issued debt financing instruments

$$r_t^\nu(j) = r_{ft}^\nu + a_j + \hat{\rho}(d_t^\nu) + \Phi\left(\Delta p_t^{S,M}\right). \tag{16}$$

Through this equation, S and M enter the stochastic debt dynamics.

We use the discrete distributions of the stock and flow ratios on the scenario tree to assess debt sustainability. We consider debt sustainable when stock is on a non-increasing trajectory in the long run with a high probability (Blanchard, 2022), and refinancing needs are below a threshold that markets can finance with high probability. 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 we can 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 gross financing needs stochastic variable over all periods, the CVaR of flow (conditional Flow-at-Risk) is given by

$$\Psi(gfn) \doteq \mathbb{E}\left(gfn \mid gfn \geq gfn^{\diamond}\right), \tag{17}$$

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 the model to determine 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 I_t^{ν} plus service payments on the debt created by the financing decisions. Exploiting the tree structure, we calculate the service payments on a path leading to ν. Let $CF_t^{\nu}(j,m)$ denote the nominal amount of interest payment due at state ν of period t, per unit of debt $X_{\tau(m)}^{m}(j)$ issued at state m of an earlier period $\tau(m)$ on path $\mathcal{P}(\nu)$. This amount is computed from scenarios of the term structure of interest rates, including the premia (7) and 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

$$\text{NIP}_t^\nu = I_t^\nu + \sum_{m\in\mathcal{P}(\nu)} \sum_{j=1}^{J} X_{\tau(m)}^m(j)\, CF_t^\nu(j,m). \tag{18}$$

Recall the dependence of the DSA variables on the transition narrative scenario S under projections from model M, through transition spreads (7) or growth adjustments (13). Hence, for each transition S and model M, we minimize the expected cost of debt subject to a flow risk constraint by solving

$$\underset{X}{\text{Minimize}} \qquad \sum_{\substack{\nu\in\mathcal{N}_t,\\ t=0,1,2,\ldots T.}} \text{Prob}^{(\nu)}\, \text{NIP}_t^\nu \tag{19}$$

$$\text{s.t.} \qquad \Psi(gfn) \leq \omega. \tag{20}$$

Issuing debt at the lowest yield maturity lowers the financing cost but increases refinancing risk when all maturing debt must be refinanced. Varying the parameter ω, we trade off debt financing cost with refinancing risk. If ω is below the threshold, we can ascertain, with high confidence, that debt financing needs can be met. However, debt stock increases for lower ω, and there is a tension between stock and flow.

We can impose a constraint on the inter-temporal rate of change of debt, using the CVaR risk measure of the debt stock ratio, i.e., $\Psi\left(\frac{\partial d^\nu}{\partial t}\right) \leq 0$. However, if debts are not sustainable, as our research question seeks to answer, the model with both debt flow and stock sustainability constraints will have no feasible solution. Instead, we solve for the minimum cost solution with the flow constraint (i.e., ω below the threshold) and check if the debt stock dynamics are sustainable with a non-increasing trajectory with a high probability. If debt stock turns out to be on an increasing trajectory, we use a model extension (Zenios et al., 2021, section 6) to optimize fiscal adjustments that satisfy the debt stock constraint to stabilize debt in the long run with high probability. We introduce a variable z_t to denote adjustments as a proportion of GDP and write the debt financing eqn. (14) as

$$\sum_{j=1}^{J} X_t^\nu(j) + z_t Y_t^\nu \geq GFN_t^\nu. \tag{21}$$

$z_t Y_t^\nu$ is the part of gross financing not financed by issuing debt; it is the required fiscal adjustment that increases the primary balance to 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 (19), 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. Adding this amount to the country's long-term primary balance stabilizes the debt trajectories. This is the *debt-stabilizing primary balance* (PB*) as 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 answer affirmatively the question of whether sovereign debts are sustainable under transition.

We reformulate the model using weights $w_t^\nu(j) = \frac{X_t^\nu(j)}{GFN_t^\nu}$, with $\sum_{j=1}^{J} w_t^\nu(j) = 1$. With this formulation, we have three alternative strategies to optimize debt financing, with improved cost-risk tradeoff but decreasing computational tractability: (i) weights can be time-invariant $w(j)$, following a *fixed-mixed strategy* with simple *rules* for all periods; (ii) weights can be time-dependent but state-invariant $w_t(j)$, following an *adaptive fixed-mix strategy* that adapts with time but is identical for all states at each period; (iii) weights can also be state contingent $w_t^\nu(j)$. A dynamic strategy can be more efficient than the adaptive, which in turn is more efficient than the fixed-mix. To isolate the transition effects on debt from changes in debt financing strategy, we use fixed-mix as the default.

In online Appendix A, we give the full model with the computation of the risk measure.

3 Model calibration

We now estimate the transition spread and describe the data for the scenario tree calibration. We start in December 2023 with a horizon extending to 2070 beyond the 2050 target of current transition policies, such as the EU goal of achieving neutrality by 2050 and the COP28 pledge for a significant increase in renewable power capacity by 2030.[12]

3.1 Data and scenario trees

The sources for country data for the debt term structure to be financed, the transition risk variables, and the data to calibrate the scenario trees —yield curves on government

[12]See, respectively, Regulation EU 2021/1119, available at `https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32021R1119`, and Carbon Brief available at `https://www.carbonbrief.org/cop28-key-outcomes-agreed-at-the-un-climate-talks-in-dubai/`, accessed on December 13, 2023.

bonds, economic growth, fiscal balance— are in online Appendix Table B.1.

Sovereign debt. The term structure of the outstanding bond debt, is from Eikon-Refinitiv. We consider debt 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.[13] The average scaling across countries is ±6% with a net of zero.

Energy sector contribution to gross value added. The contribution of each energy sector to the economy, m^k, is computed from its 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 B.1.

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

Risk premia over the risk-free rate are computed for the eurozone countries over the AAA rates according to (6), with $\hat{\rho}_c = 3.25$ as estimated by Zenios et al. (2021), within the range 2-4 from Blanchard et al. (2021), $d_{min} = 60$, and $d_{max} = 160$. There are no risk premia over their yield curves for the US, UK, and Japan. 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. Term premia computed from the historical averages of 2001-2020 are in Figure B.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 and the UK, we use nominal projections from the 2023 IMF World Economic Outlook until 2028, with long-term projections converging to their 1995-2020 historical averages; see Appendix Table B.2, Panel A. For the transition effects on growth, we adjust these

[13] 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.

data using the NiGEM/NGFS coefficients $\kappa^{S,M}$ in (13). The adjustment factors have a temporal average until 2070 in the range 0.998 to 1.012 for all countries, with a minimum of 0.985 and maximum of 1.028; the transition effects on growth are minor.

Primary balance. We use the 2023 IMF World Economic Outlook projections, in % of GDP, over the period 2023-2028 with long-term projections as the historical averages over the period 1995-2020; see Table B.2, Panel B.

Standard deviations and correlations. To calibrate the scenario trees, we computed the standard deviations and correlations of the state variables using twenty years of data just before the 2020 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 the data of 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 computations of the relative contribution of the carbon tax as % of GDP are adjusted by 2010 US GDP, under the assumption that the ratio does not change.

3.2 Transition spread and the Paris Agreement

To compute the transition spread (8), we need changes in the default probabilities and β. Changes in default probabilities are obtained from (9)-(10) using IAM projections under the transition scenarios, and are displayed in Figure 3 for our sample of major economies.

[Insert Figure 3 Near Here]

To estimate β, we run a panel regression of the spreads on changes of default probability with country and global control variables on a balanced panel of the eurozone countries spanning 2001-2022. We include a structural break for the Paris Agreement and random effects to account for unobserved country-specific factors that are not always measurable or included in the dataset.[14]

[14]Following Brogaard, Dai, Ngo, and Zhang (2020) we also used country fixed effects with consistent results.

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 time change in the implied probability of defaults (p) and use a dummy variable D, taking value 0 before the Paris Agreement and one otherwise, controlling for other spread determinants from the literature (Afonso, Furceri, and Gomes, 2012; Delatte, Fouquau, and Portes, 2017). We use nominal debt-to-GDP ratio (d) and changes in the debt-to-GDP ratio (Change) for government controls together with a high debt dummy (H) taking value 1 when the debt ratio is above 60% and 0 otherwise, and real GDP growth (Real) macroeconomic controls. For global controls, we use the US 10-year yield (YieldUS), market volatility measured by the VIX as a proxy for risk appetite (Longstaff, Pan, Pedersen, and Singleton, 2011), world real GDP growth (World), the rate of change of the HICP (ΔHICP), and the country's primary balance (PB). X is the matrix of interaction terms of D with the regressors excluding Δp, with coefficients vector Γ

$$\begin{aligned} s_{i,t} = \alpha_0 + \alpha_1 d_{i,t-1} + \alpha_2 \Delta p_{i,t-1} + \alpha_3 D_{i,t-1} \times \Delta p_{i,t-1} + \alpha_4 \mathrm{H}_{i,t-1} + \alpha_5 \mathrm{Real}_{i,t-1} + \\ + \alpha_6 \mathrm{Change}_{i,t-1} + \alpha_7 \mathrm{YieldUS}_{i,t-1} + \alpha_8 \mathrm{VIX}_{i,t-1} + \alpha_9 \mathrm{World}_{i,t-1} + \\ + \alpha_{10} \Delta \mathrm{HICP}_{i,t-1} + \alpha_{11} \mathrm{PB}_{i,t-1} + \Gamma X_{t-1} + \epsilon_{i,t}. \end{aligned} \tag{22}$$

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.

[Insert Table 1 Near Here]

Table 1 summarizes our results. 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 the spread of a unit change in default probabilities is $\hat{\alpha}_2 + \hat{\alpha}_3 = 0.60$ after the Paris Agreement and $\hat{\alpha}_2 = 0.19$ before. The post-Paris increase is in line with similar effects documented, e.g., for bank loan pricing (Delis et al., 2024), corporate debt creditworthiness (Capasso et al., 2020), and firm leverage (Ginglinger and Moreau, 2023).

We can also obtain an estimate of β from the well-known linear relation

$$p = \frac{s}{1 - R}, \tag{23}$$

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 developed countries, we obtain $\beta = 0.60$.

4 Transition effects on sovereign debt

We put the model to work on our sample of countries. We take the flow threshold to be 20% as set for developed economies 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 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 reference debt dynamics using the agnostic DSA model. We compare our agnostic debt projections with the medium-term projections from the IMF Article IV reports; see Appendix Figure C.1. Our medium-term projections are remarkably close to Article IV for most countries, and our reference DSA can be considered reliable. The differences are explained by the fact that Article IV data are from 2021 or 2022, immediately after the COVID-19 lockdowns, preceding our analysis by at least one year, and the sources of financial, economic, and fiscal projections available to us are not identical to those of the IMF. The initial (2023) differences are small, averaging 6.88 percentage points (p.p.).[15]

For cross-country consistency in comparing the transition effects, we first adjust for the fact that some countries have precarious debt positions while others can afford more debt. Specifically, we estimate fiscal adjustments that stabilize long-run debt under climate agnostic DSA to obtain the debt-stabilizing primary balance PB*; see Table 2.

