The Green Transition and Public Finances

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Research question

- Policymakers are confronted with a growing urgency to act upon climate change
- Additional mitigation efforts are needed to keep global warming to no more than 1.5°C – as called for in the Paris Agreement.
- Governments have several policy options for mitigation:
  1. charging private agents in proportion to their level of pollution via **carbon pricing**
  2. bearing part of the costs through **public investment** in abatement technologies, or through **subsidies** to the private sector.
- While carbon pricing policies generate revenues for the government, supporting the transition through public spending measures entails significant budgetary costs that can make public debt unsustainable.
- Using a dynamic general equilibrium model, we analyse the macroeconomic implications of the green transition and its consequences for public finances.

Policy issues

- The transition to a low-carbon economy requires huge investment in abatement technologies.
- Such investment represents between 2 and 4% of GDP every year at world level.
- In Europe, estimates of additional investments reach close to 4% of GDP to achieve both the objectives of the Green Deal and those of the RepowerEU initiative.
- The share of public investment ranges from 28% (Wolff and Darvas, 2022) to 50% (Pisani-Ferry and Mahfouz, 2023).
- The sustainability of public debt should act as a ceiling on the share of public investment.
- If the transition were to be mainly financed by public support (and debt), debt would become unsustainable (IMF, 2023).

Literature

- While addressed in policy debates (Emambakhsh et al., 2023, IMF, 2023), the topic is absent in the academic literature.
- Rare contributions include
  1. Agarwala et al., 2021 shows how the physical and transition impacts from climate change translate into fiscal risks.
  2. Zenios, 2022 combines two Integrated Assessment Models (IAMs) with a stochastic debt sustainability analysis (DSA) to assess the available fiscal space to finance climate policies.
- A few papers also investigate empirically the link between transition risk and sovereign bond yields (Battiston and Monasterolo, 2020, Klusak et al., 2021).
- This paper is at the crossroad of two literature streams, which integrate into NK models:
  1. **environmental components**: macro-climate real model to analyze economic dynamics in the presence of the greenhouse gas-related externality (Heutel, 2012; Annicchiarico and Di Dio, 2015)
  2. **public debt sustainability considerations**: integration of public debt sustainability issues into macroeconomic models (Corsetti et al., 2013, Darracq et al., 2016)

Main Results

- Relying too heavily on public expenditure-based measures implies increased probability of sovereign default and higher interest rates on government bonds.
- Carbon pricing policies offer a more viable alternative for public finances and remain effective in reducing greenhouse gas emissions, despite higher economic costs.
- When including spillover effects, the macroeconomic costs of expenditure-based measures, in a high-debt country, become similar to the carbon tax costs.
- Intermediate policy choices reduce the economic cost, without increasing sovereign risk $\Longrightarrow$ optimal policy

A macro-climate model with risky government debt

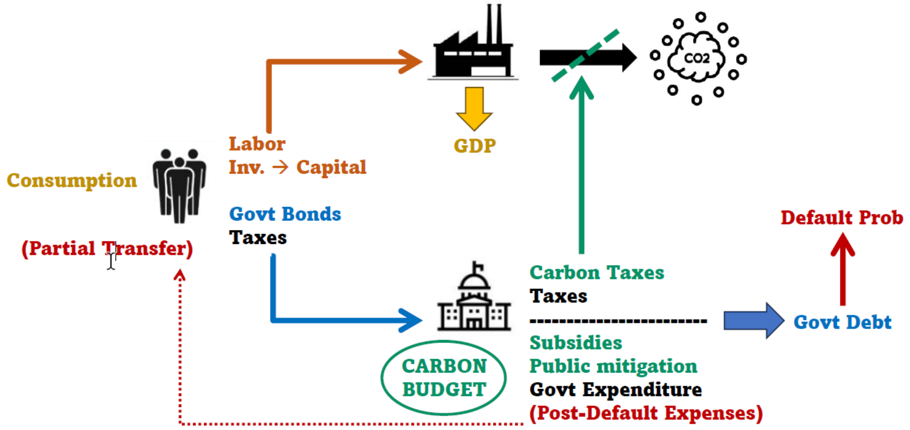


Figure: The model's structure. Variables between parentheses are not null only in case of default on government debt.

The Macro-climate model

- Carbon budget in line with the Paris Agreement and IPCC indications: $\sum_{j=0}^{+\infty} E_j \leq \bar{E}_0^n$
- Emissions are a by-production of GDP: $E_t(i) = \xi_t[1 - m_t(i) - m_t^g]Y_t(i)$
- Standard Cobb-Douglas production function $\Longrightarrow$ without or with climate damages.
- Each firm i maximizes profits, produces an unique good Y, remunerates labor and capital, pays abatement costs and carbon taxes: $\Pi_t(i) = Y_t(i) - W_t L_t(i) - R_t^k K_t(i) - (1 - s_t^A)A_t(i) - \tau_t^E E_t(i)$
- The representative household consumes, works, invests in capital, pays lump-sum taxes and invests in risky government bonds.

  In case of sovereign default she is compensated only by $(1 - f)$ of the lost value

  $\Longrightarrow R_t \approx (1 - f\vartheta \mathrm{PD}_{t+1})R_t^d$

Model appendix

Fiscal Policy and Abatement Costs

- Investors evaluate PD according to:

$$b_M e^{\epsilon_t} < b_t \quad \text{where} \quad \epsilon_t \sim N(0, \sigma_B) \tag{1}$$

  b_M: fiscal limit in terms of maximum sustainable government borrowing-to-GDP ($b_t \equiv \frac{B_t}{Y_t}$), subject to uncertainty $\Longrightarrow$ PD writes as a standard normal c.d.f.:

$$\text{PD}_{t+1} = \Phi\left(\frac{\ln(b_t) - \ln(b_M)}{\sigma_B}\right) \tag{2}$$

- Consolidated government budget constraint: Govt budget contraint

$$B_t = B_{t-1} R^d_{t-1} - S_t \tag{3}$$

- "Consolidated" primary surplus: $S_t = T_t + \tau^E_t E_t - G_t - s^A_t A_t - A^g_t$
- Private and public abatement costs: $A_t = \theta_1 [m_t]^{\theta_2} Y_t, \quad A^g_t = \theta_3 [m^g_t]^{\theta_4} Y_t; \quad \theta_3 = \theta_1, \quad \theta_4 < \theta_2$

Calibration

- Quarterly calibration. ▸ Parameters
- Follows existing literature for the traditional Neoclassical model aspects.

