Debt sustainability and monetary policy: The case of ECB asset purchases

Enrique Alberola[1] Gong Cheng[1] Andrea Consiglio[2] Stavros A. Zenios[3]

DRAFT: Do not cite or distribute.
Version of March 3, 2022.

Abstract

We develop a novel model of stochastic debt sustainability analysis under monetary policy interventions and evaluate the impact of unconventional policies on debt dynamics. The model uses a risk measure of debt stock and flow to trade off financing cost with refinancing risks subject to sustainability restrictions, and optimizes endogenously the financing strategies. We show that the pandemic emergency-purchase program (PEPP) induces a substantial improvement on debt sustainability for high-debt euro area countries. The improvement extends beyond the PEPP time horizon, with a scale dependent on the schedule of unwinding the asset purchases. We use the model to also study how PEPP can affect the financing strategies of debt management offices, the monetary-fiscal policy mix that stabilizes, or reduces, debt, and the implications of an inflation shock inducing monetary tightening.

Keywords: Debt sustainability analysis; risk management; unconventional monetary policy; monetary-fiscal mix; PEPP; CVaR optimization.

[1]Bank for International Settlement, Basel, Switzerland.
[2]University of Palermo, Palermo, Italy.
[3]University of Cyprus, Nicosia, CY, Cyprus Academy of Sciences, Letters, and Arts, Non-Resident Fellow, Bruegel, Brussels. Corresponding author zenios.stavros@ucy.ac.cy.

Contents

1 Introduction **4**

2 Debt sustainability analysis with monetary policymaking **10**
2.1 Public debt management 10
2.1.1 Debt dynamics 10
2.1.2 Uncertainty and a risk measure 11
2.1.3 The DSA Model 13
2.2 Macroeconomic framework and monetary policy regimes 15
2.2.1 Macroeconomic framework 15
2.2.2 Risk and term premia under conventional monetary policy 16
2.2.3 Unconventional monetary policy with asset purchase programs . . 17
2.3 DSA with monetary policy 17

3 The effect of PEPP on sovereign spreads **19**
3.1 Empirical estimation of the counterfactual 19
3.2 Statistical calibration of PEPP induced spreads 19

4 Model at work **24**
4.1 Data 24
4.2 Counterfactual 24
4.3 Debt sustainability with PEPP 25
4.4 Fiscal-monetary policy mix for debt stabilization 27
4.5 The cost-risk tradeoff 28
4.6 Optimal debt financing strategies with PEPP 30
4.7 Inflation shock 32

5 Conclusion **34**

A Data Appendix **1**
A.1 Conventional monetary policy 1
A.2 Scenario tree 1
A.3 Risk and term premia 1
A.4 Inflation shock 3
A.5 Legacy debt 3

B A model fitting sovereign spreads to PEPP **3**

C Additional results **6**

List of Figures

1 Pandemic Emergency Purchase Program 6
2 Spread suppression with PEPP: Actual vs. counterfactual spread changes. 7
3 Modeling uncertain debt dynamics on a scenario tree. 12
4 Cost of debt financing and refinancing risks 14
5 Actual vs. fitted sovereign spreads (in basis points) 20
6 Spread suppression rates vs ECB holdings. 21
7 The PEPP spread suppression model for each country. 23
8 Debt sustainability analysis without PEPP 25
9 Debt sustainability analysis with PEPP 26
10 Stabilizing debt dynamics with extra fiscal effort 28
11 Reducing debt ratio to 100% with extra fiscal effort 29
12 Efficient frontiers of cost-risk tradeoffs 30
13 Fixed-cost risk reduction under PEPP 31
14 The effects of inflation shock under different monetary policy responses . 33
A.1 Fan charts from the scenario tree 2
A.2 Inflation shock and conventional monetary policy responses 4
A.3 Legacy debt of eurozone representative high-debt country 5
B.1 Diagnostic tests of a mixed-effects PEPP model of sovereign spreads. . . 5
C.1 Debt sustainability analysis without PEPP with different debt financing strategies 6
C.2 Debt sustainability analysis with PEPP of different unwinding schedules 7

List of Tables

1 Spread suppression models ranked by Akaike (AIC) and Bayesian (BIC) information criteria. 22
A.1 Parameters of the calibrated macroeconomic and monetary policy frameworks 1
A.2 Parameterisation 1
A.3 Moments for the calibration of a scenario tree 3

1 Introduction

Motivated by the strengthened nexus of monetary-fiscal policies, we integrate monetary policy into stochastic debt sustainability analysis (DSA) to study its impact on sovereign debt dynamics. This issue has increased in importance since the great financial crisis of 2008, as policy rates reached the zero lower bound and central banks in advanced economies started to implement unconventional monetary policies with large asset purchase programs. The Covid-19 emergency has further reinforced the nexus, raising concerns (BIS, 2020). We add to DSA a macroeconomic framework that includes standard IS and Philips curves to determine the output gap and inflation dynamics, and a Taylor rule to determine the short-term policy rate under conventional monetary policymaking. Importantly, we add an unconventional monetary policy regime through sovereign asset purchases. We apply the novel DSA model to evaluate the sovereign debt effects of the Pandemic Emergency Purchase program (PEPP) of the European Central Bank under alternative exit strategies.[1]

Basic macroeconomic models, starting with Mundell-Fleming, recognise the link among policies and the impact of inflation on fiscal accounts, but these interactions are constrained to the short term. In fact, conventional wisdom has monetary policy and inflation to be neutral in the long run, with real variables governing economic growth and fiscal dynamics. This view, together with the difficulties in predicting future interest rates, explain why the prevalent frameworks of debt sustainability analysis dismiss monetary policy. In the frameworks used by multilateral institutions, sovereign debt dynamics are determined by the initial level of debt, projected output growth, interest and exchange rates, and fiscal balance.[2]

The intensification of the monetary-fiscal nexus in recent years challenges some of the conventional wisdom. The deployment of unconventional monetary policies, as a response to the financial crisis or the pandemic, has removed large quantities of sovereign debt from the market, keeping interest rates low across the yield curve and reducing sovereign funding costs. In 2010, the ECB holdings of euro area government debt accounted for only 2% of total outstanding euro area government debt, but surged to 20.5% by end 2020. Likewise, the share of US government debt held by the Federal Reserves increased from 7.8% to 18.3% during the same period.[3] The removal of public debt from the markets and the duration of debt hoarding reduce credit risk and interest rates for government financing at medium and long-term maturities. The schedule of unwinding the purchases works in the opposite direction, and both can have a potentially significant effect on

[1] See urlwww.ecb.europa.eu/mopo/implement/pepp/html/index.en.html, accessed February 2022.

[2] See, among others, the DSA models of the International Monetary Fund, the European Central Bank, the European Commission, and the European Stability Mechanism (Bouabdallah, Checherita-Westphal, Warmedinger, de Stefani, Drudi, Setzer, and Westphal, 2017; Commission, 2020; IMF, 2021; Zenios, Consiglio, Athanasopoulou, Moshammer, Gavilan, and Erce, 2021)

[3] Data from Arslanalp and Tsuda (2014), with the euro area data excluding Latvia and Lithuania.

sovereign debt dynamics and debt sustainability. There is also a growing concern about fiscally driven inflation due to the helicopter money during the pandemic, according to the fiscal theory of the price level (Carlstrom and Fuerst, 2000; Cochrane, 2022). The long-term nexus between monetary and fiscal policy has been built and may persist, justifying the need for DSA to incorporate monetary policymaking.

We contribute to the literature a stochastic DSA model with a central bank pursuing conventional and/or unconventional monetary policy, in a partial-equilibrium setting of inflation, output gap, and risk free interest rates. In line with Zenios et al. (2021), our setting accounts for correlated deviations from the steady-state of the economic and monetary variables, using *scenario trees* calibrated to match historically observed volatilities and correlations. In line with current DSA practices, we model both debt stock and flow variables, and use a tail risk measure (Conditional Value-at-Risk) to draw conclusions with high confidence level. The model also preserves the unique, among DSA models, feature of our earlier work to optimize sovereign debt financing strategies in a trade off between the cost of debt and risk of debt refinancing, and it estimates the primary balance required to stabilize debt dynamics. Within this setting, we model the unconventional monetary policy as a spread suppression function of the central bank's asset purchase program. This is our methodologallows us to examine the impact of unconventional monetary policy on debt sustainability.[4]

We point out that monetary policy is scarcely mentioned in current DSA methods. The word "monetary policy" (or related "monetary variables" etc) appears only once in the ECB debt sustainability framework (Bouabdallah et al., 2017), in a context unrelated to DSA, and three times in the IMF (2021) framework to warn that monetary policy changes can render uninformative the DSA fan charts. None of the two reports mention "unconventional monetary policy" or "asset purchase programs", and to not include monetary policy in their DSA. The EC report (Commission, 2020) acknowledges that monetary policy in the eurozone has alleviated debt concerns and warns that results may change if monetary policy shifts. They discuss the asset purchase programs of the ECB in relation to the EU member states financing needs, and suggest a downward adjustment to the slope of the term structure by a fixed amount, to account for the unconventional monetary policy. Our methodological contribution is to fully integrate both conventional and unconventional policymaking in DSA.

Our innovation is relevant beyond the study of asset purchase programs, which are the focus of this paper. Specifically, introducing a central bank allows us to consider DSA for long-horizon problems such as those arising from the fiscal pressures from an ageing population (Dieppe and Guarda, 2015; Jensen and Nielsen, 1995; Kamiguchi and Tamai,

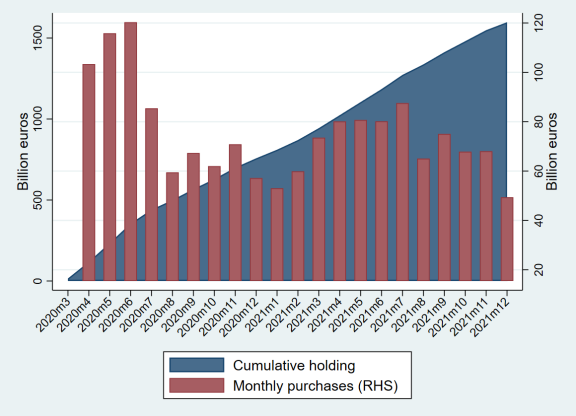
[4]The driver of spreads in our model is the credit risk calibrated on the ECB PEPP, but the model can be adapted to include term premia, which played a central role in other asset purchase programs, such as the Federal Reserve's Large-Scale Asset Purchases during the great financial crisis (Bowdler and Esteves, 2013; Gagnon et al., 2011).

2019) or from climate change (Boone et al., 2021; Zenios, 2021). For these long-horizon problems, extending to the end of the century, projections about monetary conditions from historical data are of limited reliability, whereas a central bank module provides theoretically sound projections.

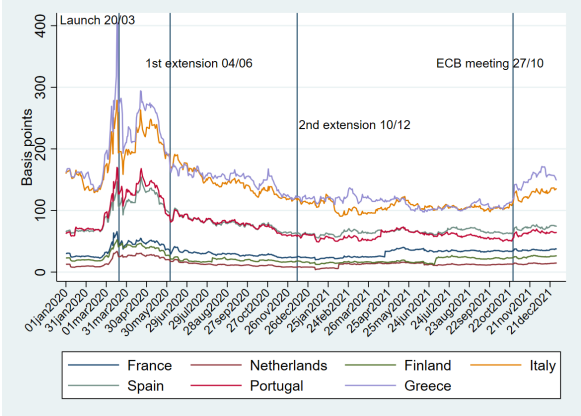
Our empirical contribution is to use the model to evaluate the sovereign debt effects of PEPP. This program was launched at the beginning of the COVID-19 pandemic in March 2020, enabling the ECB to purchase private and government securities to inject liquidity into the financial system. The initial envelope of the purchases was €750 billion, expanded to €1850bn in June and December 2020.[5] By December 2021, the ECB had purchased a total of €1598bn of euro area government securities, corresponding to 86% of the targeted envelope. From Figure 1 (Panel A), we observe that the purchase program started with the fastest pace, with the highest purchases between April and July 2020, with strong purchases during 2021 as well, before the ECB decided to dial back the pace in its policy meeting of December 2021. In that meeting, the ECB also decided to discontinue net asset purchases at the end of March 2022, while extending the horizon to reinvest the principal payments from maturing securities purchased under the program to the end of 2024. Net purchase will be conducted if deemed necessary by the ECB until the Covid-19 crisis is over.[6]

Figure 1 – Pandemic Emergency Purchase Program

(a) PEPP purchases



(b) Impact on sovereign 10-year spreads



The ECB purchases affect the quantity and the price of sovereign debt financing for the euro area governments and help to cover the higher borrowing requirements facing euro area governments during the pandemic. In 2020 the program financed more than 1.5 times Greece's borrowing needs, all of the Netherlands', and over 1/2 of the needs of

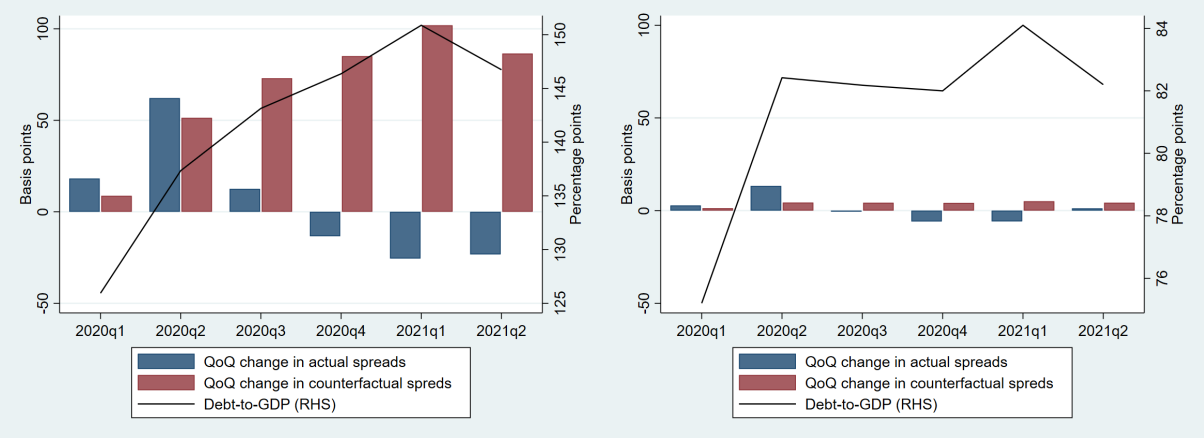
[5] All asset categories eligible under pre-existing ECB asset purchase programmes are also eligible under the PEPP, and a waiver has been granted for Greek Government bonds. The residual maturity of public sector securities eligible for purchase ranges from 70 days to 31 years.

[6] See the ECB Monetary policy decisions on 16 December 2021, `https://www.ecb.europa.eu/press/pr/date/2021/html/ecb.mp211216~1b6d3a1fd8.en.html`.

thirteen other euro area countries, including Portugal, Spain, and Germany. Its impact on sovereign financing costs, which is the focus of our paper, has been significant, as we can see from the euro sovereign 10-year bond spreads relative to the German Bund since 2020 in Figure 1 (Panel B). Spreads spiked at the wake of the pandemic, especially in fiscally vulnerable countries, raising debt sustainability concerns and thereby credit risks. With the announcement of the PEPP, the spreads fell and tightened further with the PEPP implementation, moving below the pre-pandemic level. With the speculation of early PEPP unwinding, which especially took place around the ECB monetary policy meeting in October 2021, some countries saw their financing costs rise again.

Figure 2 – Spread suppression with PEPP: Actual vs. counterfactual spread changes.