[Insert Table 2 Near Here]

Negative PB* implies that a country can run deficits without jeopardizing debt sustainability, and positive indicates a need for surplus. We notice that an average adjustment of 1.14% of GDP can stabilize current debts with countries running on average a long-term deficit of -0.11%.We obtain reference values of how much primary surplus may be feasible

[15] One of us has used the agnostic model for Italy, UK, Finland, Netherlands, Cyprus, and Japan. The DSA findings were discussed with the Ufficio parlamentare di bilancio (IT), HM Treasury (UK), the Finnish Ministry of Finance, the Dutch State Agency Treasury, the Cyprus Auditor General, and the Bank of Japan, and, without implicating them, we consider our analyses reliable. Some of those works are published in the literature (Alberola, Cheng, Consiglio, and Zenios, 2023; Consiglio, Kikas, Michaelides, and Zenios, 2023; Zenios, Consiglio, Athanasopoulou, Moshammer, Gavilan, and Erce, 2021).

from Eichengreen and Panizza (2016), who discuss episodes of fiscal adjustments and tell us 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, but under solid growth, high debt ratios making the adjustment urgent, and governments with strong political bargaining positions. The adjustments in Table 2 can be considered feasible, albeit challenging, and with significant differences among countries.

We proceed with the main tests after applying these adjustments. That is, we assume that countries put their public finances in order before we document the transition effects on stabilized debt dynamics and estimate the *additional fiscal effort* that offsets transition debts. Thus, we disentangle 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 the transition on stabilized current debts. In the tables, we report both adjustments for completeness.

4.1 Cost-risk tradeoffs

In Figure 4, we display the risk-cost tradeoff of debt financing for the major economies under the agnostic DSA and orderly and disorderly transitions. The risk of debt refinancing is on the x-axis, and the cost of debt financing is on the y-axis. The blue frontiers are agnostic, and fan charts cover the frontiers with the three IAMs under orderly (green) and disorderly (red) transition. The solid frontiers denote the mean values.

[Insert Figure 4 Near Here]

First, we observe that transition risk shifts the tradeoffs toward higher cost and risk. All transition 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. Second, disorderly transitions generally have more adverse effects than orderly transitions, but differences are relatively small and not uniform across countries. An orderly transition is preferable for the US, Japan, and the UK; for India and Australia, the differences are marginal.

4.2 Debt sustainability

We zoom in on frontier points with refinancing risk at the 20% threshold and examine the debt stock trajectories. We illustrate the results in Figure 5 for the five major economies using REMIND for orderly (column A, green fan charts) and disorderly (column B, red fan charts) transitions, overlaying the fan charts of the agnostic DSA (blue). The debt trajectories are adversely affected, with the median and 0.75 percentile shifting upwards starting from the mid-2030s. This aligns with the finding of Klusak et al. (2023) on the direction and timing of sovereign creditworthiness changes from rising temperatures. Orderly transition is only marginally less impactful: even if the debt increase starts earlier, it is more abrupt under disorderly transitions. Country debts shift clearly towards non-sustainable trajectories, except for Australia, which experiences marginal debt worsening.

[Insert Figure 5 Near Here]

We report in Table 3 the debt increases at 2070 over the stabilized current debts for the full country sample. We give the median and 0.75 percentile under orderly (Panel A) and disorderly (Panel B) transitions with the three IAMs. Looking at the 0.75 percentile debt increases under orderly transition, we notice significant transition effects with cross-country average increases of 9.90-17.64 p.p. for the three IAMs. However, there are substantial differences among countries. For instance, under REMIND, eight countries have long-term debt increases of 10 p.p. or less, three have increased up to 20 p.p., and two go above 40 p.p. Under MESSAGE, five countries experience small debt decreases, six have increases below 10p.p. and three have up to 26p.p. The debt increases are somewhat larger under disorderly transition, with cross-country average increases of 0.75 percentile by 14.73-22.23 p.p. with the three IAMs. In Appendix Table C.1, we report the debt increases if countries are to run their historical primary balance without stabilizing current debts. The increases are larger, showing that the transition effects worsen with higher debt.

[Insert Table 3 Near Here]

In the map of Figure 6, we display the 2070 debt increases over the no-transition stabilized 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 under the 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 1.66% of GDP under REMIND, with GCAM and MESSAGE projecting debt decreases of up to -4.32% of GDP, see Table 3.

[Insert Figure 6 Near Here]

We ask whether countries can offset the transition debt increases by computing the additional fiscal effort to offset the debt with a high probability. We report the results in Table 4. We observe that under orderly transition, countries need up to 1.12% (US) of GDP additional fiscal effort average p.a. until 2070 to stabilize their debt under REMIND, with a cross-country average of 0.30%; only Germany has stable transition debt dynamics. Under disorderly transition, the range goes up to 1.29% with an average of 0.37%. The number of years of persistent effort is in column "Yrs" and, in general, is slightly lower than the 47-year horizon by one to four years, allowing some space for countries to stabilize their pre-transition debts. Lower estimates are obtained with GCAM and MESSAGE, with Austria, Finland, and France also running stable transition debts. Across IAMs, the total effort to stabilize transition debt over the whole horizon has a cross-country average of 3.73-10.68% of GDP (orderly) and 6.69-13.56% (disorderly).[16]

[Insert Table 4 Near Here]

Adding these adjustments to the agnostic PB^* we obtain primary balances well within the 3% reference values from Eichengreen and Panizza (2016), and although prolonged, they can be cyclically adjusted and still offset the transition debts. Hence, it is feasible to offset transition debts, assuming that the countries first stabilize their current debts.

We take another step and compute the total fiscal effort to stabilize the current high debts plus transition debts to get the *net* PB^*. The range of required primary balance under all IAMs for orderly transition is shown in Figure 1 (red bars) together with the historical average primary balance (**x**) and the adjustments (arrows). The total adjustments are relatively large, with cross-country averages of 1.28-1.44%. We find marginally higher adjustments for disorderly transition (1.36-1.51%, not shown). Given the current high debt levels, the sovereigns' capacity to stabilize its debts after transition is restricted, although the stabilizing primary balance is below 3% for all countries.

Overall, stabilizing current and transition debts can be considered feasible, albeit challenging. Countries that do not stabilize their debt early face difficult adjustments during the transition. While the effects of disorderly transition are somewhat higher than those

[16] We also performed this test with the energy mix of only fossil fuel sources, without renewables, and found that the required fiscal effort would have been higher. Results are available from the authors.

of orderly transition, the differences are small and heterogeneous among countries. This heterogeneity can exacerbate coordination difficulties for an early, orderly transition.

4.3 Deep uncertainty

To increase the "public acceptance" of our findings (Howe, MacInnis, Krosnick, Markowitz, and Socolow, 2019), we acknowledge the impact of two sources of deep uncertainty stemming from the IAM and long-term interest rate projections. These sources of uncertainty are "deep" (Lempert, Lawrence, Kopp, Haasnoot, Reisinger, Grubb, and Pasqualino, 2024) in that IAMs are subject to non-linearities and tipping points, and interest rates respond to many factors, including the climate policies to be adopted and the state of policy implementation. We do not know the probabilities and can not consider differences as noise, so we report the range of results given all available information and ask whether our conclusions hold.

4.3.1 IAM projections

The deep uncertainty surrounding IAMs is manifested in Figure 4 with the cross-IAM dispersion of cost-risk tradeoffs for most countries 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 13.89 p.p. (orderly) and 19.00 p.p. (disorderly), there are significant differences among countries. For five countries (Japan, Austria, Finland, France, Portugal), there is no consensus among the IAMs on whether the transition to a low-carbon economy will increase or decrease debt. Consistent cross-IAM differences are noticed in the additional fiscal efforts to offset transition debts in Table 4 of 0.16-0.15 p.p. for orderly and disorderly transitions. Under two models —GCAM and MESSAGE— some eurozone 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 mid-2030s; (iii) 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 risk without a debt increase.

4.3.2 Interest rates

We repeat the main tests for the low interest rates of Appendix Figure B.1, Panel B. In Table 5, we report the fiscal adjustments required to stabilize the current high debt levels.[17] We find that with low interest rates, more countries besides Germany (India, UK, Australia, Austria, Italy, Netherlands) have stable debts. The rest require significantly lower fiscal effort to stabilize their debt than under the medium interest rates.

[Insert Table 5 Near Here]

We perform DSA under transition using REMIND and estimate the fiscal effort to offset the debt increase. We report the results in Table 6 together with the corresponding results under medium rates from Tables 3-4. The fiscal effort required to offset transition debts is significantly reduced under low interest rates and is zero for the UK, Australia, Austria, and Italy. (Fan charts of debt dynamics are shown in Appendix Figure C.2.) Offsetting transition debts is much easier under low rates, as expected, with most countries in our sample requiring fiscal adjustments below 0.10 p.p. However, the conclusion that transition puts upward pressure on debt remains valid.

[Insert Table 6 Near Here]

5 The Porter hypothesis

We test whether the Porter hypothesis's green growth can offset the transition debts. Following the Paris Agreement goals of reducing emissions by 45% by 2030 and reaching net zero by 2050, we assume that the transition will be completed by 2050 with significant changes noticeable from 2030. Hence, we consider a long-term Porter-hypothesis green growth that increases linearly from its steady state by GDP^{+}_{G} by 2050. We compute the value that stabilizes debt with probability 0.75; see Table 7.

[Insert Table 7 Near Here]

We observe that under medium rates, cross-country average green growth of 0.5% (orderly) and 0.6% (disorderly) could offset transition debts, but with significant differences among countries; US requires up to 1.9% and Australia 0.4%. The required average green growth under low rates is 0.3% (orderly) to 0.5% (disorderly). Australia, Austria, Ger-

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

many, 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.

6 Carbon tax recycling

An underlying assumption of the Battiston-Monasterolo model applied to the estimation of transition spreads is that a shock in the CPRS results in a proportional shock to both fiscal revenues and investments and subsidies for each energy sector. To study the effect of recycling carbon tax revenues that may accrue to the government during the transition into debt repayment, we follow Darracq, Dees, De Gaye, Parisi, and Sun (2023), who studied the impact of tax recycling on GDP. That is, instead of assuming that transition effects are reflected in the spreads under fiscal neutrality, we consider recycling (part of) the carbon taxes to repay debt while the government finances (part of) the transition.