Transition Setup:

- Global cumulative CO_2-equivalent emissions till 2023: 3497 Gt (Source: Greenhouse gas emissions, ourworldindata.org).
- Global carbon budget: 240 Gt CO_2 (IPCC, 2023) $\Rightarrow$ Fair per-capita national budgets: France: 1.9 Gt CO_2, Italy: 1.7 Gt CO_2, Germany: 2.4 Gt CO_2.
- Private abatement cost function coefficients calibrated to match a (detrended) long-term carbon tax for France of US$ 1000 per ton of CO_2, in the case of a transition to 1.5°C with 67% probability, achieved only through carbon pricing (in line with D'Arcangelo et al., 2022 and Quinet et al., 2019).
- $\theta_4 < \theta_2$: abatement costs relatively higher for the public than for the private sector.
  Marginal costs lower for the private at the beginning of the transition, and increasing above public marginal costs as we approach a full decarbonisation. Conversely, marginal public costs are much higher immediately, in line with huge investment in green infrastructure (Criqui, 2023, Pisani-Ferry and Mahfouz, 2023).

▸ Abatement cost functions

Calibration

Country-Specific Parameters:

▸ Parameters

- TFP for France normalized to 1. Italian and German parameters reflect productivity ratios relative to France. (Bergeaud, Cette, and Lecat, 2016)
- Carbon intensity of GDP sourced from ourworldindata.org; public expenditure ratio from data.worldbank.org.

Public debt sustainability:

- Log-normal probability of default parameters determined in order to match government risk premia with current evidence.
- National fiscal limits in line with evidence provided by Collard, Habib, and Rochet, 2015 and Seghini, 2023.
- Consolidated haircut $f\vartheta = 0.21$, reasonably conservative for advanced economies: product of high haircut $\vartheta = 0.7$ and fraction $f = 0.3$ (post-default government expenditure as a fraction of investors' lost value $\vartheta_t R^d_{t-1} B_{t-1}$)

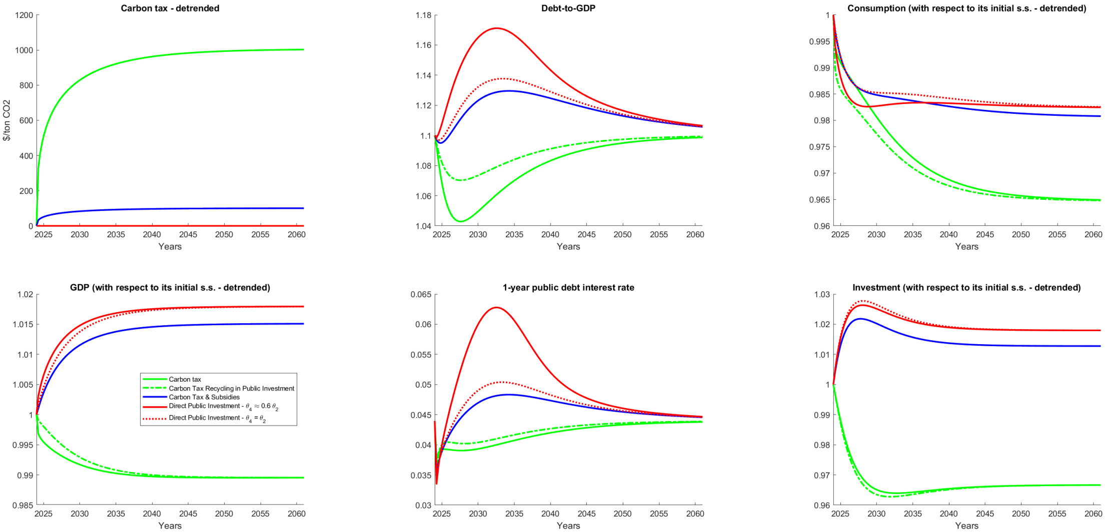
Results

- Three main scenarios:
  (1) carbon tax (green line)
  (2) direct public investment (red line);
  (3) carbon tax with subsidies at 90% (blue line).
- Benchmark results calibrated for France.

  Sensitivity analysis on: public abatement costs and redistribution of carbon tax proceeds.
- Incorporate climate damages to evaluate the potential impact of physical risks on public finances.
- Differentiate our results based initial indebtedness: comparing France with a high-debt country (Italy) and a low-debt country (Germany).
- Include financial spillovers, linking the cost of private investment to the sovereign risk premium.