(a) Countries with lower ratings **(b)** Countries with higher ratings



To what extent did the PEPP provide relief to sovereign borowers with the onset of the pandemic? We show in Figure 2 a counterfactual analysis of changes in sovereign spreads after the announcement of the PEPP, together with the increase in sovereign debt-to-GDP ratios, using panel regressions, separately, for countries with lower and higher ratings.[7] The counterfactual is obtained by estimating the relationship between 10-year sovereign spreads and debt levels before the PEPP, and projecting the changes in sovereign spreads out-of-sample for the period from 2020Q1 onwards as the debt-to-GDP ratio increases. The red bars represent cumulative quarter-over-quarter changes in the spreads had the PEPP not been introduced, and the blue bars show the actual cumulative changes. Panel A shows significantly lower actual spreads then the counterfactual with the implementation of the PEPP from 2020Q2 onward, for the lower-rated countries. The spread compression is more than 100 basis points. The divergence of actual and counterfactual spreads is consistently noticeable in higher-rated countries (Panel B), but the spread suppression is an order of magnitude smaller. Indeed, one of the justifications of the PEPP was to avoid the segmentation of euro area debt markets between core and

[7]Lower-rated countries include Cyprus, Greece, Italy, Portugal, Spain; higher-rated countries include Belgium, Finland, France, Ireland, the Netherlands.

periphery Treasury that occurred during the euro area sovereign debt crisis (Battistini et al., 2014; Ehrmann and Fratzscher, 2017; Lane, 2012).

The rich setting of the model allows us to draw several conclusions relating to the effects of PEPP on the debt dynamics, especially as the program is wound down. Focusing on the lower-rated countries, our main empirical findings as follows: (i) PEPP had significantly positive effect on debt dynamics, and effects remain positive even if the program is reversed as early as 2024. Naturally, the longer it persists the stronger are the positive effects; (ii) Early reversal incrreases debt financing costs, but does not create unsustainable debt dynamics. We find that modest primary balance of 0.5-0.75% of GDP over a period of five to ten years can stabilize debt dynamics, whereas without PEPP the stabilizing balance would have to be sustained at more than 1% of GDP over fifteen years; (iii) PEPP improves the trade off between the cost of debt financing and the risk of debt re-financing quite substantially; (iv) an inflation shock accompanied by appropriate monetary tightening marginally worsens the debt dynamics, why the dynamics improve if the central bank considers the shock transitory, and, in either case the PEPP has the intended positive effect on spreads and debt stock.

Our study is related to the extensive literature on what determines sustainable debt levels (D'Erasmo et al., 2016), although the literature on the tradeoffs between borrowing costs and refinancing risks takes interest rates as exogenous.[8] We follow Zenios et al. (2021) where the fiscal agent plays an active role in sovereign debt management to minimize net interest payments while avoiding, if possible, exploding debt dynamics or excessive financing needs that could lead to exclusion from market access and potential default. However, this reference and the papers we cite above, look for optimal sovereign debt financing in the context of debt crises and sovereign defaults. We look instead at optimal debt financing for long-term fiscal sustainability in the presence of an active monetary policymaker.

The introduction of a macroeconomic framework and monetary policy regimes in stochastic DSA is largely inspired by a blossoming literature on the interactions between monetary and fiscal policies, during the financial crisis and the pandemic. Zampolli (2012) is among the first to look at the role of sovereign debt management as a tool of monetary policy in the aftermath of the great financial crisis. Debrun et al. (2021) revisits the policy mix in the euro area during the pandemic, from a central bank's perspective, with a focus on the ramifications for price stability and maintaining central bank credibility. Hofmann et al. (2021a) presents a general equilibrium model to explore the implications on fiscal sustainability of monetary policy at the zero lower bound, with Arslan et al. (2020) and Alberola-Ila et al. (2020) analyzing empirically the impact of central bank

[8]See Angeletos (2002); Arellano and Ramanarayanan (2012); Bocola and Dovis (2019); Chatterjee and Eyigungor (2012); Cole and Kehoe (2000); Conesa and Kehoe (2017); Fernández and Martin (2014); Hatchondo and Martinez (2009); Missale (2012); Niepelt (2014), among others.

bond purchases on government financing conditions during the pandemic. These papers look at the monetary-fiscal nexus from the monetary perspective, whereas we examine the other side of the coin, namely how monetary policy contributes to fiscal sustainability. We rely on these papers for the parametrization of our model.

The rest of the paper is organised as follows: Section 2 presents the stochastic DSA model enriched with the macroeconomic framework, and introduces monetary policy-making. Section 3 calibrates the impact of PEPP on sovereign spreads. Section 4 puts the model to the data on a representative eurozone high debt country, presenting results under different PEPP unwinding paths and debt management strategies. We also use the model to study the effects of inflation shock scenarios. Section 5 concludes.

2 Debt sustainability analysis with monetary policy-making

We first describe the economic setting of public debt management, introduce uncertainty of the key parameters using scenario trees, and introduce a risk measure to deal with uncertainty. We then give the optimization model that seeks to finance public debt with the lowest possible cost of borrowing within acceptable levels of risk and ensuring high level of confidence on debt sustainability. We build on the model of Zenios et al. (2021), to which we then add both conventional and unconventional monetary policymaking.

2.1 Public debt management

2.1.1 Debt dynamics

We consider a sovereign that at period t is endowed with nominal output Y_t, runs a primary balance PB_t, and owes a stock of debt D_{t-1}. The sovereign's *gross financing needs* are given by the *flow*

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

where i_{t-1} is the *effective nominal interest rate* on debt at $t-1$, and A_t denotes the amortization schedule corresponding to D_{t-1}. The *debt stock* is given by

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

The sovereign finances its needs choosing from J debt instruments of different maturities, with *financing decisions* $X_t(j)$ denoting the nominal amount of instrument j issued at t. The *debt financing equation* satisfies

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

The interest on issued debt is determined by the market risk-free rate plus premia idiosyncratic to the sovereign, and they depend on the debt level (Bassanetti et al., 2018; Paesani et al., 2006).An important feedback effect, which is especially strong for high-debt countries is between a sovereign's debt and the level and slope of the yield curve. We model this feedback loop of a response of interest rates to debt using *risk* and *term premia*. Following the literature we model premia as a function of debt-to-GDP, $d_t = \frac{D_t}{Y_t}$, and of the maturity of the issued instrument. The interest rate for instrument j issued at t given by

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

where r_{ft} is the term structure of the baseline maturity forward risk-free rate, and $\rho(d, j)$ captures *risk premium* and *term premia* for different maturities j.

The financing decisions determine the *effective interest rate*, or cost of debt:

$$i_t = \frac{i_{t-1}(D_{t-1} - A_t) + \sum_{j=1}^{J} r_t(j) X_t(j)}{D_t}. \tag{5}$$

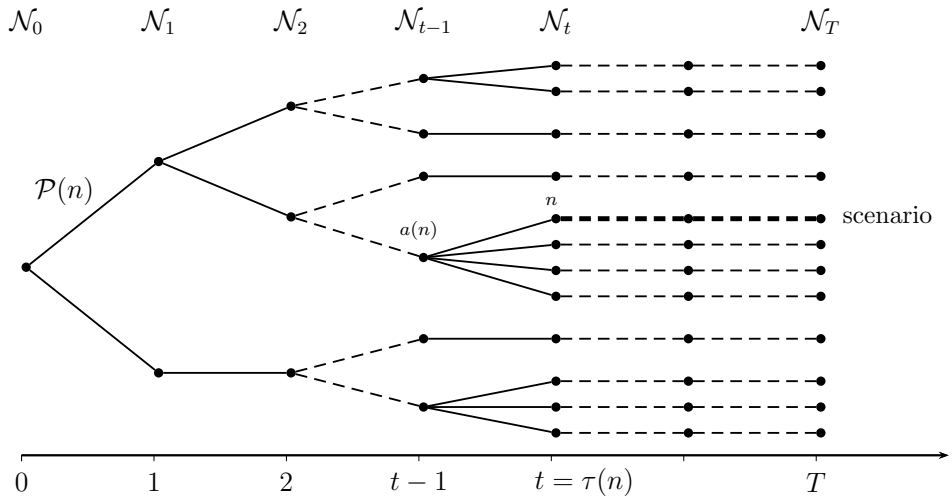
The stochastic DSA model determines the optimal debt financing decisions to achieve sustainable debt dynamics. The financing decisions determine the debt dynamics, that determine risk and term premia, which, in turn, influence the financing maturities. The *feedback loop* $X \to D \to r \to X$ links stock and flow not only through quantities but also through prices. It is a salient feature of the model for multi-dimensional analysis of risks.

2.1.2 Uncertainty and a risk measure

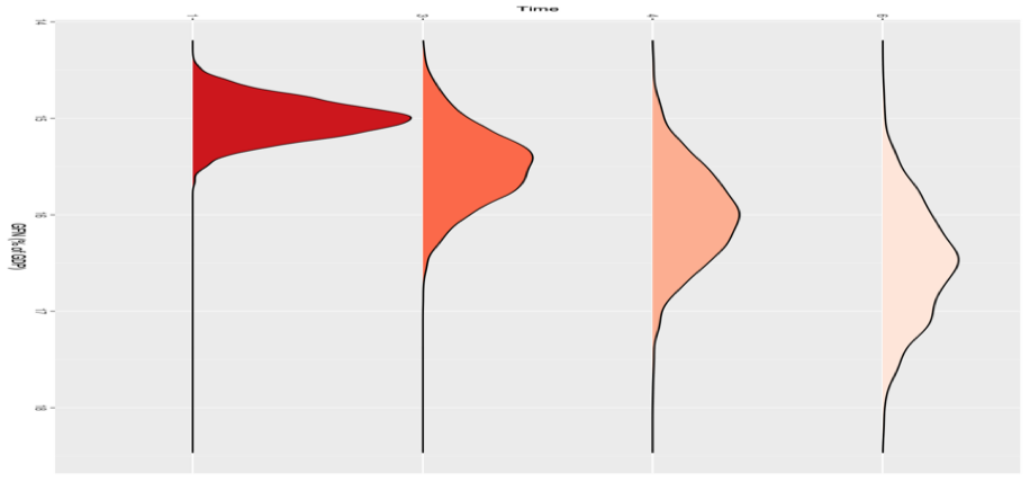
The key parameters of the sovereign's debt problem —economic output, primary balance, debt financing rates— are uncertain. We represent correlated macroeconomic, financial, and fiscal uncertainty by a discrete time- and state-space *scenario tree*, see Figure 3 (Panel A). Time steps are indexed by $t = 0, 1, 2, \ldots T$, where 0 is now and T is the risk horizon. Data are indexed by a set of *states* $\mathcal{N}_t$, with each $n \in \mathcal{N}_t$ representing a possible state of the economy at t. $\mathcal{N}$ denotes all possible states during the risk horizon. The number of states at t is N_t, and the total number of states is N. Not all states at t can be reached from every state at $t-1$, and $\mathcal{P}(n)$ denotes the set of states on the unique *path* from the *root state* 0 to n. Each path leading to a terminal state $n \in \mathcal{N}_T$ is a *scenario*. For state n at t, all information at states m on the path $\mathcal{P}(n)$ is known since m precedes n.

Problem data and model variables are indexed by the state to which they belong, and we can now define the debt financing decisions on the tree, and model the stochastic dynamics of debt stock and flow. Panel B illustrates the distribution of gross financing needs at different time periods on the tree. We observe in this specific example an increase in gross financing needs with increasing variability for longer horizons.

These simulated distributions of debt stock and flow dynamics provide rich information on debt sustainability. We can assess, for instance, if debt stock as a proportion to GDP, remains on a non-increasing trajectory or it decreases from very high levels, with high probability, or we can see if refinancing needs (i.e., debt flow) remain at a level that markets can reasonably finance, which is taken to be in the range 15% to 20% of GDP. We summarize this information using a risk measure of the distributions. We follow the risk management literature and define a coherent measure of refinancing risk, and trace the debt stock-flow tradeoff bounded by sustainability thresholds on the *conditional Value-at-Risk* (CVaR) of tail risks (Artzner et al., 1999), This risk measure is widely used



(a) Scenario tree



(b) Distributions of debt dynamics on the tree

Figure 3 – Modeling uncertain debt dynamics on a scenario tree.

in finance and banking, and is well suited for DSA since debt un-sustainability is a rare extreme event best captured by a tail measure. This allows sustainability assessment with a high confidence.

We measure gross financing needs as a ratio to GDP, to account for economic output uncertainty, so that it takes scenario values $gfn_t^n = \frac{GFN_t^n}{Y_t^n}$ at t, where Y_t^n is the state-dependent economic output. We use gfn to denote this stochastic variable over all time periods. Using CVaR we bound the expected value of the tail of the distribution of gross financing needs at a confidence level α that is acceptable for policymakers, e.g., $\alpha = 0.95$. We define the risk function $\Psi(\cdot)$ as

$$\Psi(gfn) \doteq \mathbb{E}\left(gfn \mid gfn \geq gfn^{\diamond}\right). \tag{6}$$

$gfn^{\diamond}$ 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. $gfn^{\diamond}$ is the Value-at-Risk of debt flow.

2.1.3 The DSA Model

Debt flow dynamics indicate an issuer's ability to rollover the debt, at any risk horizon, whereas stock dynamics reflect long-term insolvency risks, and these variables are interlinked through the interest rates. The stock and flow dynamics evolve on the scenario tree, accounting for uncertainty. Rollover risks are constrained by the tail risk measure of flow, and for insolvency risks we constrain the tail of debt stock dynamics to be non-increasing.

We minimize the cost of public debt financing, which is the expected interest payments on the debt, and impose debt stock and flow constraints using the risk measure to safeguard sustainability. We write the optimization problem as:

$$\underset{X}{\text{Minimize}} \quad \sum_{\substack{n\in\mathcal{N}_t,\\ \text{for all } t=0,1,2,\ldots T.}} p^n NIP_t^n \tag{7}$$

s.t.

$$\Psi(gfn) \leq \omega, \tag{8}$$

$$\frac{\partial d}{\partial t} \leq \delta. \tag{9}$$

This is a parametric optimization model of cost-risk tradeoffs. It trades off the cost of debt financing, with the risk of violating sustainability conditions on debt by constraining the flow and stock dynamics by thresholds ω and δ, respectively.