We obtain carbon taxes from REMIND and use our model to account for the government's carbon tax revenues and transition spending. We adopt "a balanced approach, where the share of the mitigation effort undertaken by the public sector ranges from 25% to 40% between 2030 and 2050" (Seghini and Dees, 2024), and assume that 50% of the carbon taxes are recycled into debt while the government pays one-third of the 3% GDP p.a. transition investments until 2050. REMIND accounts for the effects of carbon taxes on real GDP and inflation but not for recycling effects. However, (Darracq et al., 2023, Chart 10) find that recycling all carbon taxes into debt repayment has a marginal effect on GDP; real GDP will decrease by about -1.5% by 2050 and inflation increase by 0.15 p.p. Hence, we abstract from any tax recycling effects on growth.

We display the results in Figure 7 and make two observations consistent with our main findings. First, there are no significant differences in the long-run debt trajectories under orderly or disorderly transitions; both transitions result in debt increases for all major economies by 2070, except for India, which is projected to run persistently high carbon taxes. Second, the long-term debts align with our estimates using Battiston-Monasterolo, although not the same given the different assumptions on the fiscal effects of transition underlying the two approaches.

[Insert Figure 7 Near Here]

We also tested the extreme case of 100% tax recycling into debt repayments without any government transition investments and found that debt is put on a downward trajectory under both orderly and disorderly transitions (not shown) for all economies. The resulting debt reduction aligns with the findings of the corresponding test of (Darracq et al., 2023, Chart 10). They find a debt reduction of about 10% by 2040 for the eurozone, with our estimates ranging from 8% for the UK and Germany to 13% for Italy. Under 50% tax recycling and no government transition investments, debt is on a downward trajectory under orderly transition while it stays at about its no-transition projections under disorderly (Appendix Figure C.3).

In conclusion, carbon tax recycling can improve debt sustainability but is offset by any government spending on transition financing. Striking the right balance between carbon tax recycling and government spending on the transition requires further study.

7 Conclusion

Our work contributes a study of the transition risk channel to the literature on climate change effects on sovereign debt. We developed a debt sustainability analysis model and calibrated it on a sample of developed economies to study the effects of an orderly or disorderly transition to a low-carbon economy on sovereign debt sustainability.

We find that transition has a significant impact on debt financing tradeoffs. It puts upward pressure on debt stock with increases for most countries starting from the mid-2030s, with potentially unsustainable debt dynamics. Modest but persistent fiscal adjustments can offset the countries' transition debts without significant differences between orderly and disorderly transitions. The problem is exacerbated by the current high debt levels, with relatively large adjustments required under transition if countries fail to stabilize their current debt levels. Our findings are consistent under the three IAMs, although two of the IAMs suggest that some eurozone countries can weather the transition risk without a debt increase. Our findings are qualitatively the same but quantitatively muted if we assume very low long-term interest rates as a result of the transition.

We find that modest green growth can offset the transition debts. Carbon tax recycling's positive impact on debt sustainability is offset by any government expenditures on transition financing. Striking the right balance requires further work on the growth effects of recycling policies, opening an avenue for further investigations.

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Figure 1 – Primary balance to stabilize current and transition debts

This figure displays the primary balance required to stabilize the current high debt levels and the orderly transition debt increases under the REMIND, GCAM, and MESSAGE integrated assessment models. **x** denotes the historical average primary balance used for the long-term projections in the transition DSA, red bars denote the range of estimates under the three IAMs, and the arrows indicate the required fiscal adjustments. 3% is the maximum primary balance sustained over long periods of historical fiscal adjustment episodes reported in Eichengreen and Panizza (2016).

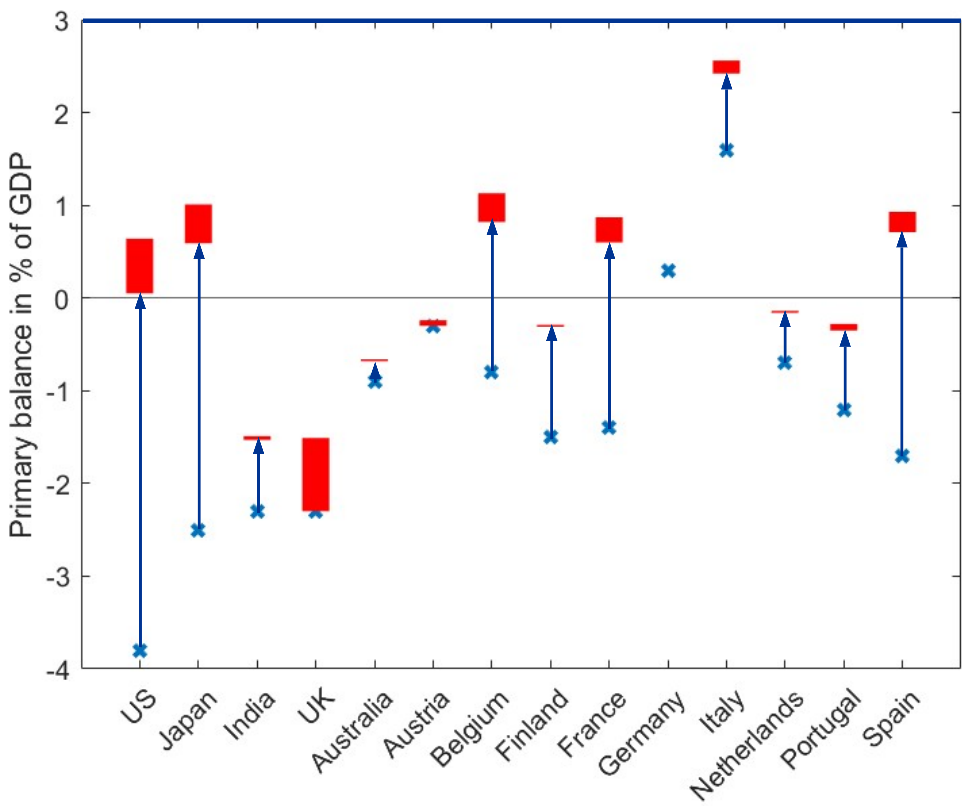


Figure 2 – Scenario tree and stochastic debt dynamics

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 $\nu \in \mathcal{N}_T$ is a scenario.

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

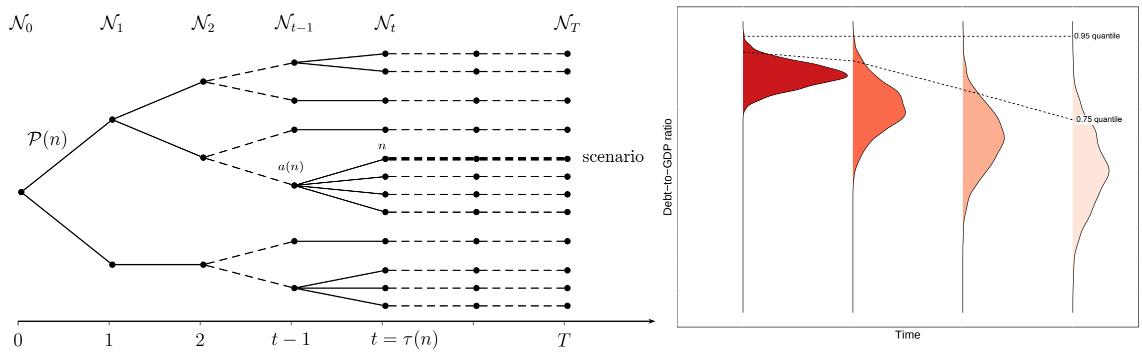


Figure 3 – Default probabilities under orderly and disorderly transition

This figure displays the changes in default probabilities for the sample of major economies calculated from eqn. (9) under (a) orderly and (b) disorderly transitions, using projections from the REMIND, GCAM, and MESSAGE integrated assessment models until 2070.

(a) Orderly (b) Disorderly

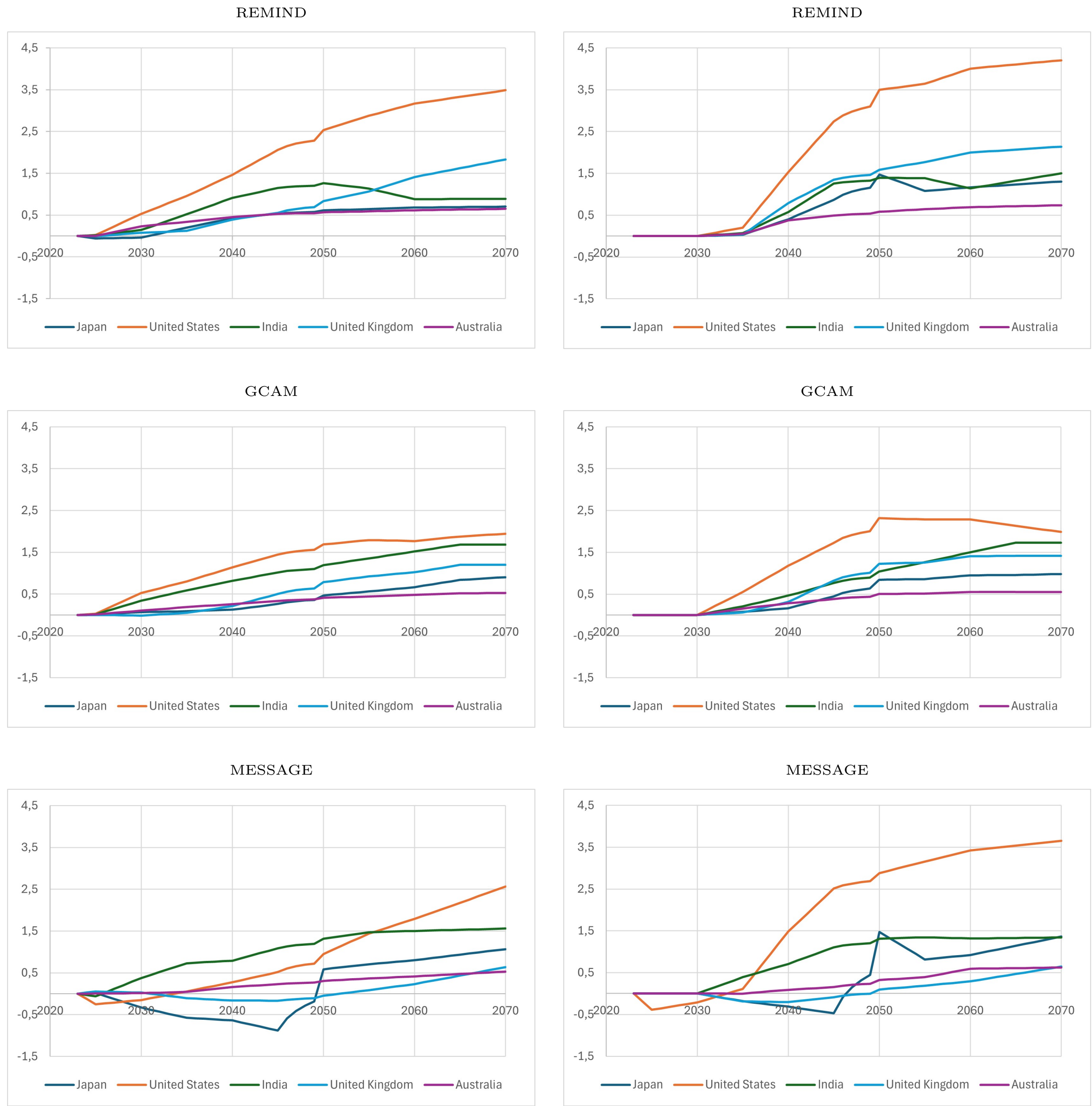
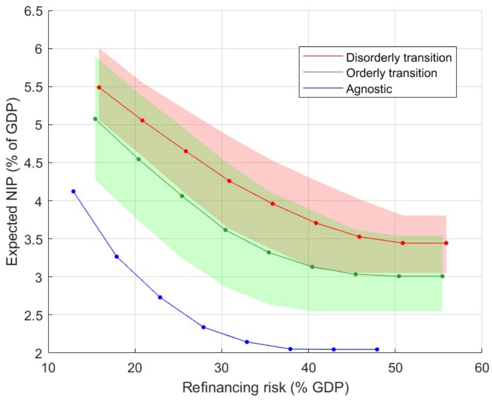