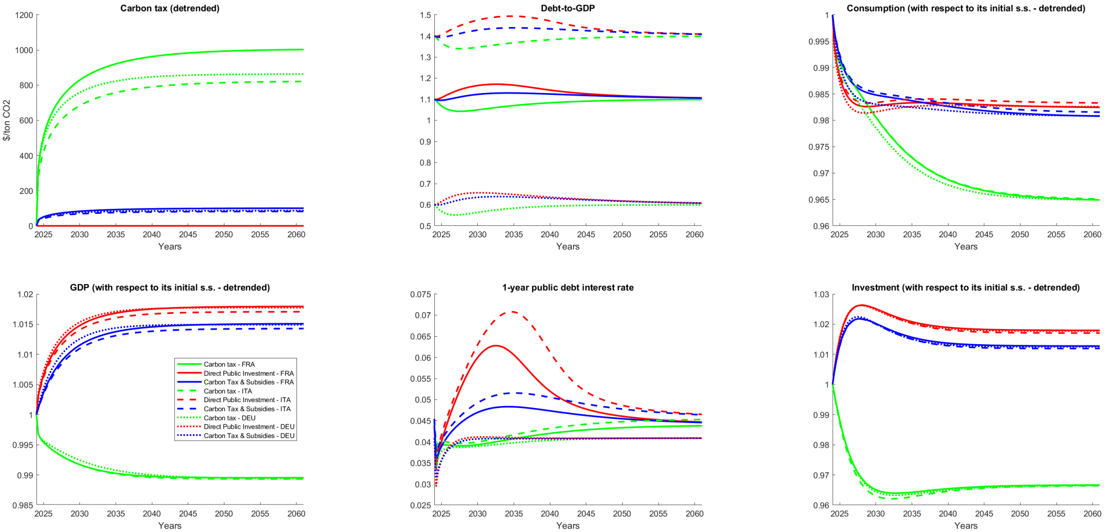
Benchmark Results

▸ Other Variables



Initial debt-to-GDP levels

Other Variables



Financial spillover of high public debt risk to private financing conditions

▸ Spillover Mechanism

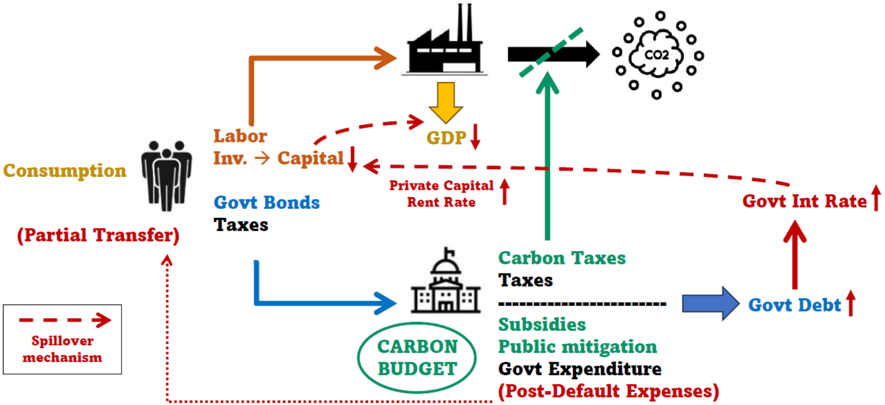
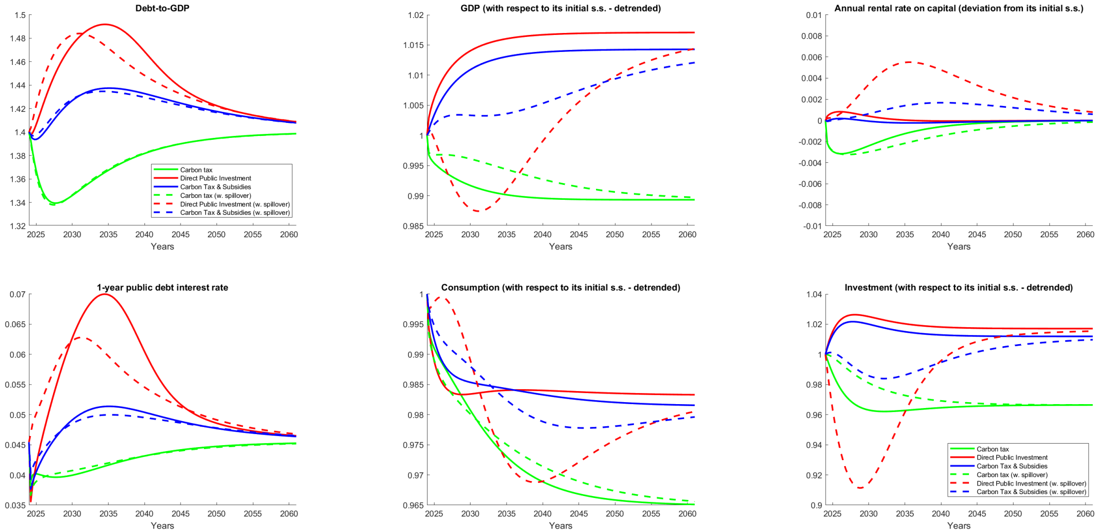


Figure: The financial impact of higher government debt on private sector financing conditions. Variables between parentheses are not null only in case of default on government debt.