The cost objective function minimizes expected *net interest payments* (NIP), which is the main relevant variable for a PDMO.[9] Interest payments consist of interest on legacy debt I_t^n, plus interest on debt created by the financing decisions. To track service payments on endogenously created debt on a path leading to n we exploit the tree structure. Let $CF_t^n(j,m)$ denote the nominal amount of interest payment due at state n of period t, per unit of debt $X_{\tau(m)}^m(j)$ issued at state m of an earlier period $\tau(m)$ on the path $\mathcal{P}(n)$. This amount is computed from scenarios of the term structure of interest rates, the terms of previously issued instruments, and the premia (cf. eqn. 15). The net interest payments

[9]For instance, the primary goal of the US Treasury debt management function is to finance government borrowing at the lowest cost, against acceptable risks, with a medium and long term view. The same is true for the Dutch State Treasury Agency and the Italian Treasury. See, respectively, `https://www.treasury.gov/resource-center/data-chart-center/quarterly-refunding/Pages/overview.aspx`, the preface in DSTA Outlook 2019 at `https://www.dsta.nl/documenten/publicaties/2018/12/14/outlook-2019`, and Italian Treasury Outlook 2017 (Section I) at `http://www.dt.tesoro.it/export/sites/sitodt/modules/documenti_en/debito_pubblico/presentazioni_studi_relazioni/Public_Debt_Report_2017.pdf`. All sites accessed in March 2019.

are given by

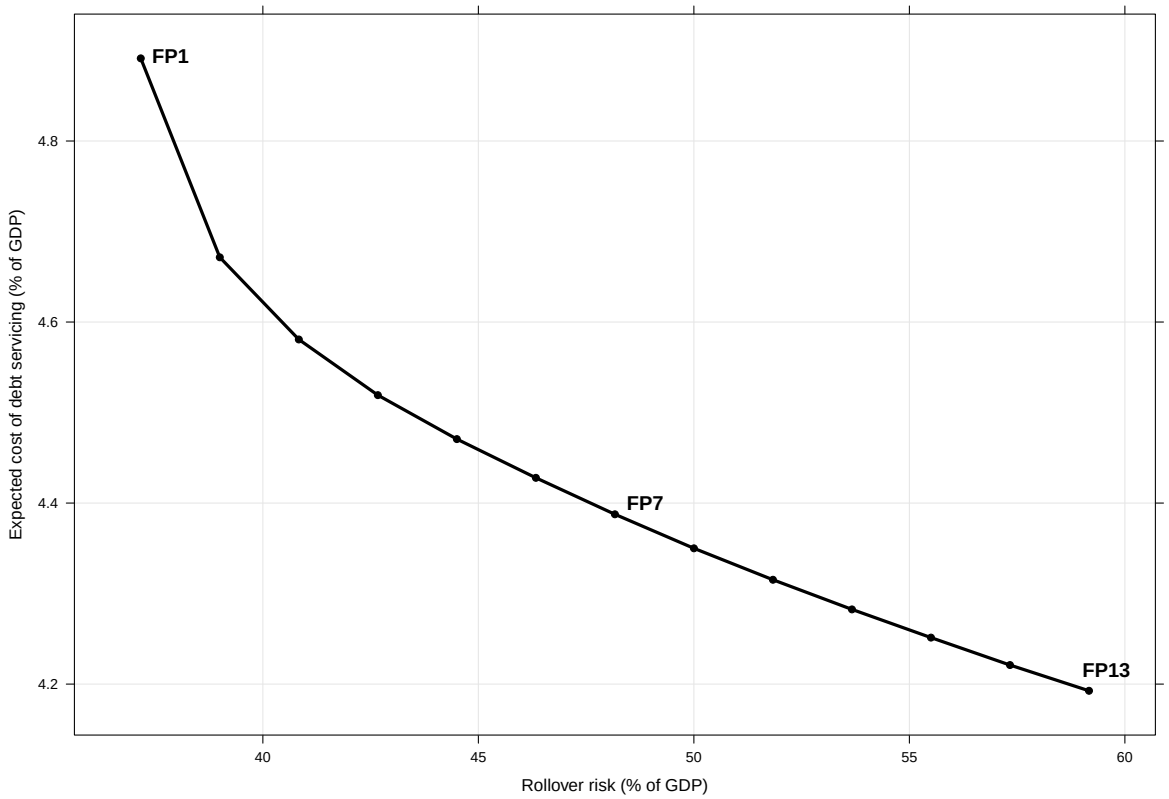
$$NIP_t^n = I_t^n + \sum_{m \in \mathcal{P}(n)} \sum_{j=1}^{J} X_{\tau(m)}^m(j) CF_t^n(j,m). \tag{10}$$

Net interest payments minus interest on legacy debt is what the PDMO controls through financing decisions. Total NIP/D is the effective interest rate of debt (eqn. 5).

The parametric risk constraint (8) bounds the risk on gross financing needs by the risk tolerance ω, as a percentage of GDP. By varying this parameter we trace an efficient frontier of cost of payment and refinancing risks, such as the one illustrated on Figure 4.[10]

Figure 4 – Cost of debt financing and refinancing risks

In this figure we show the efficient frontier of the tradeoffs between the expected net interest payments on debt (cost) vs. the tail risk of gross financing needs (refinancing risk). Point FP1 denotes minimum risk, point FP13 denotes minimum cost, and intermediate points (e.g., FP7) denote a tradeoff.



As refinancing risk is lowered —typically by issuing long-maturity debt— the cost of debt financing increases, putting pressure on debt stock. This tension between debt stock and ?ow tension is controlled by eqn. (9) that constrains the stock dynamics. d is a random variable taking scenario values d_t^n, so this constraint is also implemented using the risk measure. We can ignore this constraint from the model and test ex post

[10]The figure corresponds to the high debt country described in section 4.5.

if debt dynamics are exploding at a given point in the efficient frontier, or, for high debt countries, we can set $\delta < 0$ targeting a reduction pace. The debt sock and flow constraints are satisfied at confidence level α (i.e., the probability at which we compute the conditional Value-at-Risk of flow and stock), allowing us to draw conclusions with high level of confidence.

2.2 Macroeconomic framework and monetary policy regimes

We now describe the macroeconomic framework and introduce monetary policymaking. Conventional policies operate on the (nominal) risk free rate. We assume conventional monetary policy that sets interest rates following the Taylor rule, in response to changing inflation which is a function of inflation expectations, assuming it remains anchored, and the output gap. Unconventional policies operate through asset purchase programs.

2.2.1 Macroeconomic framework

The inflation dynamics π_t are modeled with the Phillips curve (Abel, Bernanke, and Croushore, 2011; Phillips, 1962)

$$\pi_t = \beta_\pi \pi_{t-1} + (1 - \beta_\pi)\mathbb{E}\pi_{t+1} + \gamma \hat{y}_t + \epsilon_{\pi,t}, \tag{11}$$

where $\mathbb{E}_t \pi_{t+1}$ is the expectation at time t of inflation at $t+1$, $\hat{y}_t$ is the output gap, β_π and γ are parameters, with β_π denoting persistence. $\epsilon_{\pi,t}$ is a centred error term.

To model output gap we use the IS curve (Abel, Bernanke, and Croushore, 2011)

$$\hat{y}_t = \delta_{\hat{y}} \hat{y}_{t-1} + (1 - \delta_{\hat{y}})\mathbb{E}\hat{y}_{t+1} - \alpha_{\hat{y}}(i_t - r^*) + \epsilon_{\hat{y},t}. \tag{12}$$

The output gap at t depends on the expected output gap $\mathbb{E}\hat{y}_{t+1}$ and the difference of interest rates i_t from the natural rate r^*. $\alpha_{\hat{y}}$ and $\delta_{\hat{y}}$ are parameters, with the later denoting persistence, and $\epsilon_{\hat{y},t}$ is the centred error term.[11]

The risk free rate i_t follows a Taylor rule (Abel, Bernanke, and Croushore, 2011; Taylor, 1993), responding to inflation expectations and the output gap:

$$i_t = \theta_i i_{t-1} + (1 - \theta_i)[\pi_{t-1} + r_t^* + \alpha_\pi(\pi_{t-1} - \pi_t^*)] + \alpha_i \hat{y}_{t-1} + \epsilon_{i,t}. \tag{13}$$

a_π, a_y are parameters, θ_i denotes persistence, and $\epsilon_{i,t}$ is a centred error term.

The interest for debt (re)financing includes premia depending on debt dynamics that

[11] Economy theory specifies that an increase in the average interest rates throughout the yield curve will depress output, thus lowering output gap, and a more appropriate specification would take into account the full term structure $\hat{y_t} = \delta_y \hat{y_{t-1}} + (1 - \delta_y)\mathbb{E}\hat{y_{t+1}} - \alpha_y(\frac{1}{J}\sum_j r_t(j) - r^*)$ To limit the number of state variables in our stochastic DSA model we approximate the average of the the term structure by the baseline interest rate of eqn. (12).

are idiosyncratic to the ith sovereign. To account for both conventional and unconventional policies, we model the spread over the risk free rate i_t using two regimes, without and with PEPP. The spread $\rho(d_{i,t}, p_{i,t}, i, j)$ is a function of the debt dynamics of the country $d_{i,t}$, the holdings by the central bank asset purchase program $p_{i,t}$ as % of GDP, and the maturity of the issued debt j. It is the product of a function $\rho_C(d_{it}, j)$ when there is no PEPP times $\rho_{U_i}(p_{i,t}) \in [0, 1]$, which takes a value greater than zero when PEPP is active and equal to zero when there is no PEPP. We have

$$\rho(d_{i,t}, p_{i,t}, j) = \rho_C(d_{i,t}, j) \times (1 - \rho_{U_i}(p_{i,t})). \tag{14}$$

Note that the risk premia are a function of the marketable debt, which, in the case of asset purchases, is less than the total debt. In the DSA we track the stock and flow dynamics of total debt, but use marketable debt to estimate risk premia.

Switching from conventional to unconventional policies in the context of PEPP is easy, given the known timing of the PEPP and its calibrated effects. However, reverting to the conventional regime requires assumptions on when and how this will be achieved, and on the smoothness of the transition from one regime to another. We assume a smooth linear transition from the unconventional term to the conventional.[12]

2.2.2 Risk and term premia under conventional monetary policy

For the spread with conventional monetary policy we following Zenios et al. (2021) and incorporate *risk premia* depending on debt-to-GDP, $d_t = \frac{D_t}{Y_t}$, and *term premia* depending on maturity. Since conventional monetary policy is not country specific, we drop for convenience the country index i. The j-period interest rate at t is given by

$$r_t(j) = r_{ft} + \rho_C(d_t, j). \tag{15}$$

This is the *refinancing rate* at which a sovereign will finance its maturing debt by issuing new debt of maturity j. $\rho_C(d, j)$ is the risk and term premia function,

$$\rho_C(d_t, j) = a_j + (1 + b_j)\hat{\rho}_C(d_t), \tag{16}$$

[12]The Economic Counsellor of the IMF, Gita Gopinath, commented about the "unclear effects on term premium, output and inflation in subsequent months", regarding the broader central bank QE policies at the 2021 Jackson Hole meeting, and on the importance for smooth changes, with policymakers announcing clear triggers and acting in line with the communication. See `https://www.kansascityfed.org/documents/8330/A6_Jackson_Hole_Symposium_Presentation_v9_Gopinath.pdf`

where a_j and b_j are maturity-specific constants (term premia), and $\hat{\rho}_C(d)$ is the effect of debt stock on interest rates under conventional monetary policy,

$$\hat{\rho}_C(d) \doteq \hat{\rho}\left[\frac{d_{max}-d}{1+\exp\left(d_{max}-d\right)} - \frac{d_{min}-d}{1+\exp\left(d_{min}-d\right)}\right]. \tag{17}$$

Eqns. (16–(17) generate yield curves that shift and twist with debt changes. If $b_j = 0$ for all maturities, changes in debt level cause parallel shifts. When b_j is higher (lower) for long- than short-term debt, a debt increase causes curve steepening (flattening) around the baseline maturity rate. Equation (17) is a smooth nonlinear (sigmoid) approximation of a piece-wise linear function, with a lower bound of zero for debt-to-GDP ratio at most 60% GDP, as set in the Stability and Growth Pact. For higher debt ratios it increases linearly until it hits a ceiling when the sovereign loses market access and is financed by the official sector.

2.2.3 Unconventional monetary policy with asset purchase programs

We model the effect of asset purchases through a function that suppresses the risk premia through a non-linear relation of the PEPP holdings. The spread suppression is 0 (i.e., no effect) for very small purchases, below a threshold $\underline{p}$, and it increases nonlinearly with purchases until it reaches its maximum suppression level when purchases exceed a threshold $\overline{p}$. The unconventional policies have country specific effects, and we estimate a piecewise quadratic-linear relation for each country i:

$$\rho_{U_i}(p_{i,t}) = \begin{cases} 0 & p_t \leq \underline{p}_i \\ \beta_{0i} + \beta_{1i} p_{i,t} + \beta_{2i} p_{i,t}^2 & \underline{p}_i < p_{i,t} < \overline{p}_i \\ \rho^* & p_t \geq \overline{p}_i. \end{cases} \tag{18}$$

We will focus on the effectiveness of PEPP to suppress sovereign spreads from the level determined by debt-to-GDP ratios (see section 3). This effectiveness is non linear, depending on a country's debt level, and it is higher on the Greek and Italian spreads, for instance, than on the Dutch and Finnish. We assume that the spread suppression obtained from this relationship is the same when ECB purchases assets, or when it reduces its balance sheet when unwinding the PEPP.

2.3 DSA with monetary policy

We now integrate the macroeconomic framework within the debt sustainability analysis model. The DSA model take as input the nominal value of legacy debt, primary balance, nominal value of GDP, and debt refinancing rates. In stochastic DSA these variables are sampled from a calibrated distribution, such as the one represented by a scenario tree.

We first solve eqns. (11)–(12) to obtain equilibrium inflation and output gap. Assuming that the potential growth does not change, the dynamics of real GDP growth g_t^* are determined by changes of the output gap from the simple recursion

$$g_{t+1}^* = g_t^* + \Delta\hat{y}_t. \tag{19}$$

where $\epsilon_{g^*,t}$ is a centred error term set to zero at equilibrium.

We use the equilibrium inflation, output gap, and real growth as the expectations, to build a scenario tree for these three state variables using a moment matching method (Consiglio et al., 2016). Specifically, we match the first moments to the equilibrium values, and match the second (or higher) moments and correlations of the error terms $\epsilon_{\pi,t}, \epsilon_{\hat{y},t}$ as well as the variability of the real growth ($\epsilon_{g^*,t}$) to historically observed moments and correlations of inflation, output gap, and growth. The interest rate is derived from the inflation and output gap state variables of the tree using the Taylor rule (13). Hence the expected value of interest rates matches the equilibrium rate, and for each sample of state variables from the tree, the nominal interest rate is in a Taylor rule equilibrium with the inflation and output gap scenario.

A fourth state variable of the scenario tree is the primary balance. This is calibrated to match the expected primary balance of the sovereign (e.g., obtained from the IMF World Economic Outlook projections), its historically observed second moment, but also, and importantly, the historically observed correlations with the macroeconomic state variables. Calibrating the model to historical correlations of the state variables helps overcome the limitations of our partial equilibrium setting.

DSA works with nominal economic output, since debt is in nominal values, and we obtain the nominal growth by

$$g_t = g_t^* + \pi_t, \tag{20}$$

with the nominal value of GDP is obtained recursively from $Y_t = Y_{t-1}(1 + g_t)$.

This completes DSA with a monetary policy block. We consider this a significant methodological innovation of our paper. We point out that monetary policy is scarcely mentioned in current DSA methods. The word "monetary policy" (or related "monetary variables" etc) appears only once in the ECB debt sustainability framework Bouabdallah et al. (2017), in a context unrelated to DSA, and three times in the IMF report IMF (2013) warning that monetary policy changes can render uninformative the DSA fan charts. None of the two reports mention "unconventional monetary policy" or "asset purchase programs" or consider monetary policy in their analysis. The EC report Commission (2020) does mention that monetary policy support in the eurozone has alleviated debt concerns and warns that results may change if monetary policy shifts. They discuss the asset purchase programs of the ECB in relation to the EU member states financing needs, and in a footnote they offer a downward adjustment to the slope of the term structure by

a fixed amount, to account for the unconventional monetary policy. Our approach fully integrates monetary policy in DSA, accounting for both conventional and unconventional policymaking.

3 The effect of PEPP on sovereign spreads

We now turn to the issue of model calibration, particularly for the innovative unconventional monetary policy part, in two steps. First, we obtain an estimate of the effects of PEPP on sovereign spreads by computing a counterfactual. Then, we calibrate a simple relation that predicts PEPP effects as a function of cumulative holdings of sovereign debt by the ECB.