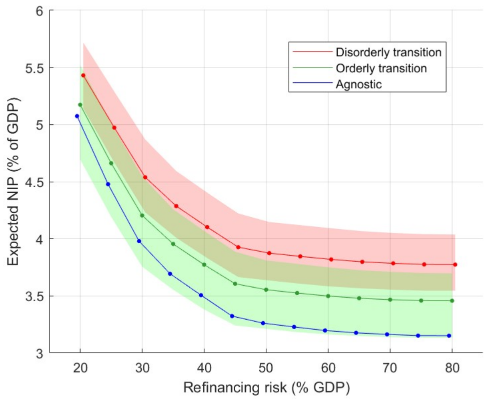
Figure 4 – The cost-risk tradeoff under transition risk

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

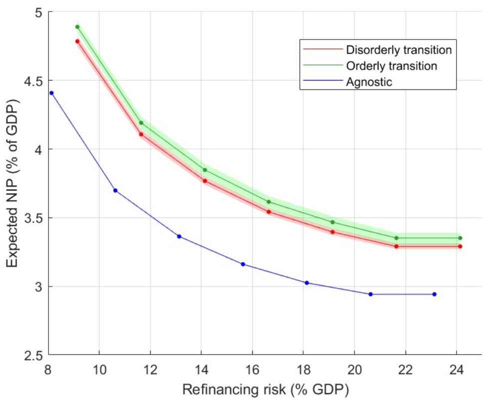
US



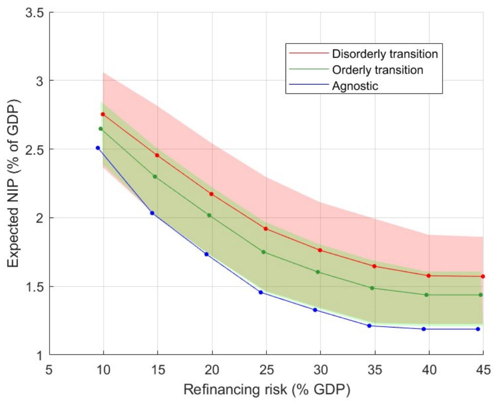
Japan



India



UK



Australia

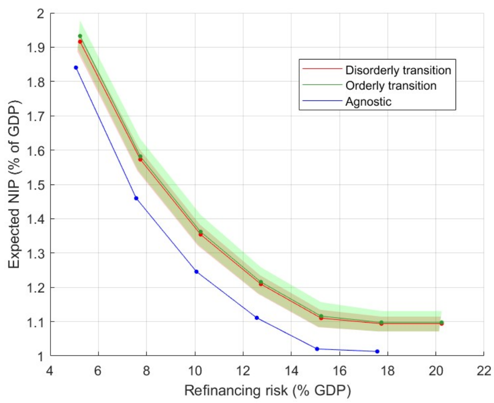
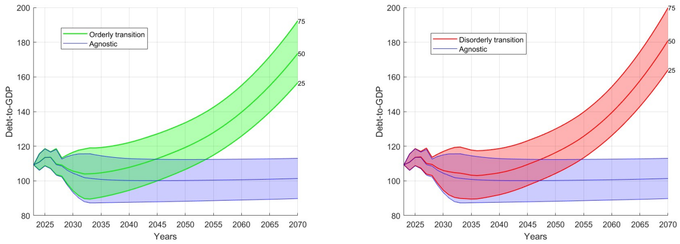


Figure 5 – Transition effects on debt dynamics

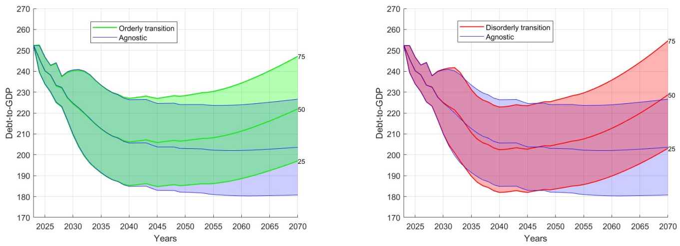
This figure shows debt stock dynamics fan charts with transition risk under (a) orderly (green) and (b) disorderly (red) transitions, using REMIND. The fan charts are overlayed on the fan charts of the stabilized debt with the agnostic DSA (blue). The solid lines display the 0.25, 0.50, and 0.75 percentiles.

(a) Orderly (b) Disorderly

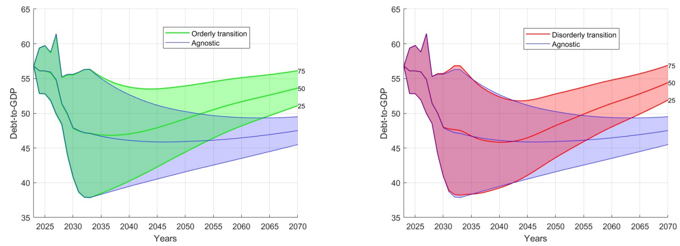
US



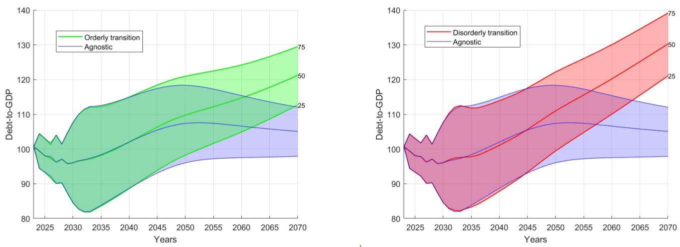
Japan



India



UK



Australia

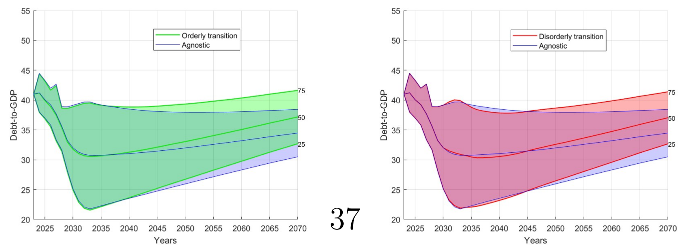
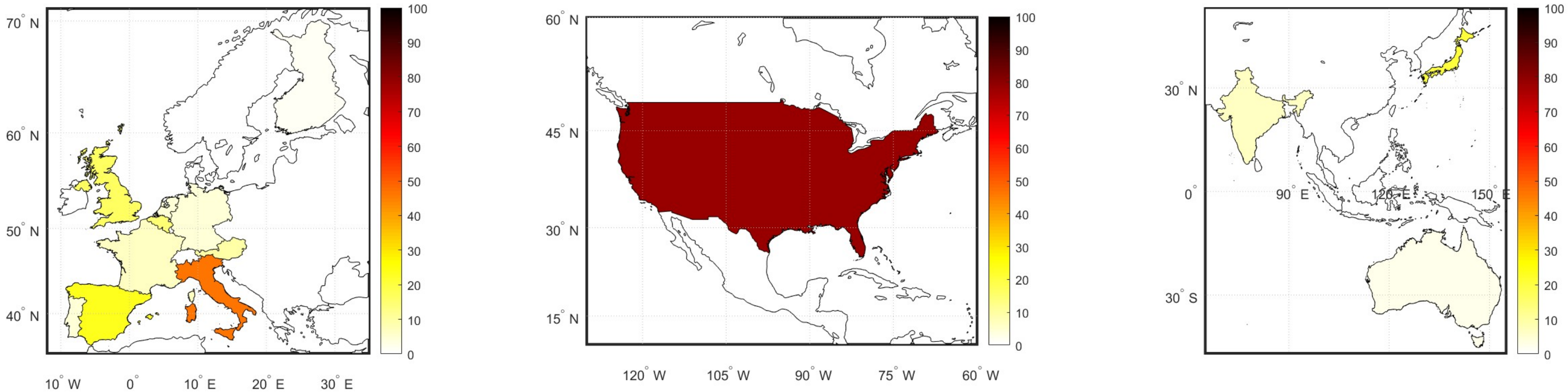


Figure 6 – Sovereign debt increases from transition risk at 2070

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 100 p.p.