Financial spillover of high public debt risk to private financing conditions

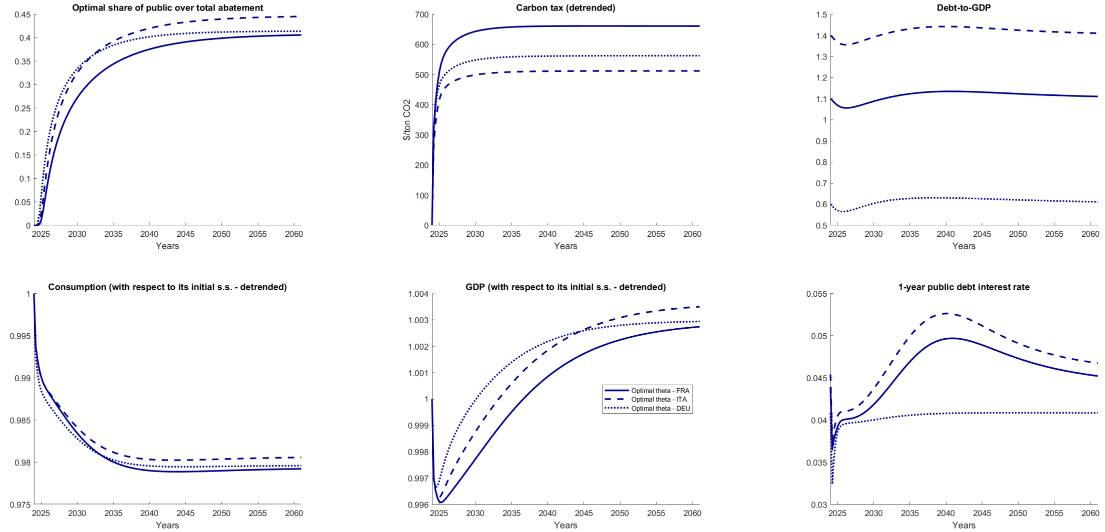
Other Variables



Welfare maximization

Optimal public over total abatement, under zero subsidies and no spillover:

▸ Welfare Maximization ▸ Sensitivity analysis



Concluding remarks

- Main findings: while transition policies are crucial for a low-carbon future, those increasing public debt present significant challenges, potentially making the debt unsustainable or leading to higher financing costs, thus hindering the transition.
- Incorporating climate-related damages into the model exacerbates the situation, negating any positive macroeconomic impact of public expenditure-driven policies on aggregate demand.
- Spillover from increased public debt riskiness to private financing conditions reveals a more severe macroeconomic impact.
- Pivotal role of initial debt conditions: highly indebted countries face greater negative impacts on public finances from transition policies $\Rightarrow$ need for prudent fiscal strategies.

- Carbon budget in line with the Paris Agreement and IPCC, 2023: $\sum_{j=0}^{+\infty} E_j \leq \bar{E}_0^n$
  E_t: national emissions in one period; $\bar{E}_0^n$: economy's carbon budget.
- Emissions are a by-product of GDP: $E_t(i) = \xi_t[1 - m_t(i) - m_t^g]Y_t(i)$
  $m_t(i)$: private abatement effort; m_t^g: public abatement intervention; ξ_t: output's carbon intensity
- Cobb-Douglas production function with capital $K_t(i)$ and labor $L_t(i)$ as inputs, with potential addition of climate damages on productivity. Each firm i produces:

$$Y_t(i) = D_f(H_t^G)K_t(i)^{\kappa}[Z_t L_t(i)]^{1-\kappa}, \quad \kappa \in (0,1), \quad f \in \{NC, AD, DV\} \tag{4}$$

κ: elasticity of output with respect to capital; Z_t: labor-intensive technological progress.
D_f: TFP, potentially decreasing in global cumulative GHG emissions, (since 1850)

$$H_t^G = H_{-1}^G + \frac{\bar{E}_0^G}{\bar{E}_0^n} H_t = H_{t-1}^G + \frac{\bar{E}_0^G}{\bar{E}_0^n} E_t \tag{5}$$

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Appendix – The macro-climate model: climate damages and abatement costs

- TFP and climate damages ⇒ Three specifications:
  1. No climate (NC):
  $$D_{NC}(H_t^G) = \bar{D} \tag{6}$$
  2. AD for Annicchiarico and Di Dio, 2015:
  $$D_{AD}(H_t^G) = \bar{D}(1 - \gamma_0 - \gamma_1 H_t^G - \gamma_2 {H_t^G}^2) \tag{7}$$
  3. DV for Dietz and Venmans, 2019:
  $$D_{DV}(H_t^G) = \bar{D} \exp\left\{-\frac{\gamma_3}{2}(\gamma_4 H_t^G)^2\right\} \tag{8}$$
- Abatement technology cost (Annicchiarico and Di Dio, 2015; Jondeau et al., 2023):
$$A_t(i) = \theta_1 [m_t(i)]^{\theta_2} Y_t(i), \quad \theta_1 > 0, \theta_2 > 1. \tag{9}$$

▸ Impact of Climate Damages ▸ Back to Model Summary

Appendix – Mitigation rule, profit maximization and carbon tax

- Mitigation policy rule respecting the carbon budget $\bar{E}_0^n$:

$$m_t + m_t^g = \left(\frac{H_{t-1}}{\bar{E}_0^n}\right)^p \tag{10}$$

$$\frac{m_t^g}{m_t + m_t^g} = \theta \tag{11}$$

$p > 0$: curvature of the mitigation policy rule;
θ: share of government direct investment on total abatement efforts.

- Each firm i maximizes profits:

$$\Pi_t(i) = Y_t(i) - W_t L_t(i) - R_t^k K_t(i) - (1 - s_t^A) A_t(i) - \tau_t^E E_t(i) \tag{12}$$

subject to the production function (4). W_t, R_t^k, τ_t^E and s_t^A: respectively the real wage, the rental rate on capital, the carbon tax and the public subsidy to abatement costs.

FOCs

$$\Longrightarrow \tau_t^E = \frac{(1 - s_t^A)\theta_1\theta_2[m_t(i)]^{\theta_2 - 1}}{\xi_t} \tag{13}$$

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Appendix – Household's intertemporal maximization

- The representative household consumes, works, invests in capital, pays lump-sum taxes and invests in risky government bonds.
- She maximizes:

$$\mathbb{E}_t \sum_{i=0}^{\infty} \beta^i \left(\ln C_{t+i} - \mu_L \frac{L_{t+i}^{1+\sigma_l}}{1+\sigma_l} \right), \quad \sigma_l > 0, \mu_L > 0.$$

$\beta \in (0,1)$ discount factor, C_t consumption and L_t work hours supplied by the household.

- Household's budget constraint for each period:

$$C_t + I_t + B_t = (1 - \vartheta_t) R_{t-1}^d B_{t-1} + W_t L_t + \Pi_t + R_t^k K_t - T_t + V_t. \tag{14}$$

B_t: household's investment in government bonds.