3.1 Empirical estimation of the counterfactual

To calibrate empirically the function $\rho(d_{i,t}, p_{i,t}, j)$, we first estimate the effects of debt levels on sovereign spreads. We use the panel regression

$$s_{i,t} = \alpha + \beta d_{i,t} + \epsilon_{i,t}, \tag{21}$$

where $s_{i,t}$ denotes the benchmark sovereign spreads in country i relative to German Bunds of the same maturity.

Our in-sample estimation uses data from the euro area countries with high debt (Greece, Italy, Portugal, Spain) between 2015Q1 and 2020Q1, taking 10-year bonds as the benchmark. We start the calibration at 2015 to minimise the impact of the euro area debt crisis on our estimation and end prior the launching of PEPP, and obtain as estimate β=3.2,[13] which is in line with estimates in the literature (Zenios et al., 2021). Using this coefficient we obtain out-of-sample predictions of how spreads would have evolved from 2020Q2 onwards should there be no PEPP. This is the counterfactual, illustrated in Figure 5.

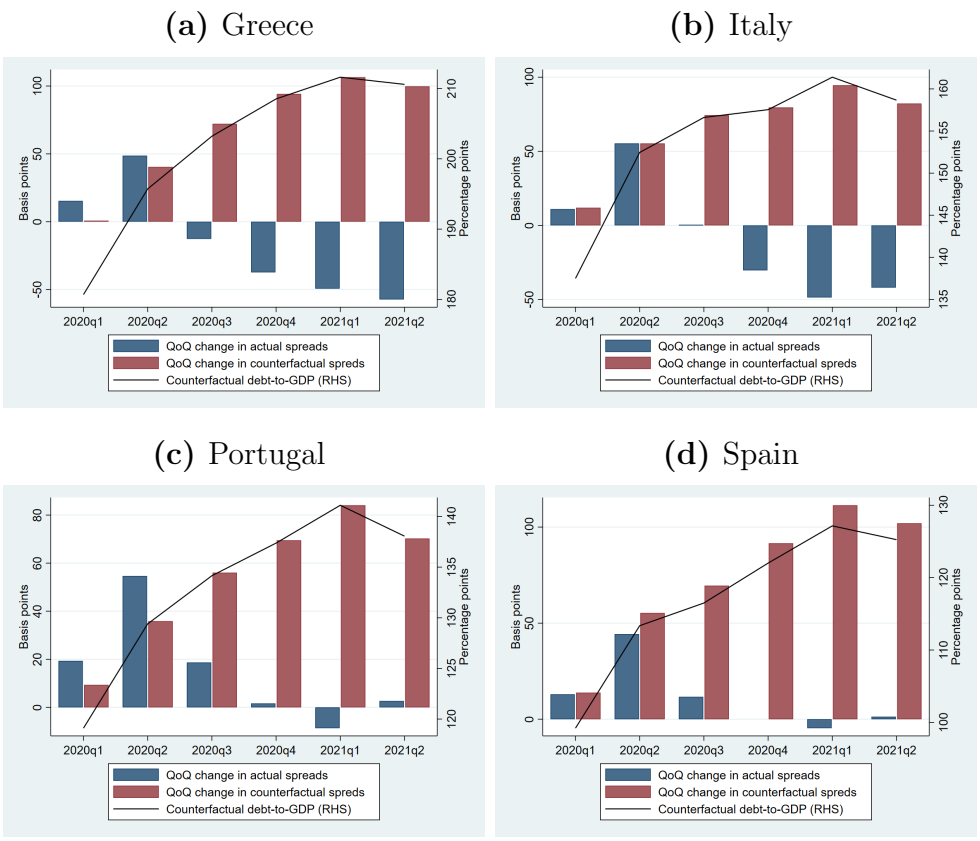
3.2 Statistical calibration of PEPP induced spreads

Unconventional policies have country specific effects, and the estimation in this section can be country specific. We focus on estimating $\rho_{U_i}(p_{i,t})$, by examining the relationship between actual spreads s_t, the out-of-sample prediction of spreads $\rho_C(d_t)$ estimated above, and the ECB holdings of sovereign debt via PEPP, normalized by the country envelope, $p_{i,t}$. We compute the spread suppression rate as the proportional reduction in

[13] Regression results are available from the authors.

Figure 5 – Actual vs. fitted sovereign spreads (in basis points)

In this figure we show the counterfactual of what the spreads would have been since 2020Q2 should there no be PEPP.



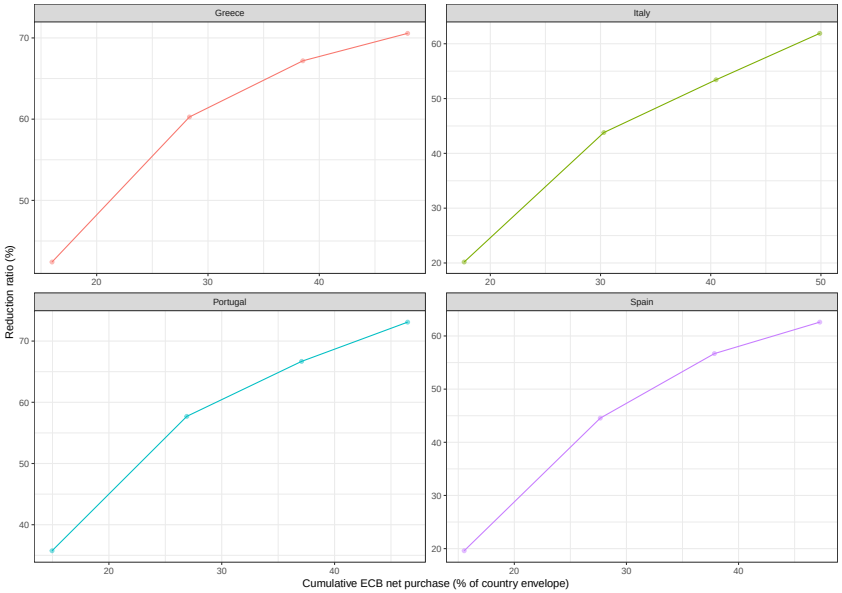
the benchmark spreads relative to the out-of-sample prediction,

$$\hat{\rho}_{U_i}(p_{i,t}) = \left[1 - \frac{s_t}{\hat{\rho}_C(d_t)}\right], \tag{22}$$

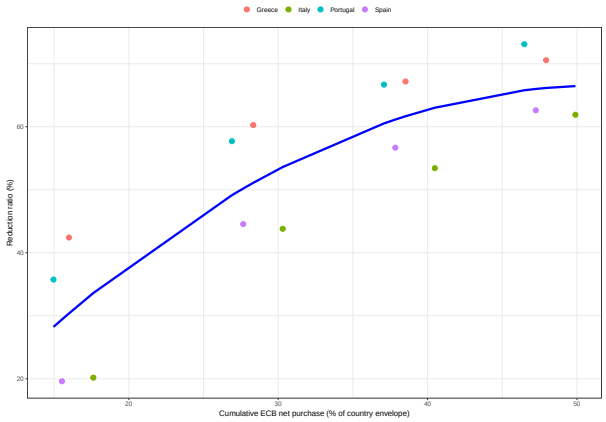
where $\hat{\rho}_{U_i}, \hat{\rho}_{U_C}$ denote empirical observations. Using data over the period spanning the start of purchases in April 2020 to January 2021,[14] we display in Figure 6 (Panel A) the realized suppression rates versus the ECB holdings of sovereign debt for each country in our sample. The curves show a strong reduction in spreads with increasing ECB purchases, albeit at a decreasing rate. Indeed, we expect spread suppression to plateau as the ECB holdings approach the maximum allocation defined by country's key in the ECB capital structure.

In Figure 6 (Panel B) we display the panel data of spread suppression rates together with a fitted second order polynomial. Data are clustered by country and a better fit is possible by fitting a curve to each group. However, given the small number of observations

[14]The ECB publishes PEPP purchases on a bimonthly basis, see `https://www.ecb.europa.eu/mopo/implement/pepp/html/index.en.html`here.



(a) Per country



(b) Panel data and the fitted polynomial

Figure 6 – Spread suppression rates vs ECB holdings.

we fit a mixed effect model over the whole data-set, which accounts for the correlation among the data due to grouped observations. The model entails *fixed* effects, due to the purchases that we assume influence the dependent variable, and *random* effects accounting for the clustering characteristics that we aim to control, i.e., the country differences.

To fit a second-order polynomial we considered different linear regression models with random intercepts and slopes, given by the country-specific equation

$$\rho_{U_i}(p_{i,t}) = \beta_{0i} + \beta_{1i} p_{i,t} + \beta_{2i} p_{i,t}^2 + \epsilon_{i,t}. \tag{23}$$

In particular, we test the following models of spread suppression:

M1 with $\beta_{0i} = \gamma_{00} + u_{0i}$, where only the intercept vary across countries, given the random effect term u_{0i}

M2 with $\beta_{0i} = \gamma_{00} + u_{0i}$ and $\beta_{1i} = \gamma_{10} + u_{1i}$, where the intercept and the first order coefficient are country dependent (u_{0i} and u_{1i} are the random effect terms)

M3 with $\beta_{0i} = \gamma_{00} + u_{0i}$, $\beta_{1i} = \gamma_{10} + u_{1i}$ and $\beta_{2i} = \gamma_{20} + u_{2i}$, where all the coefficient vary across countries and u_{0i}, u_{1i} and u_{2i} describe the grouping effect.

M0 denotes the model fitted to the whole data-set using OLS.

We estimate models M0–M3, and select the best one according to the Akaike (AIC) and Bayesian (BIC) information criteria, reported in Table 1.[15]

Model	AIC	BIC
`M2`	104.8	109.4
`M1`	109.8	113.7
`M3`	114.3	122.1
`M0`	120.3	123.4

Table 1: Spread suppression models ranked by Akaike (AIC) and Bayesian (BIC) information criteria.

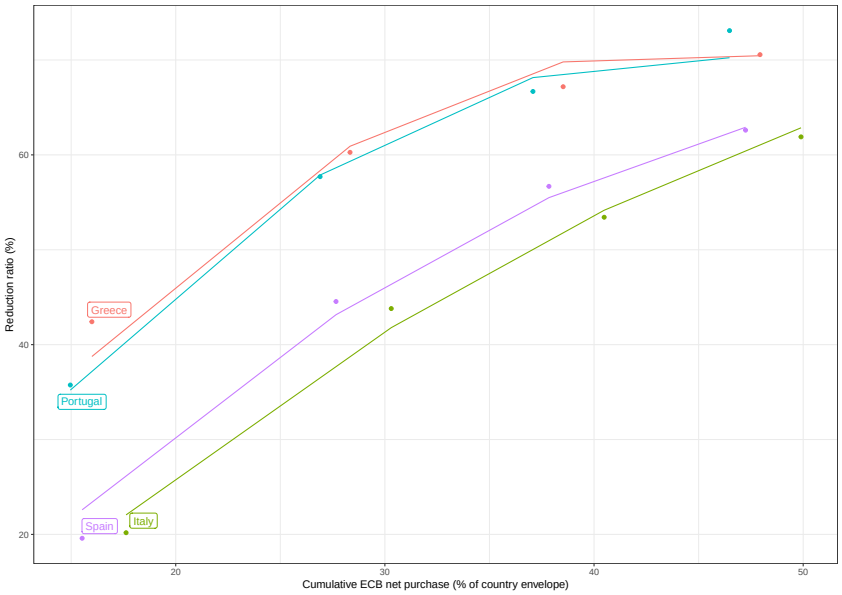
M2 is the best performing model, and we illustrate for each country in Figure 7 (Panel A). We will use only the rising part of the fitted model, with the spread suppression reaching a plateau which is visible in the case of Portugal and Greece but not yet for Italy and Spain. We are interested in positive purchases only, and from the roots of the fitted eqn. (23) we estimate the maximum ($\overline{ss}$) spread suppression rates, with the estimated purchases at which the spread suppression reaches its maximum ($\overline{p}$). In Figure 7 (Panel B) we display the parameters of the PEPP spread suppression function.

Dropping, for convenience, the country index i, we write the PEPP spread suppression function as the piece-wise relation

$$\rho_{U_i}(p_{i,t}) = \begin{cases} \underline{ss} & p_t \leq \underline{p} \\ \beta_0 + \beta_1 p_t + \beta_2 p_t^2 & \underline{p} < p_t < \overline{p} \\ \overline{ss} & p_t \geq \overline{p}. \end{cases} \tag{24}$$

This is the empirically calibrated eqn. (18).

[15] The models are estimated using the R fixed effect model package `lme4`.



(a) Model fitted per country

Country	β_0	β_1	β_2	p_t (at Jan. 2021)	$\overline{p}$	$\overline{ss}$
Greece	6.02	2.70	-0.03	47.94	47.60	70.40
Italy	-26.70	3.17	-0.03	49.90	55.79	61.71
Portugal	-1.28	2.92	-0.03	46.48	51.31	73.51
Spain	-21.12	3.12	-0.03	47.25	54.97	64.73

(b) Parameters of the fitted model per country

Figure 7 – The PEPP spread suppression model for each country.

4 Model at work

We now put the model to the data. We perform DSA for a eurozone representative high-debt country, and test the debt dynamics and optimal financing strategies, with and without PEPP. We consider PEPP schemes lasting until 2024 (i.e., the end of 2023 as per current ECB plans), 2025, 2027, or 2030, and subsequently unwound over a five year period. We also consider the limiting case where ECB purchases are rolled-over for ever ("QEternity"). Finally, we consider the effects of an inflation shock.

4.1 Data

We construct a representative high-debt country by averaging the legacy debt of Italy, Spain, and Portugal, equally weighted, maturing over a 30-year period from 2021 to 2050. Data are from the treasury sites of the three countries, and for primary balance and growth we use the IMF World Economic Outlook projections of 2021. The starting debt ratio of the representative country is 135% GDP with a risk premium of about 250bp.

For the economic environment, we use the output gap for the eurozone, starting at -3.1% in 2021 and converging to 0% by 2030, together with the eurozone inflation starting at 1.8% in 2021 and converging to 2% by 2027. From equations 12 and (19) we obtain eurozone GDP growth, starting at 5.0% in 2021 and converging to 1.4% by 2026. We set $r^* = 0$. Centred on these market expectations, we calibrate the scenario tree of stochastic variables —real GDP growth, output gap, primary balance, inflation— using the moment-matching method of Consiglio, Carollo, and Zenios (2016), on moments estimated from yearly data spanning 1998–2019.

In Data Appendix Table A.1 we give the parameters for the Phillips curve eqn. (11), Taylor rule eqn. (13), and output gap eqn. (12), drawing on existing literature (Hofmann et al., 2021b). The data used to calibrate the tree are in Table A.3, and Figure A.1 displays fan charts from the calibrated tree and the nominal interest rates obtained from the Taylor rule on the calibrated tree. Figure A.3 displays the legacy debt. This is our representative country within the uncertain economic environment of the eurozone.