(a) Debt increase after stabilizing current debt levels



(b) Debt increase without stabilizing current debt levels

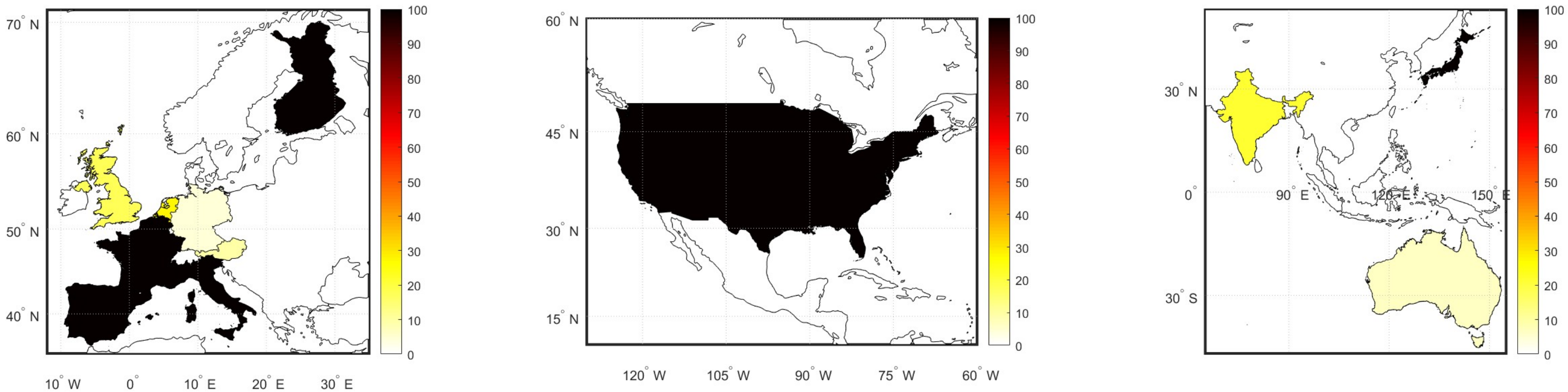
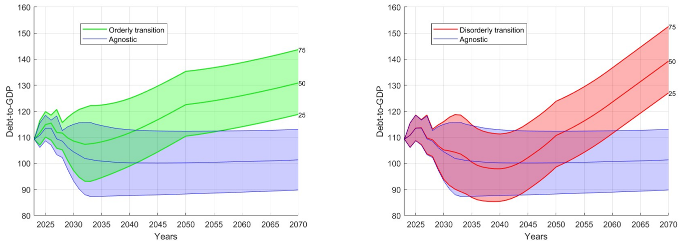


Figure 7 – Transition effects on debt dynamics under carbon tax recycling

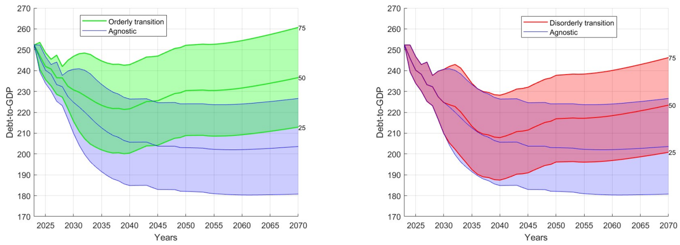
This figure shows debt stock dynamics fan charts with transition risk under (a) orderly (green) and (b) disorderly (red) transitions, using REMIND. 50% of the carbon taxes are recycled to pay debt, and 1% of GDP is used to finance the transition. The fan charts are overlayed on the fan charts of the stabilized debt with the agnostic DSA (blue). The solid lines display the 0.25, 0.50, and 0.75 percentiles.

(a) Orderly (b) Disorderly

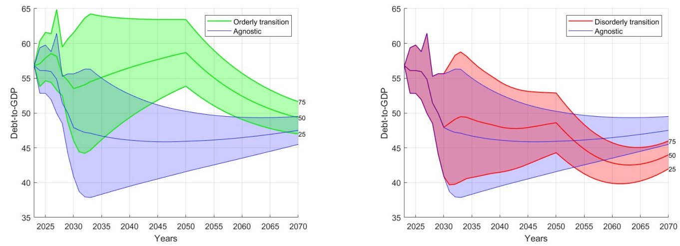
US



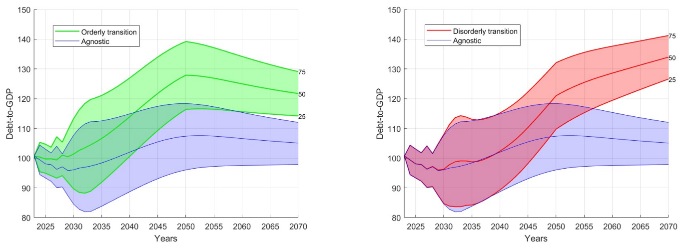
Japan



India



UK



Australia

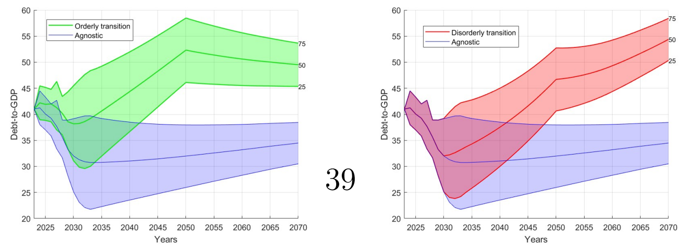


Table 1 – Estimation of transmission coefficient β

This table displays the coefficients estimated from regression (22) 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 when the debt ratio is 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 is a dummy variable taking value 0 before the Paris Agreement and one otherwise. The asterisks ***, **, 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**	0.013
$D\cdot$ 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

Table 2 – Fiscal adjustments to stabilize current debts without energy transition

This table displays the 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 DSA.

	Adj	PB*
US	3.32	-0.48
Japan	3.08	0.59
India	0.54	-1.76
UK	0.00	-2.30
Australia	0.12	-0.78
Austria	0.00	-0.30
Belgium	1.62	0.82
Finland	1.19	-0.31
France	2.00	0.60
Germany	0.00	0.30
Italy	0.48	2.08
Netherlands	0.41	-0.29
Portugal	0.85	-0.35
Spain	2.28	0.59
Average	1.14	-0.11

Table 3 – Debt increases under transition risk

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 stabilized 2070 debts with countries running the debt-stabilizing primary balances PB* from Table 2 without energy transition. 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	72.72	78.78	43.36	48.39	24.06	26.76	48.66	52.02
Japan	18.38	20.51	9.84	10.98	-7.04	-6.23	25.42	26.74
India	6.12	6.62	8.23	8.85	8.45	9.11	2.33	2.49
UK	16.16	17.44	11.19	12.10	0.39	0.44	15.77	17.00
Australia	2.69	3.19	1.81	2.10	1.50	1.74	1.19	1.45
Austria	6.43	9.68	4.12	5.82	-13.07	-11.00	19.50	20.68
Belgium	10.52	15.27	0.20	0.29	6.64	10.03	10.32	14.98
Finland	1.46	1.66	-1.58	-1.18	-5.62	-4.32	7.08	5.98
France	5.20	8.11	-2.53	-1.46	-4.00	-2.45	9.20	10.56
Germany	4.53	5.30	2.81	3.30	2.73	3.20	1.80	2.10
Italy	26.36	46.71	21.42	39.16	4.63	10.34	21.73	36.37
Netherlands	3.89	4.74	2.64	3.16	3.05	3.71	1.25	1.58
Portugal	3.39	5.05	0.96	1.09	-0.55	-0.42	3.94	5.47
Spain	13.72	23.85	3.59	6.01	6.34	11.51	10.13	17.84
Average	13.68	17.64	7.58	9.90	1.97	3.74	11.72	13.89
(a) Disorderly								
US	80.36	86.29	48.50	51.19	64.22	68.55	31.86	35.10
Japan	25.15	27.97	17.04	19.01	8.25	9.20	16.90	18.77
India	6.90	7.39	7.08	7.57	7.09	7.62	0.19	0.23
UK	25.17	27.06	16.43	17.70	0.72	0.74	24.45	26.32
Australia	2.57	2.95	1.94	2.25	1.61	1.84	0.96	1.11
Austria	9.14	13.77	6.51	9.79	-14.24	-12.02	23.38	25.79
Belgium	12.59	18.15	7.66	11.33	6.87	10.34	5.72	7.81
Finland	2.10	2.37	-0.08	-0.04	-6.19	-4.76	8.29	7.13
France	5.37	8.25	0.63	0.95	-4.35	-2.66	9.72	10.91
Germany	5.41	6.36	3.77	4.41	2.72	3.20	2.69	3.16
Italy	35.00	58.01	30.33	52.10	3.25	8.49	31.75	49.52
Netherlands	5.39	6.51	3.95	4.78	3.25	3.94	2.14	2.57
Portugal	6.19	9.48	3.62	5.40	-0.53	-0.39	6.72	9.87
Spain	21.31	36.70	11.31	19.76	6.63	12.02	14.68	24.68
Average	17.33	22.23	11.34	14.73	5.66	7.58	17.86	19.00

Table 4 – Fiscal adjustments to offset transition debts

This table displays the fiscal adjustments required to offset the debts under (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	-0.48	1.12	45	50.18	0.75	45	33.75	0.53	44	23.32	0.59
Japan	0.59	0.42	47	19.74	0.32	47	15.04	0.00	-	0.00	0.42
India	-1.76	0.23	47	10.81	0.26	47	12.22	0.27	47	12.69	0.04
UK	-2.30	0.79	44	34.76	0.68	44	29.92	0.00	-	0.00	0.79
Australia	-0.78	0.12	43	5.16	0.10	43	4.26	0.10	43	4.11	0.02
Austria	-0.30	0.06	43	2.41	0.00	-	0.00	0.00	-	0.00	0.06
Belgium	0.82	0.31	8	2.48	0.00	-	0.00	0.18	9	1.62	0.31
Finland	-0.31	0.02	43	0.86	0.00	-	0.00	0.00	-	0.00	0.27
France	0.60	0.27	6	1.62	0.00	-	0.00	0.00	-	0.00	0.27
Germany	0.30	0.00	-	0.00	0.00	-	0.00	0.00	-	0.00	0.00
Italy	2.08	0.48	10	4.80	0.48	8	3.84	0.34	3	1.02	0.14
Netherlands	-0.29	0.15	47	7.05	0.13	47	6.11	0.13	47	6.30	0.02
Portugal	-0.35	0.07	47	3.51	0.00	-	0.00	0.00	-	0.00	0.07
Spain	0.58	0.13	47	6.11	0.35	8	2.80	0.35	9	3.15	0.22
Average	-0.11	0.30	34	10.68	0.22	21	7.71	0.14	14	3.73	0.16
(b) Disorderly											
US	-0.48	1.29	44	56.76	0.83	45	37.35	1.07	45	48.15	0.46
Japan	0.59	0.65	47	30.55	0.46	47	21.62	0.36	47	16.92	0.29
India	-1.76	0.25	47	11.61	0.24	47	11.28	0.25	47	11.52	0.01
UK	-2.30	0.92	44	40.48	0.79	44	34.76	0.00	-	0.00	0.92
Australia	-0.78	0.13	43	5.59	0.10	43	4.30	0.10	43	4.12	0.03
Austria	-0.30	0.09	47	4.23	0.05	47	2.35	0.00	-	0.00	0.09
Belgium	0.82	0.42	9	3.78	0.27	8	2.16	0.25	8	2.00	0.17
Finland	-0.31	0.04	43	1.63	0.00	-	0.00	0.00	-	0.00	0.04
France	0.60	0.33	6	1.98	0.34	1	0.34	0.00	-	0.00	0.34
Germany	0.30	0.00	-	0.00	0.00	-	0.00	0.00	-	0.00	0.00
Italy	2.08	0.49	15	7.35	0.48	12	5.76	0.46	2	0.92	0.03
Netherlands	-0.29	0.18	47	8.46	0.15	47	7.05	0.14	47	6.58	0.04
Portugal	-0.35	0.13	47	6.11	0.08	47	3.81	0.00	-	0.00	0.13
Spain	0.58	0.24	47	11.28	0.11	47	5.17	0.39	9	3.51	0.28
Average	-0.11	0.37	35	13.56	0.28	31	9.71	0.22	18	6.69	0.15

Table 5 – Fiscal adjustments to stabilize current debts without energy transition for low rates

This table displays the 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 DSA.