- Capital accumulation equation with investment adaptation cost $S(\cdot)$:

$$K_{t+1} = (1-\delta) K_t + I_t \left[1 - S\left(\frac{I_t}{I_{t-1}} \right) \right], \quad \delta \in (0,1). \tag{15}$$

FOCs $\Rightarrow$ From FOCs with respect to investment and capital ($q_t^k = \lambda_t^k / \lambda_t$: Tobin's Q):

$$R_t \equiv \frac{\lambda_t}{\beta \mathbb{E}_t [\lambda_{t+1}]} = \frac{1}{q_t^k \mathbb{E}_t [\lambda_{t+1}]} \left\{ \mathbb{E}_t \left[\lambda_{t+1} R_{t+1}^k \right] + (1-\delta) \mathbb{E}_t \left[\lambda_{t+1} q_{t+1}^k \right] \right\}. \tag{16}$$

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Appendix – Risky Government Debt

⇒ From FOC with respect to investment in government debt:

$$R_t = \frac{\mathbb{E}_t\left[\lambda_{t+1}(1 - f\vartheta_{t+1})R_t^d\right]}{\mathbb{E}_t\left[\lambda_{t+1}\right]} \approx (1 - f\vartheta \mathrm{PD}_{t+1})R_t^d, \tag{17}$$

- In case of sovereign default the household is compensated only by $(1 - f)$ of the lost value: $V_t \equiv (1 - f)\vartheta_t R_{t-1}^d B_{t-1} \implies$ Government debt is risky
- Haircut $\vartheta_t = \vartheta \in [0, 1]$, when the government partially defaults on debt, event with probability PD_t.
- Investors evaluate PD according to:

$$b_M e^{\epsilon_t} < b_t \quad \text{where} \quad \epsilon_t \sim N(0, \sigma_B) \tag{18}$$

b_M: fiscal limit in terms of maximum sustainable government borrowing-to-GDP ($b_t \equiv \frac{B_t}{Y_t}$), subject to uncertainty $\implies$ PD writes as a standard normal c.d.f.:

$$\mathrm{PD}_{t+1} = \Phi\left(\frac{\ln(b_t) - \ln(b_M)}{\sigma_B}\right), \tag{19}$$

▸ Back to Model Summary

Appendix – Risky Government Debt

- Consolidated government budget constraint: ▸ Govt budget contraint

$$B_t = B_{t-1}R^d_{t-1} - S_t, \tag{20}$$

- "Consolidated" total primary surplus (excluding default transfers and expenditure):

$$S_t = T_t + \tau^E_t E_t - G_t - s^A_t A_t - A^g_t = \{\tau_t + \tau^E_t \xi_t (1 - m_t - m^g_t) - g - \theta_1 s^A_t m^{\theta_2}_t - \theta_3 (m^g_t)^{\theta_4}\} Y_t \tag{21}$$

  g: exogenous public expenditure as a fraction to GDP; $A^g_t = \theta_3 (m^g_t)^{\theta_4} Y_t$: public abatement costs, $\theta_4 < \theta_2$.

- Total borrowing proceeds :

$$B_t \equiv b_t Y_t = \frac{D_{t+1}}{R^d_t} \equiv \frac{d_t Y_t}{R^d_t} \tag{22}$$

  We recover b_t from the government budget constraint as:

$$b_t = \frac{b_{t-1} Y_{t-1} R^d_{t-1} - S_t}{Y_t}, \tag{23}$$

  and the face value of debt-to-GDP d_t implicitly from:

$$b_t = \frac{d_t}{R^d_t} \tag{24}$$

▸ Back to Model Summary

Appendix – Firm's FOCs

$$(\delta L_t(i)) \quad \Theta_t(i) D_f(H_t^G) K_t(i)^{\kappa}(1-\kappa) Z_t^{1-\kappa} L_t(i)^{-\kappa} = W_t \tag{25}$$

$$(\delta K_t(i)) \quad \Theta_t(i) D_f(H_t^G) \kappa K_t(i)^{\kappa-1} (Z_t L_t(i))^{1-\kappa} = R_t^k \tag{26}$$

$$(\delta m_t(i)) \quad \tau_t^E \xi_t = (1 - s_t^A)\theta_1 \theta_2 [m_t(i)]^{\theta_2 - 1} \tag{27}$$

$\Theta_t(i)$: Lagrange multiplier associated to (4) and the marginal cost's component attached to labor and capital.[1]

$$\Theta_t = \frac{(W_t)^{1-\kappa} \left(R_t^k\right)^{\kappa}}{D_f(H_t^G) Z_t^{(1-\kappa)} \kappa^{\kappa} (1-\kappa)^{(1-\kappa)}} \tag{28}$$

$$MC_t = \Theta_t + (1 - s_t^A)\theta_1 m_t^{\theta_2} + \tau_t^E \xi_t (1 - m_t - m_t^g) \tag{29}$$

▸ Back to Model

[1] (25) & (26) $\Longrightarrow \frac{K_t(i)}{L_t(i)} = \frac{\kappa}{1-\kappa} \frac{W_t}{R_t^k}$.