4.2 Counterfactual

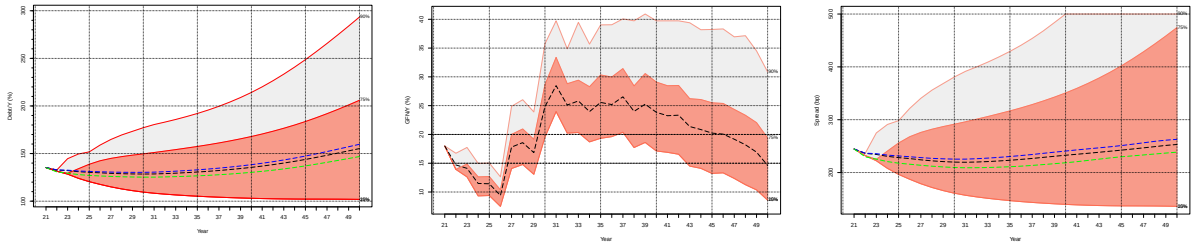
We look at the debt dynamics under the counterfactual of no PEPP, and show in Figure 8 the fan charts of debt stock as a ratio to GDP, gross financing needs, and risk premia (spreads). We perform the debt sustainability analysis with an intermediate cost-risk tradeoff financing strategy (i.e., point FP7 on the frontier of Figure 4).[16]

[16] Additional results at the minimum risk point FP1 and the minimum cost FP13 are given in Appendix Figure C.1. The results corroborate the findings we report here, showing that the minimum cost strategy

Figure 8 – Debt sustainability analysis without PEPP

This figure displays the counterfactual of debt sustainability without the unconventional PEPP intervention, with scenarios of debt-to-GDP ratio (Panel A), debt flow ratios (Panel B), and risk premia (Panel C). The debt dynamics are for the intermediate cost-risk tradeoff point on the efficient frontier (FP7).

(a) Debt stock **(b)** Debt flow **(c)** Risk premium



We clearly observe unsustainable debt dynamics. The stock ratio (Panel A) increases with very high probability, and flow (Panel B) violates the sustainability thresholds with very high probability starting at 2027 until the end of the risk horizon. Panel C shows large and growing risk premia, reminiscent of the spreads during the eurozone crisis.

The debt financing strategy by itself can not restore debt sustainability and if we impose the debt constraint (9) with $\delta = 0$, the problem becomes infeasible. We use the model extension from (Zenios et al., 2021, section 6) to compute the *stabilizing primary balance* that is required to render the debt stock dynamics sustainable with a high probability (more than 0.75). We find that an extra fiscal effort averaging 1.23% GDP over eighteen years will stabilize debt. Under minimum risk financing (FP1), an extra fiscal effort averaging 1.30% GDP per annum (p.a.) for 19 years would be required, and with minimum cost financing (FP13) the extra fiscal effort is slightly lower at 1.1% GDP p.a. for 18 years. Such levels of fiscal effort are unattainable in practice (Eichengreen and Panizza, 2016).

4.3 Debt sustainability with PEPP

We next run the model introducing PEPP. We consider PEPP schedules, lasting until 2024 or 2030, and the limiting case of QEternity. We assume that unwinding takes place over a pre-announced 5-year window, so the markets gradually adjust from the unconventional policy spreads to the conventional policy spreads. All tests are carried out with the intermediate debt financing strategy FP7, but our results remain qualitatively

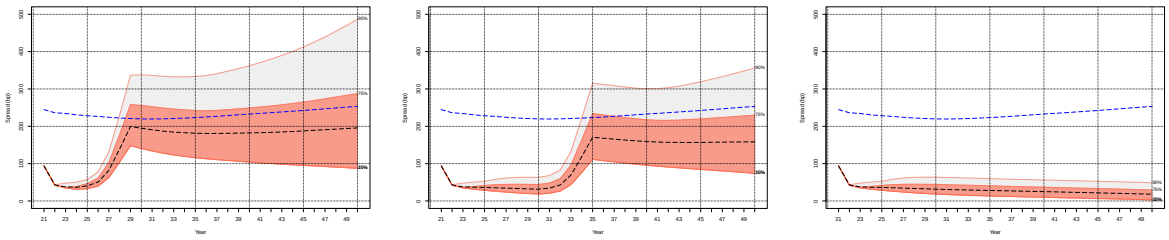
lowers the rate of increase of debt dynamics but with debt still increasing. They also reinforce the debt stock-flow tradeoffs first documented in Zenios et al. (2021).

the same with the minimum risk strategy.

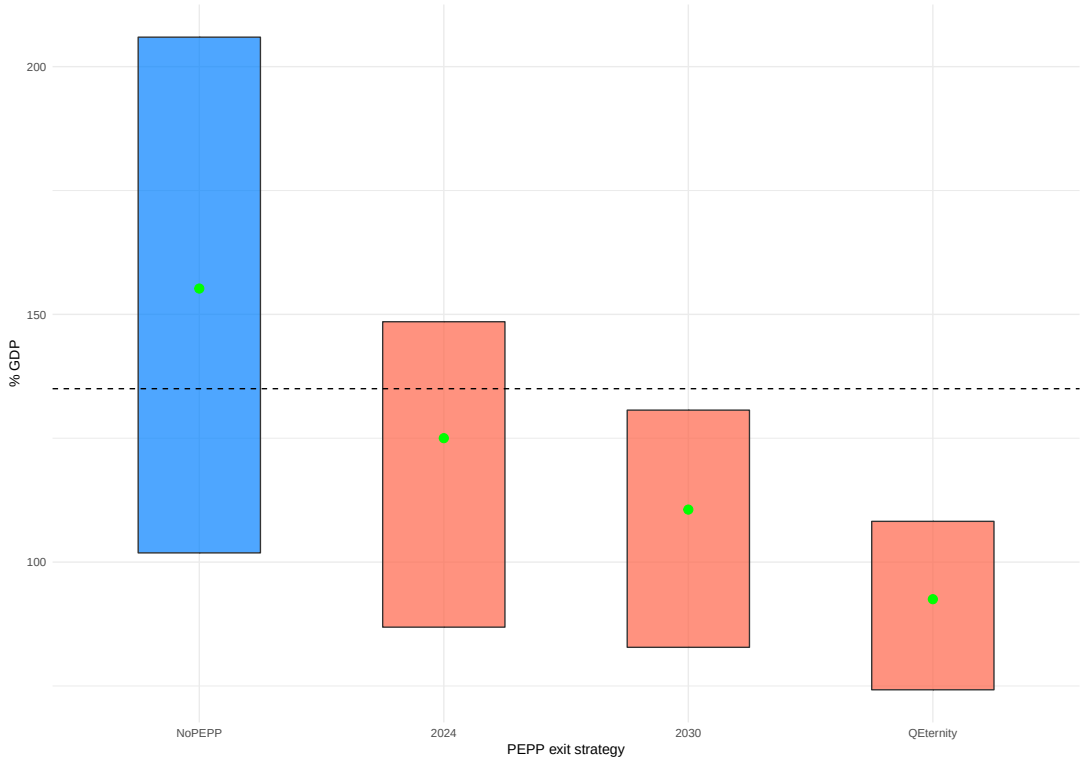
Figure 9 – Debt sustainability analysis with PEPP

This figure displays results of debt sustainability analysis under the unconventional PEPP intervention. It shows details of the debt dynamics with different PEPP programs. PEPPn denotes a program that is launched in 2020, and continues until year n, at which point it starts unwinding over a five year period. All test are done using a debt financing strategy with intermediate tradeoff between cost and risk (FP7).

(a) Risk premia, PEPP2024 **(b)** Risk premia, PEPP2030 **(c)** Risk premia, QEternity



(d) Mean value and interquartile range of debt stock at end of risk horizon



We report in Figure 9 results with the debt sustainability variables. The risk premia (Panels A-C) are significantly reduced during the program implementation, as expected. Once the program is fully implemented, but before the unwinding commences, the spreads are stable. with a probability of declining due to the denominator effect (GDP growth). Upon unwinding the program, spreads increase sharply over the five year period. With

unwinding from 2024 the spreads return return to below the pre-PEPP levels, shown as the dashed blue line, and with unwinding from 2030 the spreads are much lower then pre-PEPP levels, with high probability. The denominator effect, together with the low refinancing costs during the PEPP, reduce the debt ratio thereby reducing spreads after PEPP is withdrawn, and debt dynamics remain on stable trajectories. We summarize the debt stock dynamics in Panel D, where we show the mean value and the interquartile range of the debt-to-GDP ratio at the end of the risk horizon under different PEPP schedules. (The fan charts of the stock trajectories for all PEPP schedules are shown in Appendix Figure C.2). We observe that the counterfactual has higher expected debt ratio at the end of the horizon than at the begining, in line with the fan charts of Figure 8 (Panel A), and with a large inter-quartile range. In contrast, under all PEPP schedules, debt converges to an average value well below the starting value with much lower inter-quartile ranges.

The debt flow variables are also significantly lower than the counterfactual. Without PEPP, the flow dynamics violate the 20% threshold with high probability, for a total of 16 years from 2029 to 2045 (Figure 8, Panel B), with average gross financing needs slightly above the threshold. In contrast, with PEPP there are significantly fewer breaches of the threshold (see Appendix Table C.2, Panels D-F), with average financing needs declining to 17% with 2024 unwinding and 15% with 2030 unwinding.

4.4 Fiscal-monetary policy mix for debt stabilization

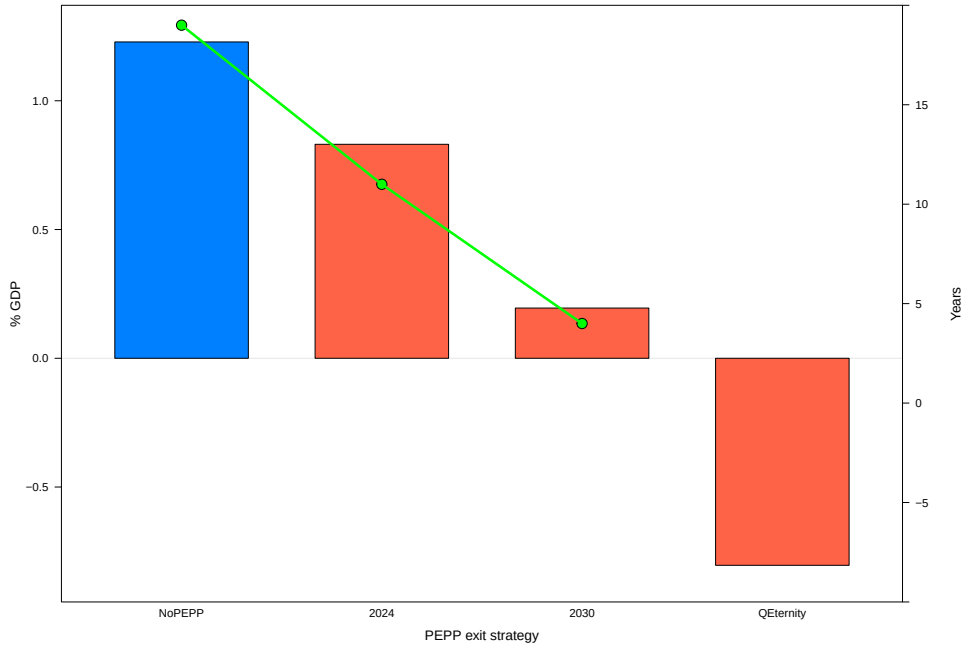
From the inter-quartile ranges of the debt dynamics (Appendix Figure C.2, Panels A-e) we observe that debt sustainability is assured with high probability only for QEternity. We calculate the extra fiscal effort required to render debt dynamics sustainable, i.e., the inter-quartile ranges are below the starting debt ratio, with probability at least 0.75. We show in Figure 10 declining fiscal efforts over shorter periods with the longer duration PEPP. For instance, the stabilizing primary balance under the earlier 2024 exit is 0.85% p.a. over ten years. This is significantly lower than the 1.30% p.a. for 19 years without PEPP, and it can even be negative if PEPP were to continue until 2030. This result shows the significant interaction of fiscal with unconventional monetary policies. Importantly, for later unwinding the stabilizing balance can be feasible, whereas for earlier unwinding the required fiscal consolidation can be unattainable (Eichengreen and Panizza, 2016), resulting into a sovereign debt crisis.

Overall, early termination implies higher stabilzing primary balance, and even with overly ambitious primary balances it can take significantly longer to stabilize debt. This raises an important issue of coordination between fiscal and monetary policies by the two independent agents –the sovereign and its CB– as earlier exits force the sovereign to increase its primary balance and achieve lower long term debt. However, in the short to

medium term the risks from earlier exit are significantly higher, and for very early exits the stabilizing primary balance may be unattainable.

Figure 10 – Stabilizing debt dynamics with extra fiscal effort

This figure displays the stabilizing fiscal balance that puts the debt stock dynamics on a declining sustainable trajectory with probaility at least 0.75. It shows results for different PEPP programs. PEPPn denotes a program that is launched in 2020, and continues until year n, at which point it starts unwinding over a five year period. All test are done using a debt financing strategy with intermediate tradeoff between cost and risk (FP7).



We also test the monetary-fiscal policy mix to reduce average debt to 100% of GDP by the end of the horizon, and report the results in Figure 11.

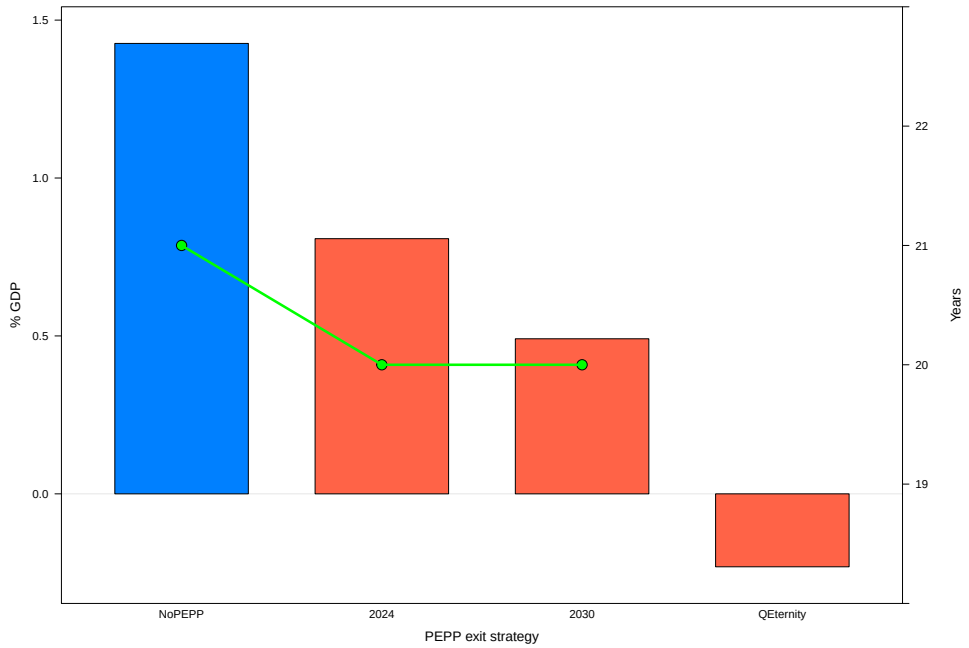
4.5 The cost-risk tradeoff

We use the model to conduct DSA under a range of tradeoffs between the cost of debt financing and the refinancing risks. We vary the risk parameter ω in eqn 8 to trace the efficient frontier, under different PEPP schemes.

We show the efficient frontiers with different unwinding schedules in Figure 12, including the counterfactual of no PEPP. We note a marked reduction of both cost of debt financing and refinancing risks, so that the efficient frontiers shift to the left with longer duration PEPP. We observe cost savings as large as 1.5% GDP when going from no PEPP to a program that lasts until 2024, with significant reduction of tail risk of gross financing needs, by about 25%, and the cost and risk improvements are larger for the longer duration programs.

Figure 11 – Reducing debt ratio to 100% with extra fiscal effort

This figure displays the fiscal balance that reduces the average debt ratio to 100% by the end of the horizon. It shows results for different PEPP programs. PEPPn denotes a program that is launched in 2020, and continues until year n, at which point it starts unwinding over a five year period. All test are done using a debt financing strategy with intermediate tradeoff between cost and risk (FP7).