	Medium rates		Low rates	
	Adj	PB*	Adj	PB*
US	3.32	-0.48	2.21	-1.59
Japan	3.08	0.59	1.04	-1.46
India	0.54	-1.76	0.00	-2.30
UK	0.00	-2.30	0.00	-2.30
Australia	0.12	-0.78	0.00	-0.90
Austria	0.00	-0.30	0.00	-0.30
Belgium	1.62	0.82	0.68	-0.12
Finland	1.19	-0.31	0.88	-0.62
France	2.00	0.60	1.27	-0.13
Germany	0.00	0.30	0.00	0.30
Italy	0.48	2.08	0.00	1.60
Netherlands	0.41	-0.29	0.00	-0.70
Portugal	0.85	-0.35	0.35	-0.85
Spain	2.28	0.58	1.51	-0.19
Average	1.14	-0.11	0.57	-0.68

Table 6 – Fiscal adjustment to offset transition debts for low rates

This table displays the fiscal adjustments required to offset the debts under (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 5.

	Medium rates				Low rates			
	PB*	Avg	Yrs	Total	PB*	Avg	Yrs	Total
				(a) Orderly				
US	-0.48	1.12	45	50.18	-1.59	1.08	44	47.52
Japan	0.59	0.42	47	19.74	-1.46	0.39	47	18.33
India	-1.76	0.23	47	10.81	-2.30	0.17	47	8.01
UK	-2.30	0.79	44	34.76	-2.30	0.00	-	0.00
Australia	-0.78	0.12	43	5.16	-0.90	0.00	-	0.00
Austria	-0.30	0.06	43	2.41	-0.30	0.00	-	0.00
Belgium	0.82	0.31	8	2.48	-0.12	0.10	47	4.70
Finland	-0.31	0,02	43	0.86	-0.62	0.02	43	0.73
France	0.60	0.27	6	1.62	-0.13	0.06	47	2.90
Germany	0.30	0.00	-	0.00	0.30	0.00	-	0.00
Italy	2.08	0.48	10	4.80	1.60	0.00	-	0.00
Netherlands	-0.29	0.15	47	7.05	-0.70	0.09	47	4.04
Portugal	-0.35	0.07	47	3.51	-0.85	0.08	47	3.90
Spain	0.58	0.13	47	6.11	-0.19	0.17	47	8.04
Average	-0.11	0.30	34	10.68	-0.68	0.15	30	7.01
				(b) Disorderly				
US	-0.48	1.29	44	56.76	-1.59	1.24	44	54.56
Japan	0.59	0.65	47	30.55	-1.46	0.64	47	30.08
India	-1.76	0.25	47	11.61	-2.30	0.22	47	10.34
UK	-2.30	0.92	44	40.48	-2.30	0.38	44	16.72
Australia	-0.78	0.13	43	5.59	-0.90	0.00	-	0.00
Austria	-0.30	0.09	47	4.23	-0.30	0.00	-	0.00
Belgium	0.82	0.42	9	3.78	-0.12	0.17	47	7.99
Finland	-0.31	0.04	43	1.63	-0.62	0.04	43	1.51
France	0.60	0.33	6	1.98	-0.13	0.08	47	3.76
Germany	0.30	0.00	-	0.00	0.30	0.00	-	0.00
Italy	2.08	0.49	15	7.35	1.60	0.00	-	0.00
Netherlands	-0.29	0.18	47	8.46	-0.70	0.12	47	5.64
Portugal	-0.35	0.13	47	6.11	-0.85	0.15	47	7.05
Spain	0.58	0.24	47	11.28	-0.19	0.29	47	13.63
Average	-0.11	0.37	35	13.56	-0.68	0.24	33	10.81

Table 7 – 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
Portugal	0.3	0.4	0.3	0.4
Spain	0.7	0.9	0.6	0.8
Average	0.5	0.6	0.3	0.5

Online Appendix

Are sovereign debts sustainable under energy transition?

Veronica Mammeti, Stavros A. Zenios, Giacomo Morelli

A The scenario optimization model

A.1 Debt refinancing risk constraint

Following Rockafellar and Uryasev (2002), we compute aggregate conditional Flow-at-Risk (cf. eqn. 17) on the tree, denoted by $gfn^{\diamond\diamond}$, using the following linear system

$$gfn^{\diamond\diamond} = gfn^{\diamond} + \frac{1}{1-\alpha}\sum_{n\in\mathcal{N}} p^{\nu} z^{\nu} \tag{24}$$

$$z^{\nu} \geq gfn_t^{\nu} - gfn^{\diamond},\ n \in \mathcal{N} \tag{25}$$

$$z^{\nu} \geq 0,\ n \in \mathcal{N}, \tag{26}$$

and the flow risk constraint (20) becomes

$$gfn^{\diamond\diamond} \leq \omega. \tag{27}$$

Since $n \in \mathcal{N}$ is equivalent to $n \in \mathcal{N}_t$ for all $t = 0, 1, 2, \ldots T$, it follows that eqn. (25) with time indexed gfn_t^{ν} but time independent z^{ν}, is well defined.

Bounding the aggregate tail risk by a threshold does not guarantee that the refinancing risk will be below the threshold at each period. It may exceed the threshold at some time t' at the α confidence level of the distribution $gfn_{t'}$, and t' will be a *hot spot.* In several tests of the model on multiple countries, we consistently found that the aggregated formulation also limits the risk at every period. However, an unusually large spike in legacy debt could create a hot spot. In such a case, we can impose CFaR constraints at the hot spot to shape risk. We define $gfn_{t'}$ over states $\mathcal{N}_{t'}$ at t', and compute the CVaR for gross financing needs at t',

$$\Psi(gfn_{t'}) \doteq \mathbb{E}\left(gfn_{t'} \mid gfn_{t'} \geq gfn_{t'}^{\diamond}\right), \tag{28}$$

where $gfn_{t'}^{\diamond}$ is the right α-percentile. The disaggregated risk measure can also be formulated using linear inequalities.

A.2 Debt stock and flow state-dependent dynamics

To give the accounting identities for debt dynamics, for states $\nu \in \mathcal{N}_t$ at $t = 0, 1, 2, \dots T$, on the tree structure, we use the state-dependent indicator function $\mathbb{1}^{\tau(\nu)}(j, \tau(m))$ to keep track of maturing endogenous debt,

$$\mathbb{1}^t(j, \tau(m)) = \begin{cases} 1, \text{ if instrument } j \text{ issued at } \tau(m) \text{ matures at } t = \tau(\nu), \text{ where } m \in \mathcal{P}(\nu), \\ 0, \text{ otherwise.} \end{cases}$$

The flow dynamics equation on the tree is written as

$$GFN_t^\nu = \underbrace{I_t^\nu + A_t^\nu}_{\substack{\text{Legacy service} \\ \text{payments}}} - \underbrace{PB_t^\nu}_{\substack{\text{Primary} \\ \text{balance}}} \tag{29a}$$

$$+ \underbrace{\sum_{m \in \mathcal{P}(n)} \sum_{j=1}^{J} X_{\tau(m)}^m(j)\, CF_t^\nu(j, m)}_{\substack{\text{Interest payment} \\ \text{of debt financing decisions}}} \tag{29b}$$

$$+ \underbrace{\sum_{m \in \mathcal{P}(n)} \sum_{j=1}^{J} X_{\tau(m)}^m(j)\, \mathbb{1}^t(j, \tau(m))}_{\substack{\text{Principal amortization} \\ \text{of debt financing decisions}}}\,. \tag{29c}$$

The debt stock dynamics can be expressed in terms of flows on the tree,

$$D_t^\nu = D_{t-1}^{a(\nu)} + GFN_t^\nu - \sum_{m \in \mathcal{P}(n)} \sum_{j=1}^{J} X_{\tau(m)}^m(j)\, \mathbb{1}^t(j, \tau(m)) - A_t^\nu. \tag{30}$$

Substituting (29) into (30), we link financing decisions to the effective interest rate on debt

$$D_t^\nu = D_{t-1}^{a(\nu)} + I_t^\nu - PB_t^\nu + \sum_{m \in \mathcal{P}(\nu)} \sum_{j=1}^{J} X_{\tau(m)}^m(j)\, CF_t^\nu(j, m). \tag{31}$$

The *effective cost of debt* i_t at state ν is given by

$$i_t^\nu = \frac{I_t^\nu + \sum_{m \in \mathcal{P}(\nu)} \sum_{j=1}^{J} X_{\tau(m)}^m(j)\, CF_t^\nu(j, m)}{D_t^\nu}. \tag{32}$$

The numerator is the net interest payment optimized in the objective function (19).

The complete model on the scenario tree consists of the decision variable definitions, objective function (19), flow risk constraint (27), flow (29) and stock (31) dynamics, and the interest rate equation with transition risk (7).

B Data

Table B.1 – Sources of input data

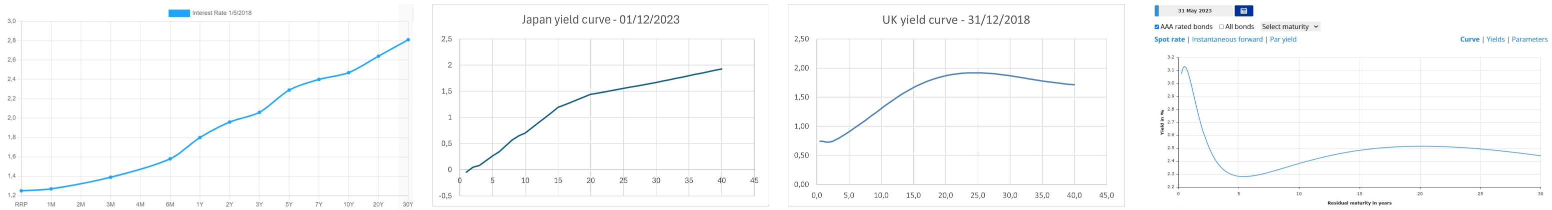
Variable	Source
Country debt	Eikon-Refinitiv
US spot yield curve	Federal Reserve Economic Data (FRED)
EU spot yield curve	European Central Bank
UK spot yield curve	Bank of England
Japan spot yield curve	Refinitiv
Primary balance	IMF Fiscal Monitor 2023
EU GDP growth	European Commission Ageing Report 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 B.1 – Yield curves

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

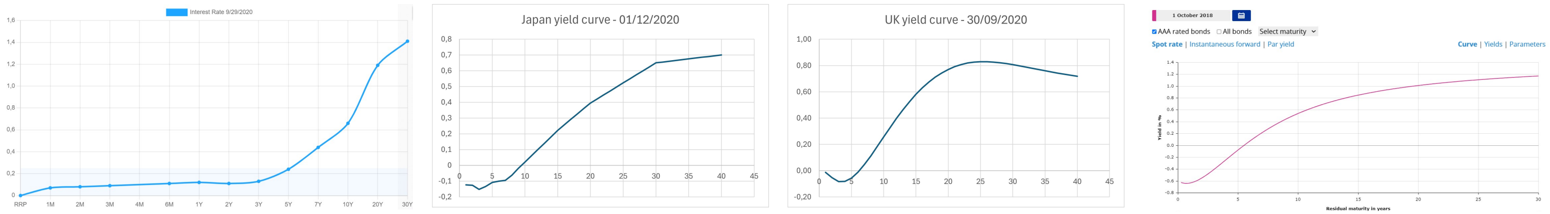
(a) Medium yields

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 B.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. We do not report GDP growth projections for the Eurozone countries as those are obtained on a yearly basis until 2070 from the 2024 European Commission Ageing Report of Table B.1.