Appendix – Household's FOCs [2]

$$(\delta C_t) \quad \frac{1}{C_t} = \lambda_t \tag{30}$$

$$(\delta L_t) \quad \mu_l L_t^{\sigma_l} = \lambda_t W_t \tag{31}$$

$$(\delta B_t) \quad \lambda_t = \beta \mathbb{E}_t \left[\lambda_{t+1}(1 - f\vartheta_{t+1}) R_t^d \right] \tag{32}$$

$$\begin{aligned}(\delta I_t) \quad \lambda_t &= \lambda_t^k \left[1 - S\left(\frac{I_t}{I_{t-1}}\right) - S'\left(\frac{I_t}{I_{t-1}}\right)\frac{I_t}{I_{t-1}} \right] + \beta \mathbb{E}_t \left[\lambda_{t+1}^k S'\left(\frac{I_{t+1}}{I_t}\right)\left(\frac{I_{t+1}}{I_t}\right)^2 \right] \\ &= \lambda_t^k \left[1 - \frac{\iota}{2}\left(\frac{I_t}{I_{t-1}} - e^z\right)^2 - \iota\left(\frac{I_t}{I_{t-1}} - e^z\right)\frac{I_t}{I_{t-1}} \right] + \beta \mathbb{E}_t \left[\lambda_{t+1}^k \iota \left(\frac{I_{t+1}}{I_t} - e^z\right)\left(\frac{I_{t+1}}{I_t}\right)^2 \right]\end{aligned} \tag{33}$$

$$(\delta K_{t+1}) \quad \lambda_t^k = \beta \mathbb{E}_t \left[\lambda_{t+1} R_{t+1}^k \right] + \beta(1-\delta)\mathbb{E}_t \left[\lambda_{t+1}^k \right] \tag{34}$$

▸ Back to Model

[2]

$$\mathcal{L}_t = \mathbb{E}_t \sum_{i=0}^{\infty} \beta^i \left\{ \ln C_{t+i} - \mu_L \frac{L_{t+i}^{1+\sigma_l}}{1+\sigma_l} + \lambda_{t+i} \left[\begin{array}{c} (1-f\vartheta_{t+i})R_{t+i-1}^d B_{t+i-1} + W_{t+i}L_{t+i} + \Pi_{t+i} + \\ + R_{t+i}^k K_{t+i} - T_{t+i} - I_{t+i} - C_{t+i} - B_{t+i} \end{array} \right] + \lambda_{t+i}^k \left[(1-\delta)K_{t+i} + I_{t+i}\left[1 - S\left(\frac{I_{t+i}}{I_{t+i-1}}\right)\right] - K_{t+i+1} \right] \right\}. \tag{35}$$

In case of default, govt pays lump-sum transfers V_t to households for compensation and is forced to unexpectedly face additional public expenditure (unexpected debt restructuring or reputational costs) $G_t^d \equiv f \vartheta_t B_{t-1} R_{t-1}^d$, which corresponds to a proportion f of financial losses.[3]

Government budget constraint:

$$B_t = (1 - \vartheta_t) B_{t-1} R_{t-1}^d - S_t + V_t + G_t^d, \tag{36}$$

$D_t \equiv d_{t-1} Y_{t-1} \equiv B_{t-1} R_{t-1}^d$: face value of debt to be repaid at t, which is decided in the previous period $t-1$.

▸ Back to Model Appendix

[3] In a similar fashion to Corsetti et al. (2013), the sum of G_t^d and each period's transfers V_t is arranged such that the real debt level remains unaltered in case of sovereign default.

- Debt stabilization equation :

$$\tau_t = \tau(y_0, b_t, b_{t-1}, b_*, \tau_{t-1}, \tau_*). \tag{37}$$

- Resource constraint:

$$Y_t = C_t + I_t + G_t + G_t^d + A_t + A_t^g \tag{38}$$

▸ Back to Model

Detrending $\Longrightarrow$ The rules of rescaling are:

$$x_t \equiv \frac{X_t}{e^{zt}} \quad \text{for } X = \{C, Y, \Pi, K, I, W, A, S, V\}, \quad b_t^z \equiv \frac{B_t}{e^{zt}} = b_t y_t, \quad \lambda_t^Z \equiv \lambda_t e^{zt},$$

$$P_t^E \equiv \tau_t^E e^{-\omega t}, \quad e_t \equiv \frac{E_t}{e^{(z-\omega)t}}, \quad h_t^G \equiv \frac{H_t^G}{e^{(z-\omega)t}}$$

Lower case letters denote detrended variables, starred variables denote steady-state values.

Appendix – Summary of equilibrium equations I

$$c_t = \frac{1}{\lambda_t^z}; \quad \lambda_t^z = \bar{\beta}\mathbb{E}_t\left[\lambda_{t+1}^z(1-f\vartheta_{t+1})R_t^d\right]; \quad w_t = c_t\mu_l L_t^{\sigma_l} \tag{39}$$

$$1 = q_t^k\left[1 - \frac{\iota}{2}\left(\frac{i_t e^z}{i_{t-1}} - e^z\right)^2 - \iota\left(\frac{i_t e^z}{i_{t-1}} - e^z\right)\frac{i_t e^z}{i_{t-1}}\right] + \frac{1}{R_t}\mathbb{E}_t\left[q_{t+1}^k \iota\left(\frac{i_{t+1}e^z}{i_t} - e^z\right)\left(\frac{i_{t+1}e^z}{i_t}\right)^2\right] \tag{40}$$

$$R_t \equiv \frac{\lambda_t^z}{\bar{\beta}\mathbb{E}_t\left[\lambda_{t+1}^z\right]} = \frac{1}{q_t^k\mathbb{E}_t\left[\lambda_{t+1}^z\right]}\left\{\mathbb{E}_t\left[\lambda_{t+1}^z R_{t+1}^k\right] + (1-\delta)\mathbb{E}_t\left[\lambda_{t+1}^z q_{t+1}^k\right]\right\} \tag{41}$$

$$k_{t+1} = \frac{(1-\delta)}{e^z}k_t + i_t\left[1 - \frac{\iota}{2}\left(\frac{i_t e^z}{i_{t-1}} - e^z\right)^2\right] \tag{42}$$

$$y_t = D_f(H_t^G)k_t^{\kappa}L_t^{1-\kappa} \tag{43}$$

$$R_t^k = \frac{\kappa}{1-\kappa}\frac{L_t}{k_t}w_t \tag{44}$$

$$1 = \frac{{w_t}^{1-\kappa}{R_t^k}^{\kappa}}{D_f(h_t^G)\kappa^{\kappa}(1-\kappa)^{(1-\kappa)}} + (1-s_t^A)\theta_1 m_t^{\theta_2} + \xi_0 P_t^E(1-m_t) \tag{45}$$

$$m_t = \left[\frac{\xi_0 P_t^E}{(1-s_t^A)\theta_1\theta_2}\right]^{1/(\theta_2-1)} \tag{46}$$