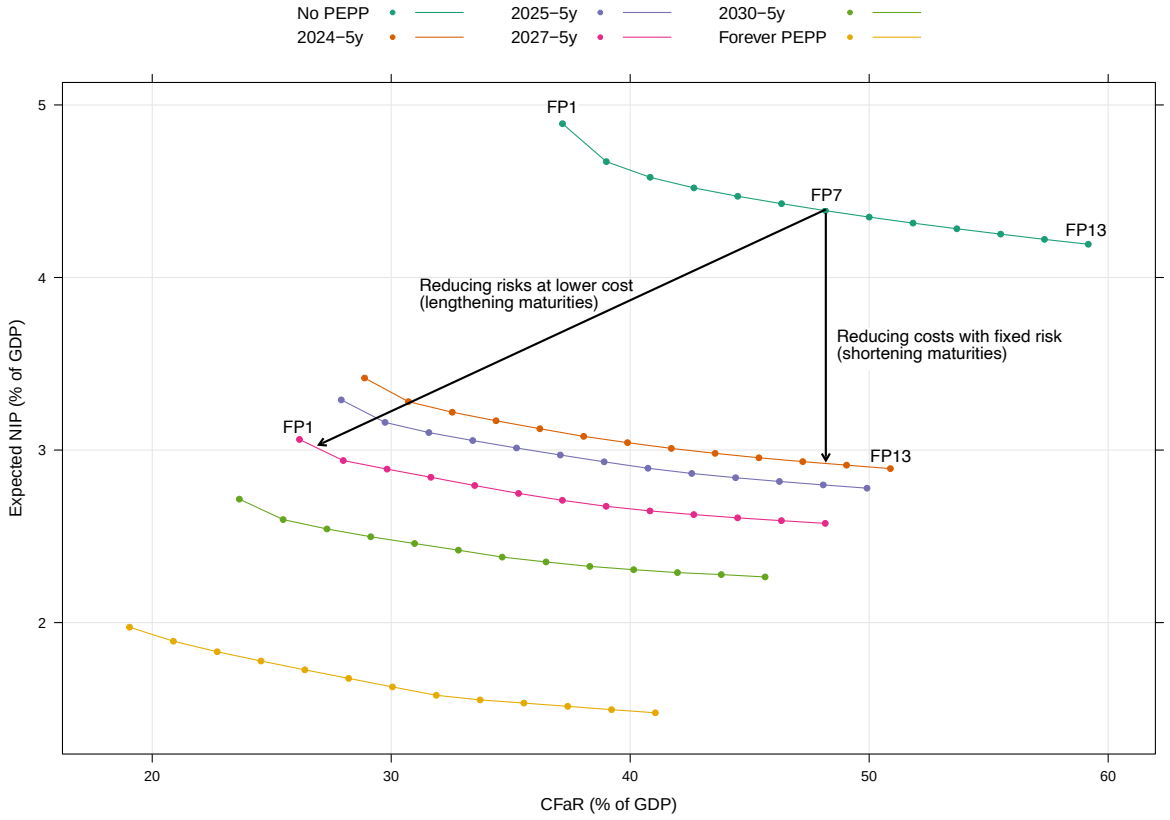
The left-most points (FP1) of the frontiers denote debt financing strategies with minimum risk, the right-most points (FP13) denote minimum cost, and the intermediate points (FP7) denote a tradeoff. We also illustrate the Pareto moves of a public debt management office (PDMO) that stays within its mandate to finance government borrowing at the lowest cost against acceptable risks, with a medium and long term view.[17] For instance, from FP7 without PEPP a move along the vertical axis will reduce financing costs, while keeping risks unchanged. Of course now we are closer to the minimum cost point FP13, so this move comes by issuing debt at shorter maturities. Alternatively, a move along the southwest diagonal reduced both costs and risks under the PEPP, but we are now closer to the minimum risk point FP1, so this move comes with maturity lengthening. We investigate further the effects of PEPP on the debt financing strategies later (subsection 4.6).

[17]See, for instance, the main goals of the US Treasury, Dutch State Treasury Agency, and the Italian Treasury. The US policy is stated at `https://www.treasury.gov/resource-center/data-chart-center/quarterly-refunding/Pages/overview.aspx`, for DSTA see the preface in Outlook 2019 at `https://www.dsta.nl/documenten/publicaties/2018/12/14/outlook-2019`, and for the Italian Treasury see Section I of Outlook 2017 at `http://www.dt.tesoro.it/export/sites/sitodt/modules/documenti_en/debito_pubblico/presentazioni_studi_relazioni/Public_Debt_Report_2017.pdf`. All sites accessed in March 2019.

These frontiers were obtained without constraint (9, so the debt dynamics may be increasing unsustainably in some cases. We examine next the debt dynamics at different points on the frontier.

Figure 12 – Efficient frontiers of cost-risk tradeoffs

In this figure we show the efficient frontier of the tradeoffs between the expected net interest payments on debt (cost) vs. the tail risk of gross financing needs (refinancing risk), under different PEPP programs. PEPPn denotes a program that is launched in 2020, and continues until year n, at which point it starts unwinding over a five year period. The left-most points (FP1) denote minimum risk, the right-most points (FP13) denote minimum cost, and the intermediate points (FP7) denote a tradeoff.



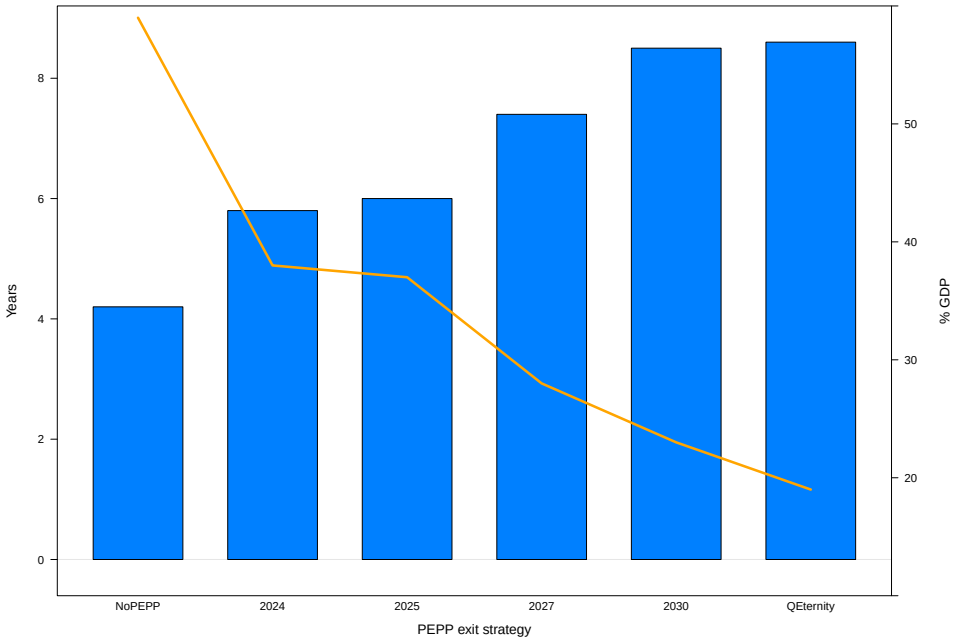
4.6 Optimal debt financing strategies with PEPP

The PEPP affects on the cost-risk trade-offs of debt financing could be significant on the financing strategy for PDMOs who act in line with their mandates. Plessen-Mátyás et al. (2021) document such behaviour by the eurozone PDMOs. They provide empirical evidence of a link between asset purchase programmes (the public securities purchase program, PSPP) and longer-dated public debt. Their results show that a one percentage point decrease in government bond yields led to a lengthening of issuance maturities by 7 months on average, and the authors argue in favour of treating funding maturities as

endogenous in impact estimations of central bank purchase programmes.

Figure 13 – Fixed-cost risk reduction under PEPP

This figure displays the weighted average maturity at issuance (WAMI) with a constant cost of debt financing (3% GDP) under different PEPP programs, and the corresponding risk measure conditional flow at risk. PEPPn denotes a program that is launched in 2020, and continues until year n, at which point it starts unwinding over a five year period.



Our model, uniquely among DSA models, optimizes endogenously over a range of discrete debt financing maturities, and we use this feature to understand the empirical observations.[18] Referring to the efficient frontiers of Figure 12, we look at the debt financing strategy that keeps the cost of financing fixed at about 3% GDP. We pick the points of intersect of the 3% horizontal line with the frontiers,[19] and for each point we plot in Figure 13 the optimal weighted average maturity at issuance (WAMI) with the corresponding risk measure (Conditional Flow at Risk). We observe a lengthening of maturities with a lowering of risks. The shift from no PEPP to the 2024 schedule increases the WAMI by 12 months. The cost of debt is on average lowered by 1.3% with PEPP2024, which corresponds to a lengthening of about 10 months per percentage point

[18]The model we use is unique among the practical DSA systems by the IMF, EC, or ECB to endogenously optimize debt financing. Among the academic literature, the earlier single-period models consider a binary maturity structure of long vs short debt (Arellano and Ramanarayanan, 2012; Cole and Kehoe, 2000; Conesa and Kehoe, 2017) whereas more recent multi-period models assume a special structure that is amenable to analytical solutions, such as consols with exponentially decaying coupons (Angeletos, 2002; Arellano and Ramanarayanan, 2012; Bocola and Dovis, 2019; Hatchondo and Martinez, 2009). We adopt a multi-period and discrete scenario tree setting which allows for a more granular and less stylized model formulation.

[19]These are points FP1 on PEPP2030 and PEPP2027, point FP5 on PEPP2025, FP9 on PEPP2024. We also take the points with cost closest to 3%, FP1 on QEternity and FP13 on NoPEPP.

cost reduction. This is slightly larger maturity extension than what has been observed empirically, but our model also suggests an optimal maturity of about 6 years (FP7) compared to the average of about 4 years before launching PSPP (Plessen-Mátyás et al., 2021).

Overall, it is possible to either lower costs or risks, or both, under PEPP, and we find that the empirically observed lengthening of maturities are consistent with a Pareto optimal move towards risk lowering. Our model predictions are in the direction of the documented eurozone PDMO behaviour, and quantitatively remarkably close.

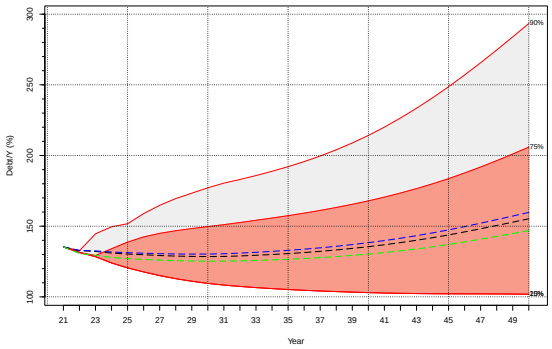
4.7 Inflation shock

We finally use the model to test the combined effects of an inflation shock with a monetary policy response, and a situation where the central bank considers inflation transitory and does not raise interest rates, under conventional and unconventional monetary policy-making. First we consider only conventional monetary policy with a short-lived inflation shock of about 4% (see Appendix Figure A.2, Panel A), with a central bank promptly raising interest rates (Appendix Figure A.2, Panel B) or a a situation where the monetary stance that does not respond to the inflation shock but instead persists in its pre-inflation path (Appendix Figure A.2, Panel C). Can we give a reference that this is a realistic test, given the current situation?

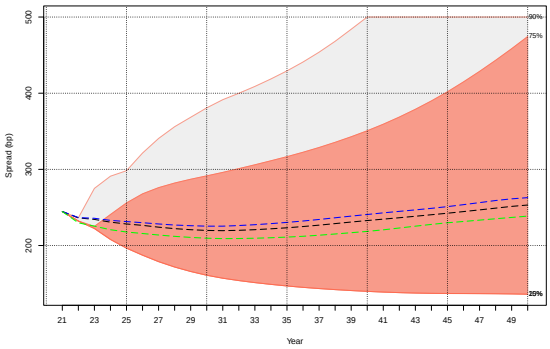
We show the effects In Figure 14. In Panel A, the color-shaded fan charts shows the debt stock dynamics of the baseline without the inflation shock. The blue line is the mean debt ratio when the central bank responds to inflation, and the green line is the mean when the central bank does not respond. The results are intuitive in the direction of change, but the magnitude of the effect is small. Specifically, debt dynamics slightly worsen if the central bank increases interest rates in response to inflation. The increase in the debt ratio is small, since the increase in debt financing costs (i.e., the numerator) is, in part, offset by the increase of nominal GDP (i.e., the denominator). If the central bank treats inflation as transitory and does not increase interest rates, the debt dynamics improve. However, the improvement is again very slight. In Panel B we show the spreads corresponding to the baseline, inflation shock with monetary response, and inflation shock without monetary response. A short lived inflation shock and conventional monetary policy have inconsequential effect on debt, and the debt dynamics of the high debt country remain on a growing path.

We repeat the experiment, introducing PEPP with 2024 exit date. We illustrate the results in Figure 14, Panel C where we show the mean and extreme 0.25/0.75 quantiles of debt ratio at the end of the horizon. That is, we illustrate a slice of the debt dynamics fan chart at year 2050, for all three cases. We observe from the three bars marked "No-PEPP " that debt increases by the end of the horizon under no inflation, inflation-interest rate

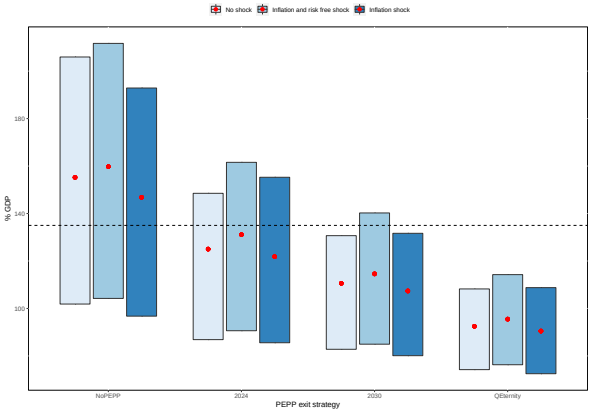
shock, and inflation-only shock. Under PEPP2024 we observe a reduction of the mean under all three inflation considerations. This is in line with the results of Figure 9 (Panel D), with a slight deterioration of debt dynamics when the central bank responds with an increase in interest rates. This experiment confirms that non-conventional monetary policymaking can also be a significant determinants of sovereign debt dynamics in the presence of inflation shocks.



(a) Debt stock dynamics



(b) Risk premium dynamics



(c) Debt ratio at the end of the horizon

Figure 14 – The effects of inflation shock under different monetary policy responses
The figure displays the fan charts corresponding to an inflation shock (Panel A) with the corresponding conventional monetary policy shock (Panel B) obtained from the Taylor rule with the parameters of Table A.1. Panel C displays fan charts assuming the central bank consider the inflation shock transitory and persists in its monetary policy rate with $\theta_i = 0.7$. The scenario tree is calibrated using moment-matching to the moments reported in Table A.3.

5 Conclusion

Disclaimer. The views presented in this paper are those of the authors and do not necessarily represent those of the Bank for international settlements.

References

A.B. Abel, B. Bernanke, and D.D. Croushore. *Macroeconomics*. Addison-Wesley, Boston, MA, 2011.

Enrique Alberola-Ila, Yavuz Arslan, Gong Cheng, and Richhild Moessner. The fiscal response to the Covid-19 crisis in advanced and emerging market economies. BIS Bulletins 23, Bank for International Settlements, June 2020. URL `https://ideas.repec.org/p/bis/bisblt/23.html`.