	2023	2024	2025	2026	2027	2028	Long-term	StDev
(a) Growth rate								
US	5.8	3.8	3.9	4.0	4.0	4.0	3.7	2.2
Japan	5.6	4.2	2.9	2.2	2.1	2.2	2.6	2.1
India	10.5	10.7	10.7	10.7	10.6	10.5	11.8	4.5
UK	6.4	4.1	4.0	4.2	3.8	3.6	3.8	2.6
Australia	3.5	1.9	5.2	5.2	4.9	5.0	5.8	2.9
(b) Primary balance								
US	-5.5	-4.3	-4.2	-3.5	-3.0	-3.1	-3.8	3.6
Japan	-5.6	-6.4	-3.0	-2.7	-2.8	-2.8	-2.5	2.3
India	-3.4	-2.9	-2.5	-2.3	-2.2	-2.2	-2.3	1.8
UK	-2.0	-1.9	-1.5	-1.4	-1.6	-1.8	-2.3	3.4
Australia	-0.2	-0.7	-0.3	0.1	0.2	0.5	-0.9	2.7
Austria	-1.7	-0.8	-0.5	-0.2	-0.1	-0.1	-0.3	1.9
Belgium	-3.3	-3.0	-2.8	-3.0	-3.1	-3.0	-0.8	3.2
Finland	-2.1	-1.8	-2.4	-2.5	-2.5	-2.6	-1.5	3.4
France	-3.3	-2.7	-2.0	-1.5	-1.1	-0.9	-1.4	2.0
Germany	-1.4	-0.7	-0.4	0.0	0.2	0.4	0.3	2.1
Italy	0.4	0.8	1.8	2.2	2.7	3.2	1.6	2.2
India	-3.4	-2.9	-2.5	-2.3	-2.2	-2.2	-2.3	1.8
Netherlands	-2.1	-1.7	-1.5	-1.2	-1.3	-1.3	-0.7	2.5
Portugal	2.0	2.3	2.2	2.2	2.2	2.2	-1.2	2.6
Spain	-2.4	-1.3	-1.4	-1.5	-1.5	-1.5	-1.7	4.0

C Supplementary results

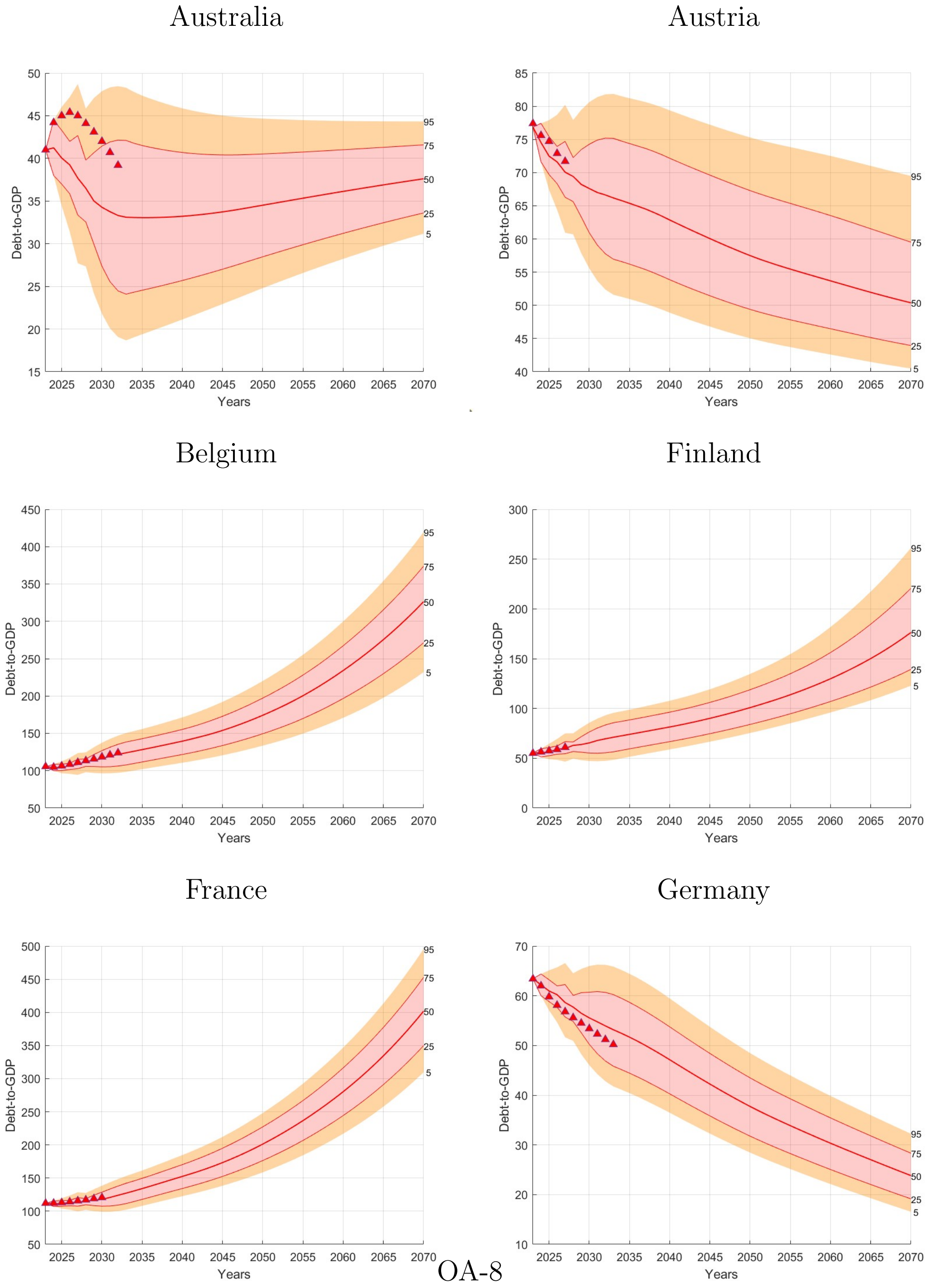
Table C.1 – Debt increases under transition risk for non-stabilized debt dynamics

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	103.80	108.30	62.46	65.23	31.68	32.66	72.12	75.64
Japan	29.28	31.46	16.52	17.66	0.44	-0.19	28.84	31.65
India	8.23	8.84	10.97	11.71	11.23	12.02	3.00	3.18
UK	16.16	17.44	11.19	12.10	0.39	0.44	15.77	17.00
Australia	2.93	3.43	1.97	2.26	1.63	1.87	1.30	1.56
Austria	6.43	9.68	4.12	5.82	-13.07	-11.00	19.50	10.68
Belgium	17.85	20.78	2.87	4.41	12.12	14.29	14.98	16.37
Finland	1.66	1.72	-7.51	-5.51	-22.60	-18.43	24.26	20.15
France	12.89	14.88	-4.98	-4.84	-9.66	-8.65	22.55	23.53
Germany	4.53	5.30	2.81	3.30	2.73	3.20	1.80	2.10
Italy	29.71	35.94	25.46	30.65	9.16	10.87	20.55	25.07
Netherlands	6.59	10.25	4.38	6.44	5.27	8.27	2.21	3.81
Portugal	6.21	7.49	-0.88	-0.17	-4.41	-2.85	10.62	10.34
Spain	33.05	39.21	10.15	12.44	16.22	19.15	22.90	26.77
Average	19.95	22.48	9.97	11.54	2.94	4.40	17.01	18.08
(b) Disorderly								
US	120.40	124.60	69.15	71.54	94.31	97.11	51.25	53.06
Japan	42.92	45.93	28.65	30.73	21.03	21.62	21.89	24.31
India	9.33	9.93	9.57	10.17	9.57	10.21	0.24	0.28
UK	25.17	27.06	16.43	17.70	0.72	0.74	24.45	26.32
Australia	2.79	3.17	2.11	2.42	1.76	1.99	1.03	1.18
Austria	9.14	13.77	6.51	9.79	-14.24	-12.02	23.38	25.79
Belgium	22.07	26.65	12.88	15.51	11.91	14.27	10.16	12.38
Finland	3.03	3.21	-1.86	-1.29	-25.72	-20.98	28.75	24.19
France	14.19	16.67	1.51	1.67	-11.76	-10.60	25.95	27.27
Germany	5.41	6.36	3.77	4.41	2.72	3.20	2.69	3.16
Italy	36.42	36.45	32.56	40.16	6.94	8.49	29.48	31.67
Netherlands	8.91	13.50	6.67	10.46	5.56	8.70	3.35	4.80
Portugal	6.19	9.48	3.62	5.40	-0.53	-0.39	6.72	9.87
Spain	51.86	62.35	27.06	31.98	16.13	19.01	35.73	43.34
Average	26.00	28.90	15.82	18.07	8.15	9.90	17.86	19.00

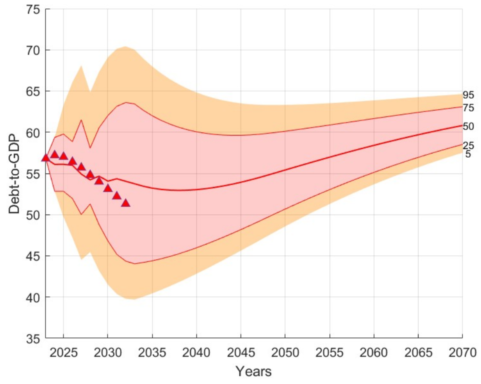
Figure C.1 – Consistency of agnostic DSA with IMF Article IV

This figure shows the debt-to-GDP ratio fan charts for our sample of countries with the agnostic DSA 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-to-GDP ratio is scaled to match the 2023 starting ratio from the sources of our analysis with average scaling ±5%.