Appendix – Summary of equilibrium equations II

$$y_t = c_t + i_t + gy_t + f\vartheta_t b_{t-1} y_{t-1} e^{-z} R^d_{t-1} + \theta_1 m_t^{\theta_2} y_t + \theta_3 (m_t^g)^{\theta_4} y_t \quad (47)$$

$$e_t = \xi_0 (1 - m_t) y_t \quad (48)$$

$$h_t^G = h_{t-1}^G + \frac{\bar{E}_0^G}{\bar{E}_0^n} e_t \quad (49)$$

$$D_{DV}(h_t^G) = \bar{D} \exp\left\{ -\frac{\gamma_3}{2} \left[\gamma_4 h_t^G\right]^2 \right\}, \quad D_{AD}(h_t^G) = \bar{D}(1 - \gamma_0 - \gamma_1 h_t^G - \gamma_2 h_t^{G2}), \quad D_{NC}(h_t^G) = \bar{D} \quad (50)$$

$$b_t = \frac{b_{t-1} R^d_{t-1} y_{t-1}}{y_t e^z} - [\tau_t + \xi_0 P_t^E (1 - m_t) - g - s_t^A \theta_1 m_t^{\theta_2} - \theta_3 (m_t^g)^{\theta_4}] \quad (51)$$

$$\tau_t = \phi_{\tau,t}[\tau_{t-1} + \phi_b(b_t - b_{t-1})] + (1 - \phi_{\tau,t})[\tau_* + \phi_b(b_t - b_*)] \quad (52)$$

$$\phi_{\tau,t} = \frac{1}{1 + \phi_{\tau,*}\tau_*} + 1_{D_f(H_t^G) \neq \bar{D}} \phi_{\tau,y}(y_{0,fr} - y_{0,n})(b_{t-1} - b_*) \quad (53)$$

$$b_t = \frac{d_t}{R_t^d} \quad (54)$$

$$\sum_{t=0}^{+\infty} e_t = \bar{E}_0^n \Longrightarrow m_t + m_t^g = \left(\frac{h_{t-1}}{\bar{E}_0^n}\right)^p; \quad m_t^g = \theta(m_t + m_t^g) \quad (55)$$

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Appendix – Calibration

Parameters		Value		Description
κ		0.33		Capital share of GDP
β		0.99		Discount factor
σ_l		1		Inverse of the Frisch elasticity of labor supply
μ_L		19.841		Disutility of labor
δ		0.025		Depreciation rate of capital
ι		15		Capital adjustment cost coefficient
σ_B		0.08		Parameter of the probability of default
ϑ		0.7		Haircut in case of public default
f		0.3		Post-default government expenditure as a fraction of lost value
$\phi_{\tau,*}$		0.25		Parameter of the stabilization function for $\phi_{\tau,t}$
$\phi_{\tau,y}$		0.9		Parameter of the stabilization function for $\phi_{\tau,t}$
ϕ_b		0.2		Parameter of the stabilization function
θ_1		0.023		Private abatement cost function coefficient
θ_2		1.8		Private abatement cost function convexity parameter
θ_3		0.023		Public abatement cost function coefficient
θ_4		1.044		Public abatement cost function convexity parameter
$\bar{E}_0^G$		240		IPCC global carbon budget 2024 in Gt CO_2-e, 1.5 degrees scenario at 67% probability
H_{-1}^G		3497		Cumulative GHG emissions in in Gt CO_2-equivalent until 2023
p		0.5		Mitigation function parameter
γ_0		1.3950e-3		Damage function parameter (Annicchiarico and Di Dio, 2015)
γ_1		-6.6722e-6		Damage function parameter (Annicchiarico and Di Dio, 2015)
γ_2		1.4647e-8		Damage function parameter (Annicchiarico and Di Dio, 2015)
γ_3		0.02		Damage function parameter (Dietz and Venmans, 2019)
γ_4		0.000749		Damage function parameter (Dietz and Venmans, 2019)
	France	Italy	Germany	
$\bar{D}$	1	0.89	1.07	TFP in the steady state
z	0.5%	0.25%	0.5%	GDP growth rate
g	5.75%	4.75%	5%	Exogenous public expenditure as fraction of GDP
$d_0 = d_*$	1.1	1.4	0.6	Steady state debt-to-GDP
b_M	1.35	1.7	1.2	Fiscal limit
$\bar{E}_0^n$	1.9	1.7	2.4	Carbon budget 2024 (per capita basis) in Gt CO_2-e
ξ_0	0.17	0.19	0.27	GDP carbon intensity
ω	0.5%	0.25%	0.5%	Average degrowth rate (quarterly) in GDP carbon intensity 1990-2020

Table: Parametrization (quarterly)

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Appendix – Calibration Abatement Cost Function

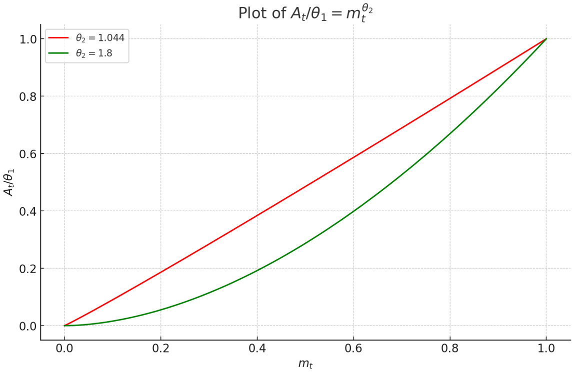

Figure: Normalized abatement cost function for different convexity of the curve. The red (green) curve represents the benchmark assumption for the public (private) sector.