G-M. Angeletos. Fiscal policy with noncontingent debt and the optimal maturity structure. *The Quarterly Journal of Economics*, 117:1105–1131, 2002.

C. Arellano and A. Ramanarayanan. Default and the maturity structure in sovereign bonds. *Journal of Political Economy*, 120:187–232, 2012.

Yavuz Arslan, Mathias Drehmann, and Boris Hofmann. Central bank bond purchases in emerging market economies. BIS Bulletins 20, Bank for International Settlements, June 2020. URL `https://ideas.repec.org/p/bis/bisblt/20.html`.

Serkan Arslanalp and Takahiro Tsuda. Tracking global demand for advanced economy sovereign debt. *IMF Economic Review*, 62(3):430–464, 2014. URL `https://EconPapers.repec.org/RePEc:pal:imfecr:v:62:y:2014:i:3:p:430-464`.

Philippe Artzner, Freddy Delbaen, Jean Marc Eber, and David Heath. Coherent measures of risk. *Mathematical Finance*, 9(3):203–228, 1999.

A. Bassanetti, C. Cottarelli, and A.F. Presbitero. Lost and found: market access and public debt dynamics. *Oxford Economic Papers*, 71:445–471, 2018.

Niccolò Battistini, Marco Pagano, and Saverio Simonelli. Systemic risk, sovereign yields and bank exposures in the euro crisis. *Economic Policy*, 29(78):203–251, 11 2014. ISSN 0266-4658. doi: 10.1111/1468-0327.12029. URL `https://doi.org/10.1111/1468-0327.12029`.

BIS. A monetary lifeline: central banks' crisis response. Annual economic report, Chapter 2, Bank for International Settlements, 2020.

L. Bocola and A. Dovis. Self-fulfilling debt crises: A quantitative analysis. *American Economic Review*, 109:4343–77, 2019.

L. Boone, J. Fels, O. Jorda, M. Schularick, and A.M. Taylor. Debt: The eye of the storm. Geneva Reports of the World Economy 24, CEPR, London, 2021.

O. Bouabdallah, C. Checherita-Westphal, T. Warmedinger, R. de Stefani, F. Drudi, R. Setzer, and A. Westphal. Debt sustainability analysis for euro area sovereigns: a methodological framework. Occasional Paper 185, European Central Banks, 2017.

Christopher Bowdler and Rui Pedro Esteves. Sovereign debt: the assessment. *Oxford Review of Economic Policy*, 29(3):463–477, 12 2013. ISSN 0266-903X. doi: 10.1093/oxrep/grt037. URL https://doi.org/10.1093/oxrep/grt037.

Charles Carlstrom and Timothy Fuerst. The fiscal theory of the price level. *Economic Review*, Q I:22–32, 2000. URL https://EconPapers.repec.org/RePEc:fip:fedcer:y:2000:i:qi:p:22-32.

S. Chatterjee and B. Eyigungor. Maturity, indebtedness, and default risk. *American Economic Review*, 102:2674–2699, May 2012.

John Cochrane. The Fiscal Theory of the Price Level: An Introduction and Overview. *Journal of Economic Perspectives*, 2022.

H. Cole and T.J. Kehoe. Self-fulfilling debt crises. *Review of Economic Studies*, 67: 91–116, 2000.

European Commission. Debt sustainability monitor. Technical report, Institutional Paper 143, 2020.

J.C. Conesa and T.J. Kehoe. Gambling for redemption and self-fulfilling debt crises. *Economic Theory*, 64:707–740, 2017.

A. Consiglio, A. Carollo, and S.A. Zenios. A parsimonious model for generating arbitrage-free scenario trees. *Quantitative Finance*, 16:201–212, 2016.

Xavier Debrun, Klaus Masuch, Guiseppe Ferrero, Isabel Vansteenkiste, Marien Ferdinandusse, Leopold von Thadden, Sebastian Hauptmeier, Mario Alloza, Chloé Derouen, and Krzyszto Bańkowski. Monetary-fiscal policy interactions in the euro area. Occasional Paper Series 273, European Central Bank, September 2021. URL https://ideas.repec.org/p/ecb/ecbops/2021273.html.

P. D'Erasmo, E.G. Mendoza, and J. Zhang. What is a sustainable public debt? In J.B. Taylor and H. Uhlig, editors, *Handbook of Macroeconomics*, chapter 32, pages 2493 – 2597. Elsevier, Amsterdam, 2016.

A. Dieppe and P. Guarda. Public debt, population ageing and medium-term growth. Occasional Paper Series 165, European Central Bank, 2015.

Michael Ehrmann and Marcel Fratzscher. Euro area government bonds – fragmentation and contagion during the sovereign debt crisis. *Journal of International Money and Finance*, 70:26–44, 2017. ISSN 0261-5606. doi: https://doi.org/10.1016/j.jimonfin.2016.08.005. URL https://www.sciencedirect.com/science/article/pii/S0261560616300948.

B. Eichengreen and U. Panizza. A surplus of ambition: can Europe rely on large primary surpluses to solve its debt problem? *Economic Policy*, 31:5–49, 2016.

Raquel Fernández and Alberto Martin. The long and the short of it: Sovereign debt crises and debt maturity. Working Paper 20786, National Bureau of Economic Research, December 2014. URL http://www.nber.org/papers/w20786.

Joseph Gagnon, Matthew Raskin, Julie Remache, and Brian Sack. The Financial Market Effects of the Federal Reserve's Large-Scale Asset Purchases. *International Journal of Central Banking*, 7(1):3–43, March 2011. URL https://ideas.repec.org/a/ijc/ijcjou/y2011q1a1.html.

J.C. Hatchondo and L. Martinez. Long-duration bonds and sovereign defaults. *Journal of International Economics*, 79:117–125, 2009.

Boris Hofmann, Marco Lombardi, Benoit Mojon, and Athanasios Orphanides. Fiscal and monetary policy interactions in a low interest rate world. CEPR Discussion Papers 16411, C.E.P.R. Discussion Papers, July 2021a. URL https://ideas.repec.org/p/cpr/ceprdp/16411.html.

Boris Hofmann, Marco Lombardi, Benoit Mojon, and Athanasios Orphanides. Fiscal and monetary policy interactions in a low interest rate world. CEPR Discussion Papers 16411, C.E.P.R. Discussion Papers, July 2021b. URL https://ideas.repec.org/p/cpr/ceprdp/16411.html.

IMF. World economic outlook: World economic outlook: A long and difficult ascent,. Technical report, International Monetary Fund, Washington, D.C., 2013.

IMF. Review of the debt sustainability framework for market access countries. Policy paper, International Monetary Fund, January 2021.

S.E.H. Jensen and B. Nielsen. Population ageing, public debt and sustainable fiscal policy. *Fiscal Studies*, 16:1–20, 1995.

A. Kamiguchi and T. Tamai. Public investment, public debt, and population aging under the golden rule of public finance. *Journal of Macroeconomics*, 60:110–122, 2019.

Philip R. Lane. The european sovereign debt crisis. *Journal of Economic Perspectives*, 26(3):49–68, September 2012. doi: 10.1257/jep.26.3.49. URL https://www.aeaweb.org/articles?id=10.1257/jep.26.3.49.

Alessandro Missale. Sovereign debt management and fiscal vulnerabilities. In Bank for International Settlements, editor, *Threat of fiscal dominance?*, volume 65 of *BIS Papers chapters*, pages 157–176. Bank for International Settlements, November 2012. URL https://ideas.repec.org/h/bis/bisbpc/65-10.html.

Dirk Niepelt. Debt maturity without commitment. *Journal of Monetary Economics*, 68:S37–S54, 2014. ISSN 0304-3932. doi: https://doi.org/10.1016/j.jmoneco.2014.08.006. URL https://www.sciencedirect.com/science/article/pii/S0304393214001330. Supplement issue: October 19-20, 2012 Research Conference on "Financial Markets, Financial Policy, and Macroeconomic Activity" Sponsored by the Study Center Gerzensee and the Swiss National Bank.

P. Paesani, R. Strauch, and M. Kremer. Public debt and long-term interest rates. the case of Germany, Italy and the USA. Working Paper Series 656, European Central Bank, Frankfurt, DE, July 2006.

A. Phillips. Employment, inflation and growth. *Economica*, 29(113):1–16, 1962.

K. Plessen-Mátyás, C. Kaufmann, and J. von Landesberger. Funding behaviour of debt management offices and the ecb's public sector purchase programme. Working Paper Series 2552, European Central Bank, Frankfurt, DE, 2021.

J.B. Taylor. Discretion versus policy rules in practice. *Carnegie-Rochester Conference Series on Public Policy*, 39:195–214, 1993.

Fabrizio Zampolli. Sovereign debt management as an instrument of monetary policy: an overview. In Bank for International Settlements, editor, *Threat of fiscal dominance?*, volume 65 of *BIS Papers chapters*, pages 97–118. Bank for International Settlements, November 2012. URL https://ideas.repec.org/h/bis/bisbpc/65-06.html.

S.A. Zenios. The risks from climate change to sovereign debt in Europe. Policy Contribution 16/2021, Bruegel, Brussels, 2021.

S.A. Zenios, A. Consiglio, M. Athanasopoulou, E. Moshammer, A. Gavilan, and A. Erce. Risk management for sustainable sovereign debt financing. *Operations Research*, 69: 755–773, 2021.

Online Companion

A Data Appendix

A.1 Conventional monetary policy

In Table A.1 we give the the parameters for the Phillips curve eqn. (11), output gap eqn. (12), and Taylor rule eqn. (13), drawing from existing literature (Hofmann et al., 2021b)..

Table A.1: Parameters of the calibrated macroeconomic and monetary policy frameworks

Variable	Value	Meaning
α_π	0.4	Coefficient of inflation in Taylor rule
α_i	0.25	Coefficient of output gap in Taylor rule
α_y	0.5	Coefficient of interest rate in output gap
γ	0.2	Coefficient of output gap in Phillips curve
β_π	0.3	Persistence of past inflation
$\delta_{\hat{y}}$	0.2	Persistence of past output gap
θ_i	0.2	Persistence of past interest rate
r^*	0	Natural interest rate
π^*	2	Target inflation rate

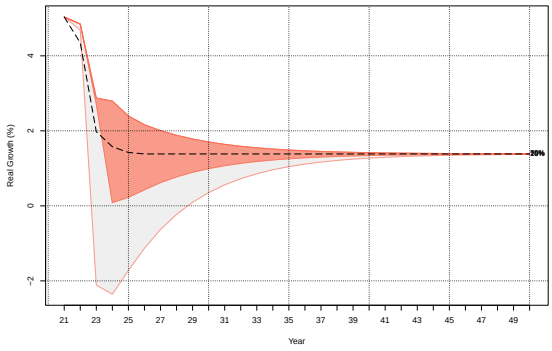
Table A.2: Parameterisation

A.2 Scenario tree

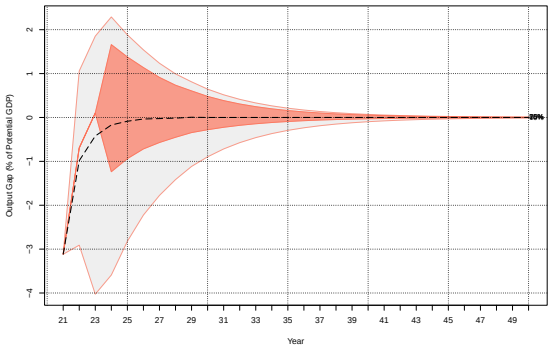
To calibrate the scenario tree centered on market expectations, we use the standard deviations and correlations estimated from historical yearly data over from the WEO data base, over the period 1998 to 2019, shown in Table A.3. Inflation rate and the output gap time series are for the Eurozone, whereas for real growth and primary balance we use the Italian time series. Using the moment-matching method of Consiglio, Carollo, and Zenios (2016) we calibrate the tree to these data. For computational tractability we calibrate a tree of 256 scenarios over five years, and after that the variables converge to their long-term averages. The scenario tree is calibrated for 2021–2050, and we display in Figure A.1 fan charts from the calibrated tree of real GDP growth, output gap, primary balance, and inflation.

A.3 Risk and term premia

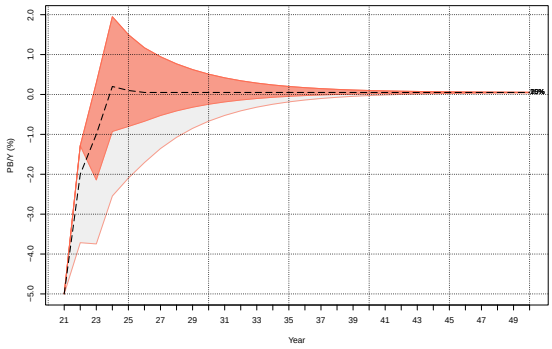
For the risk and term premia of subsection 2.2 we calibrate eqn.(17) following Zenios et al. (2021). We use panel data from 23 EU countries over the period 1995–2020, with baseline the 5-year maturity to obtain the following parameters:



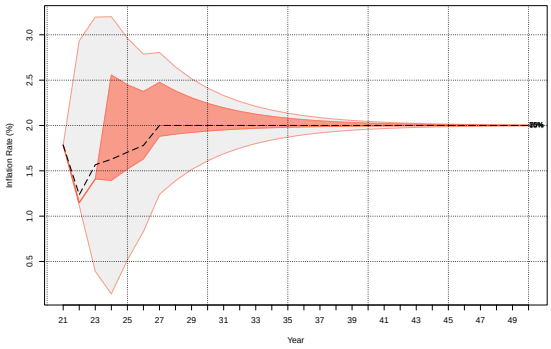
(a) Real GDP growth



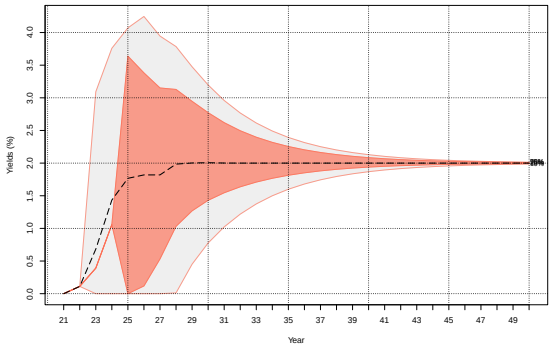
(b) Output gap



(c) Primary balance



(d) Inflation



(e) Nominal interest rates

Figure A.1 – Fan charts from the scenario tree

The figure displays fan charts for the calibrated economy from the scenario tree, as follows: real GDP growth, output gap, primary balance, and inflation scenarios. It also displays the nominal interest rates obtained using the Taylor rule with the parameters given in Table A.1. Panels A, B, and C refer to the representative eurozone high-debt country, panel D refer to the eurozone. The scenario tree is calibrated using moment-matching to the moments reported in Table A.3.

Factors	Standard deviation	Correlations			
Inflation	0.82	1.00	0.62	0.30	0.10
Output gap	1.62	0.62	1.00	0.51	0.37
Real growth	1.91	0.30	0.51	1.00	0.42
Primar balance	1.33	0.10	0.37	0.42	1.00

Table A.3: Moments for the calibration of a scenario tree

Equation (16)				Equation (17)	
Coefficient	Bond maturity			Coefficient	Value
	3	5	10		
a_j	-25	0	50	$\hat{\rho}$	2.10
b_j	-0.13	0	0.13	d_{min}	60
				d_{max}	220

The baseline maturity bond carries no term premia but only a risk premium (eqn. 17). The maximum spread with this calibration is about 340bp, as observed during the eurozone debt crisis at which level the sovereign is cut off the markets, and debt financing costs are stabilized by official sector support.