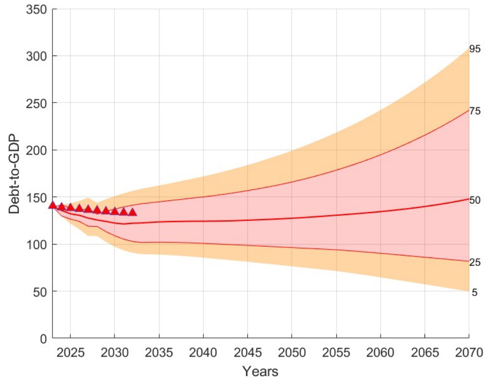


(continued)

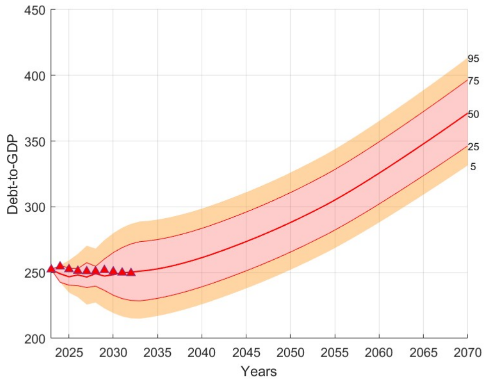
(a) India



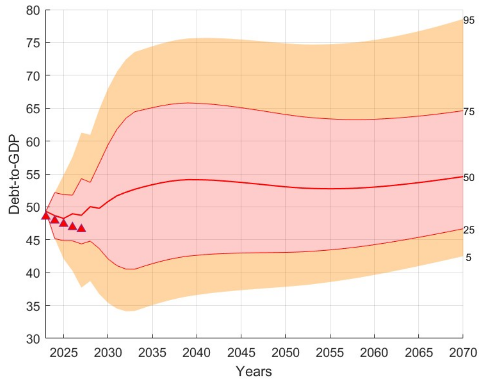
(b) Italy



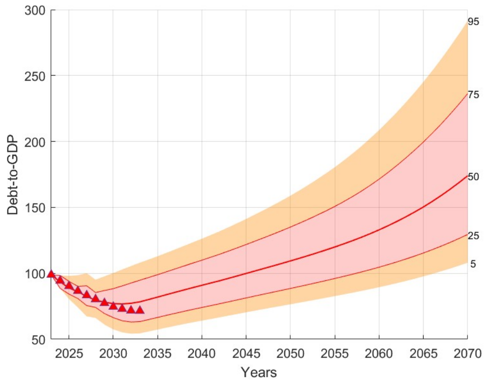
(c) Japan



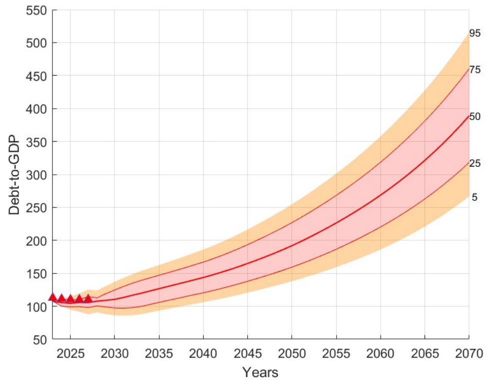
(d) Netherlands



(e) Portugal

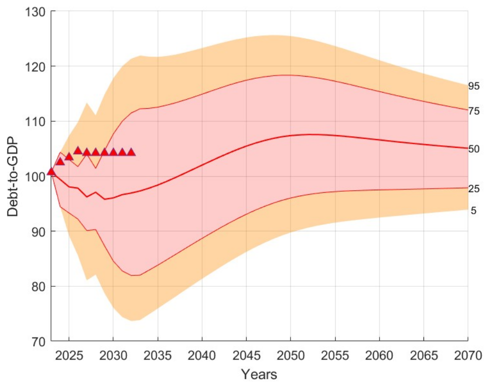


(f) Spain



(continued)

UK



US

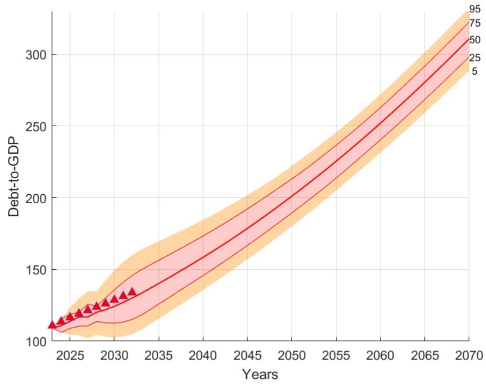
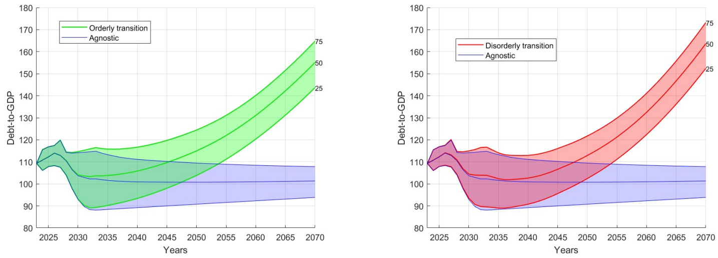


Figure C.2 – Transition risk effects on debt dynamics for low rates

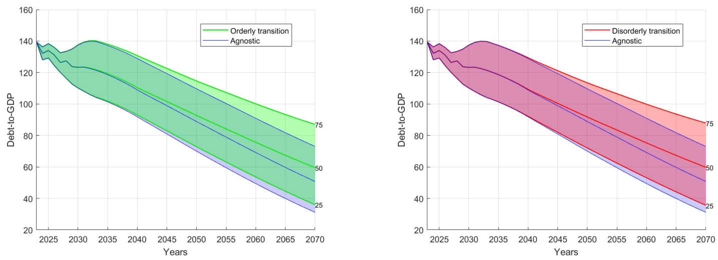
This figure shows the debt stock fan charts with transition risk under (a) orderly and (b) disorderly transition scenarios, using REMIND under low interest rates. The fan charts are overlayed on the debt dynamics without transition risk (blue). The solid lines display the 0.25, 0.50, and 0.75 percentiles.

(a) Orderly (b) Disorderly

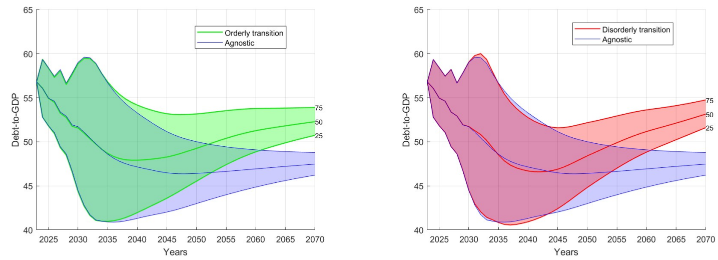
US



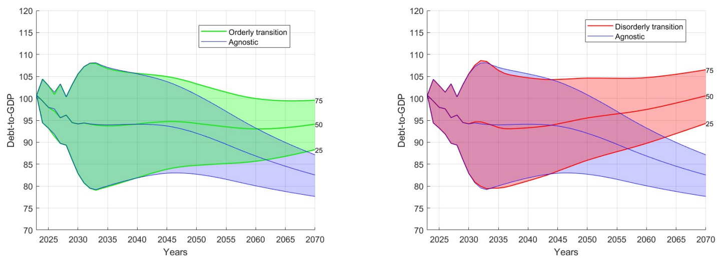
Italy



India



UK



Australia

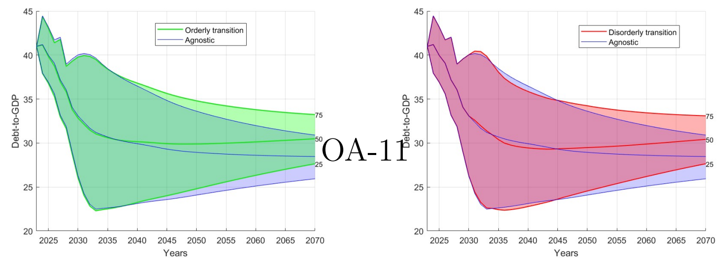
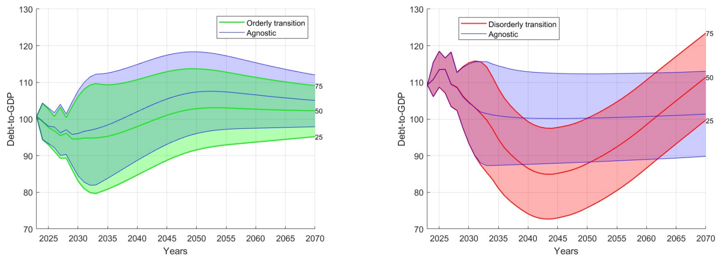


Figure C.3 – Transition effects on debt with 50% carbon tax recycling

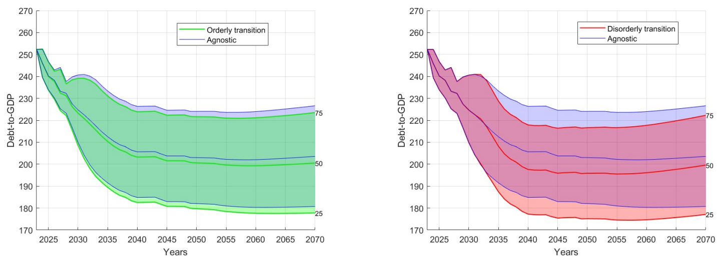
This figure shows the debt stock fan charts with transition risk under (a) orderly and (b) disorderly transition scenarios, using REMIND when 50% of the carbon taxes are recycled to pay the debt. The fan charts are overlayed on the debt dynamics without transition risk (blue). The solid lines display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

(a) Orderly (b) Disorderly

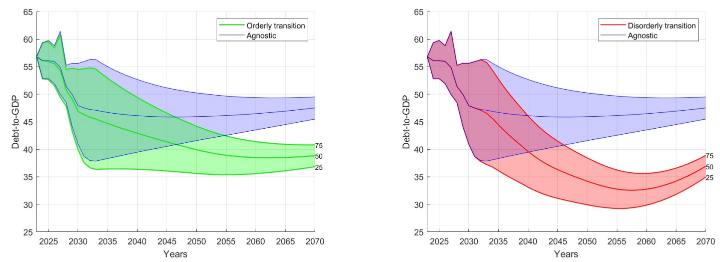
US



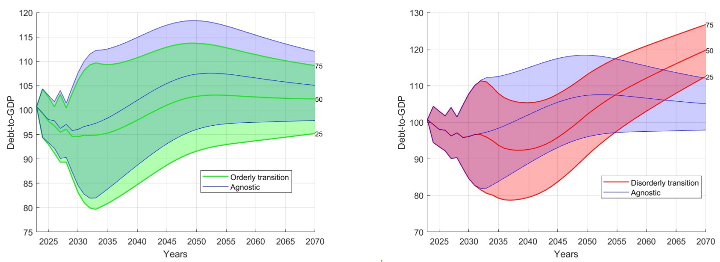
Japan



India



UK



Australia