A.4 Inflation shock

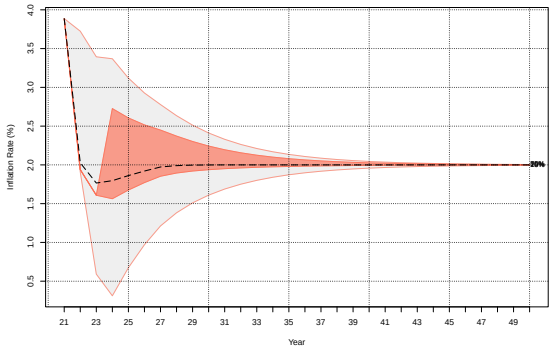
The inflation shock is shown in Figure A.2, Panel A. Panel B shows the monetary policy response to this shock, with interest rates responding according to our baseline calibration of the Taylor rule. Panel C shows the case where the central bank considers the inflation shock to be transitory and does not adjust the interest rate with the baseline Taylor rule but instead persists in its pre-inflation path; we simulate this situation by setting the persistence parameter $\theta_i = 0.7$, instead of the value 0.2 in Table A.1.

A.5 Legacy debt

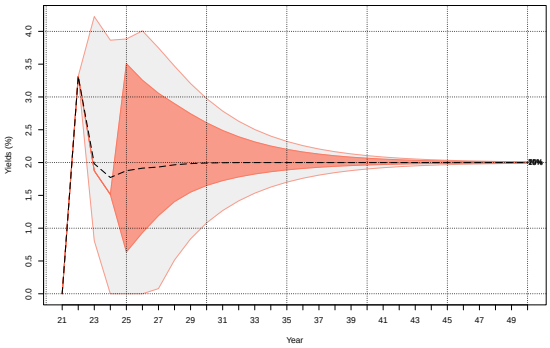
The legacy debt of the representative high-debt country is shown in Figure A.3.

B A model fitting sovereign spreads to PEPP

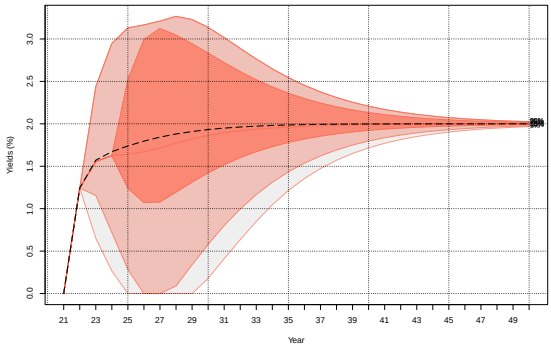
In Figure B.1 we plot the residuals versus predictive values of the model, with the QQ and index plot, and the histogram of Pearson residuals with the fitted normal. The residual plot shows no specific pattern around the horizontal dashed line (as also the index plot), suggesting that the chosen model is reasonable. Moreover, residuals scatter



(a) Inflation shock



(b) Nominal interest rates shock



(c) Persistent nominal interest rates

Figure A.2 – Inflation shock and conventional monetary policy responses
The figure displays the fan charts corresponding to an inflation shock (Panel A) with the corresponding conventional monetary policy shock (Panel B) obtained from the Taylor rule with the parameters of Table A.1. Panel C displays fan charts assuming the central bank consider the inflation shock transitory and persists in its monetary policy rate with $\theta_i = 0.7$. The scenario tree is calibrated using moment-matching to the moments reported in Table A.3.

uniformly around the 0-line, implying that the error term is homoscedastic and Gaussian distributed, also seen in the Q-Q plot and the histogram.

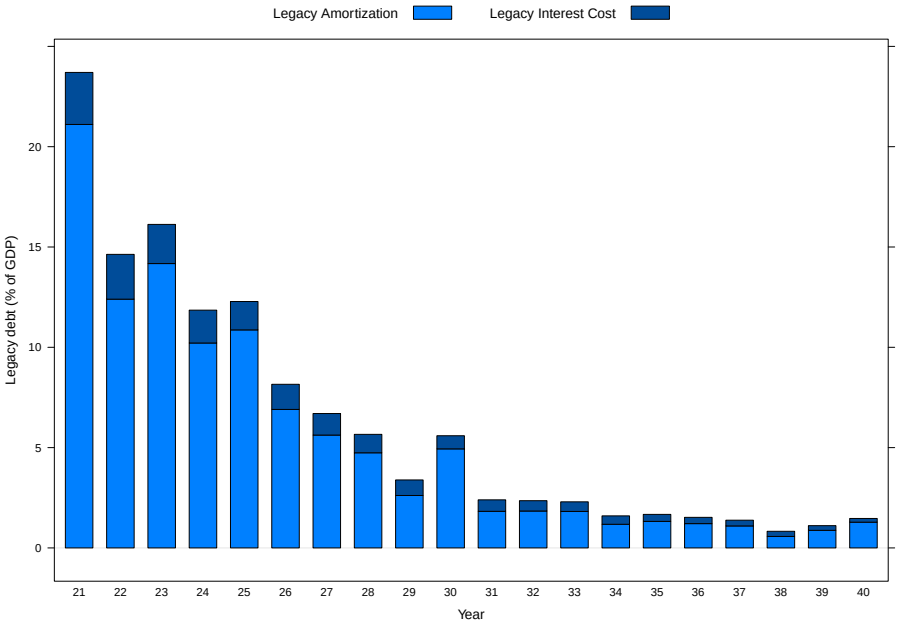


Figure A.3 – Legacy debt of eurozone representative high-debt country

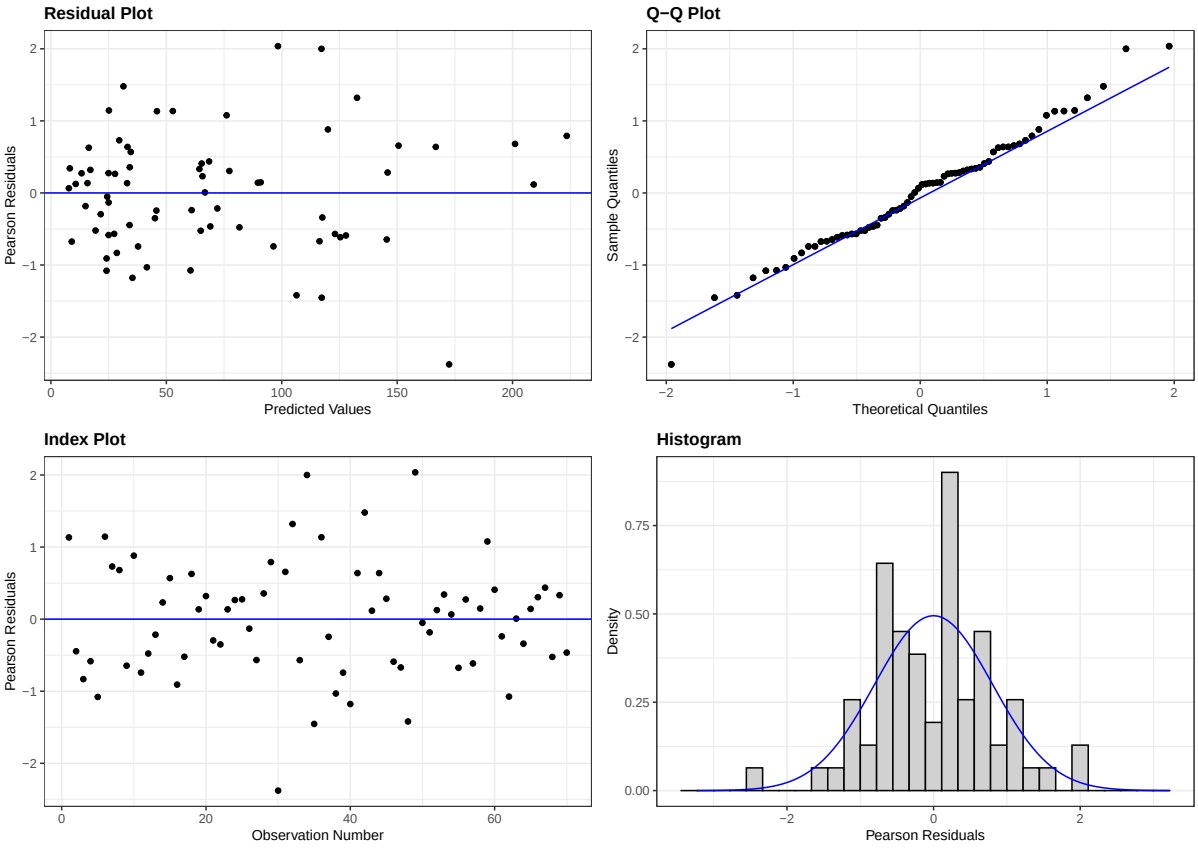


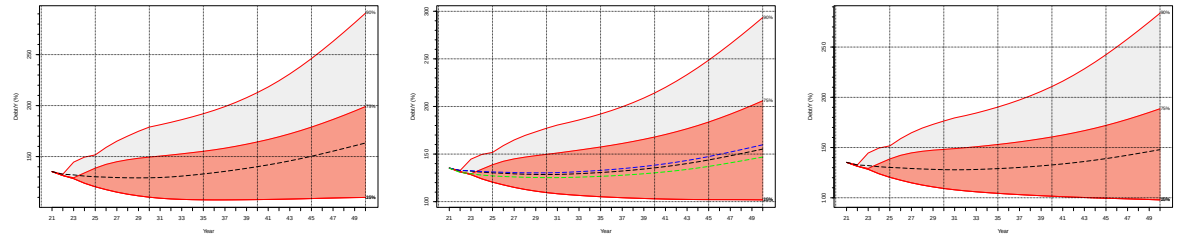
Figure B.1 – Diagnostic tests of a mixed-effects PEPP model of sovereign spreads.

C Additional results

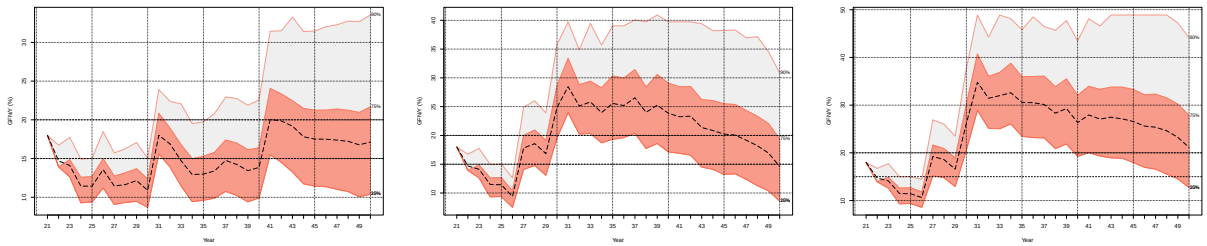
Figure C.1 – Debt sustainability analysis without PEPP with different debt financing strategies

This figure displays the counterfactual of debt sustainability without the unconventional PEPP intervention. It shows details of the debt dynamics at three different points of the efficient frontier of Figure 12: the minimum risk FP1, the minimum cost FP13, and an intermediate tradeoff FP7. Panels A-C display scenarios of debt-to-GDP ratio, panels D-F display debt flow ratios, and panels G-I display risk premia (spreads).

(a) Debt stock at FP1 **(b)** Debt stock at FP7 **(c)** Debt stock at FP13



(d) Debt flow at FP1 **(e)** Debt flow at FP7 **(f)** Debt flow at FP13



(g) Risk premium at FP1 **(h)** Risk premium at FP7 **(i)** Risk premium at FP13

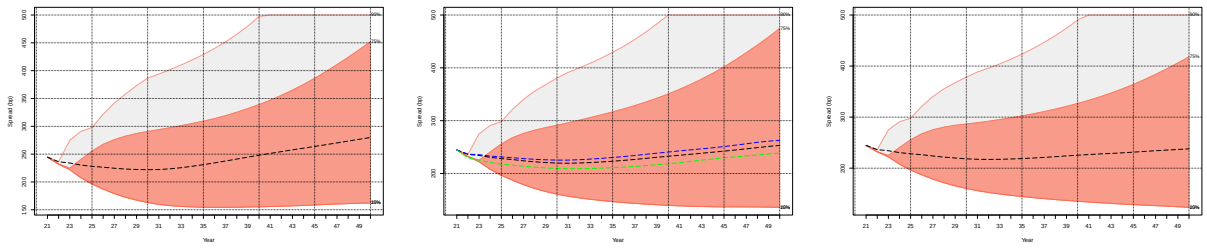
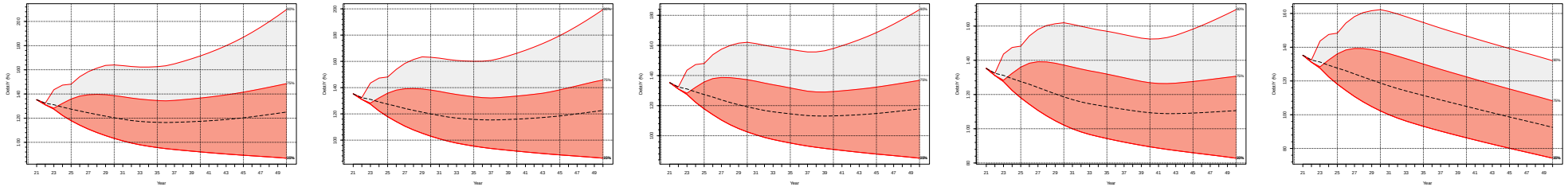


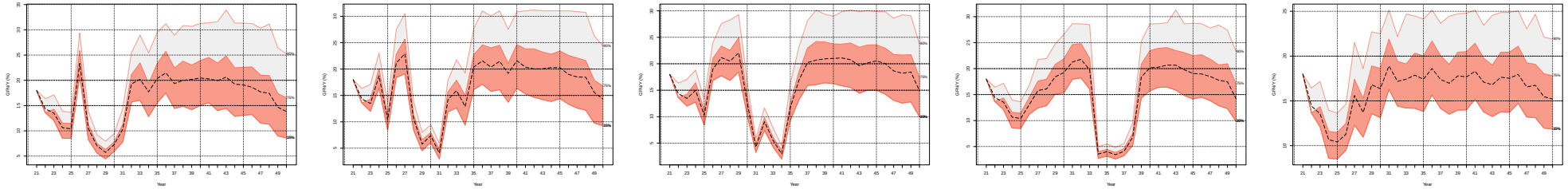
Figure C.2 – Debt sustainability analysis with PEPP of different unwinding schedules

This figure displays results of debt sustainability analysis under the unconventional PEPP intervention. It shows details of the debt dynamics with different PEPP programs. PEPPn denotes a program that is launched in 2020, and continues until year n, at which point it starts unwinding over a five year period. All test are done using a debt financing strategy with intermediate tradeoff between cost and risk (FP7).

(a) Debt stock, PEPP2024 **(b)** Debt stock, PEPP2025 **(c)** Debt stock, PEPP2027 **(d)** Debt stock, PEPP2030 **(e)** Debt stock, forever



(f) Debt flow, PEPP2024 **(g)** Debt flow, PEPP2025 **(h)** Debt flow, PEPP2027 **(i)** Debt flow, PEPP2030 **(j)** Debt flow, forever



(k) Risk premia, PEPP2024 **(l)** Risk premia, PEPP2025 **(m)** Risk premia, PEPP2027 **(n)** Risk premia, PEPP2030 **(o)** Risk premia, forever