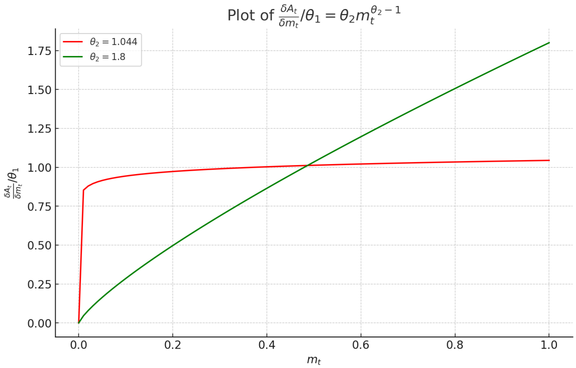

Figure: Normalized marginal abatement cost function for different convexity of the curve. The red (green) curve represents the benchmark assumption for the public (private) sector.

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Appendix – Calibration Debt Stabilization Rule

- Objective of Lump-Sum Tax: to stabilize the debt-to-GDP ratio to its final steady-state value, b_*, and to gradually reach the consistent long-term lump-sum tax value, τ_*.
- Parametrization of (52) captures the generally limited tax buoyancy in the short-term, highlighted by empirical studies on tax responsiveness (Cornevin, Flores, and Angel, 2023):
  - ϕ_b: response of τ_t to debt-to-GDP values.
  - $\phi_{\tau,t}$ defined in (53): smoothness weight on past taxes and indebtedness, reflecting that taxation changes are more difficult with higher public financing needs.
    - Baseline Value decreasing in τ_*, indicating greater difficulty in adjusting taxation with higher public financing needs.
    - Time-Varying Parameter in case of climate damages: depending on the economy's initial steady state $\Rightarrow$ challenges of poorer economies, impacted by climate change, in increasing taxation in response to higher debt.

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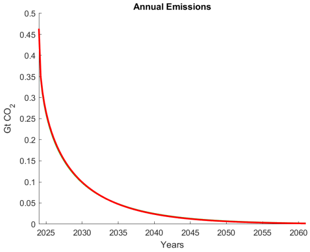
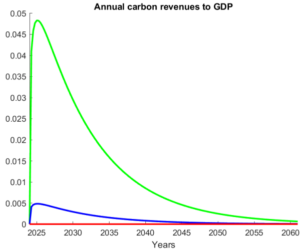
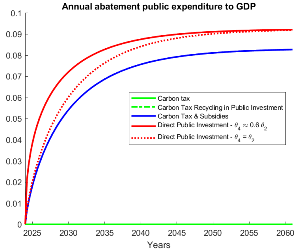
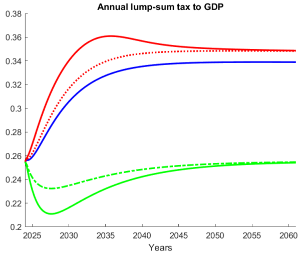
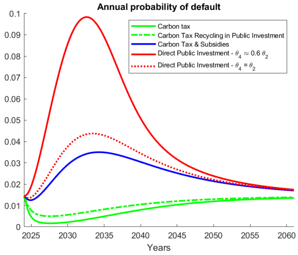
Appendix – Benchmark Results











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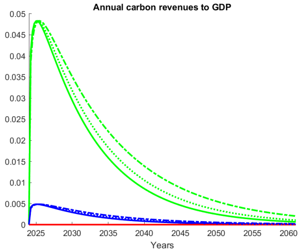
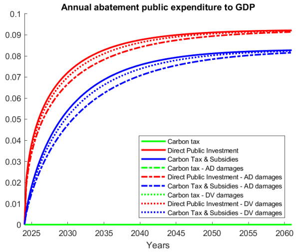
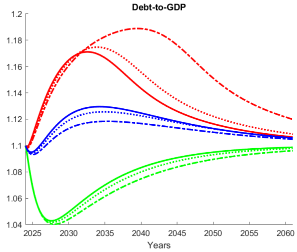
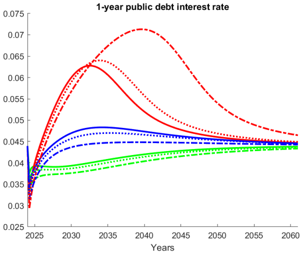
Appendix – The impact of climate damages I

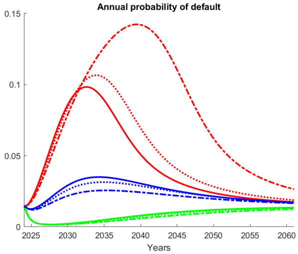
▸ Damage Functions





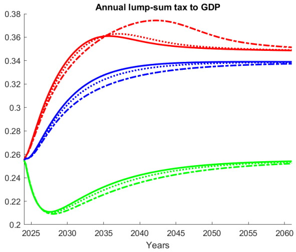


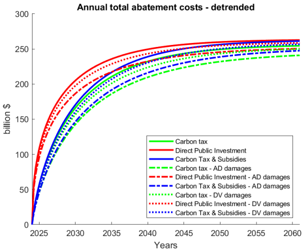


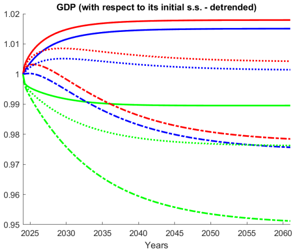


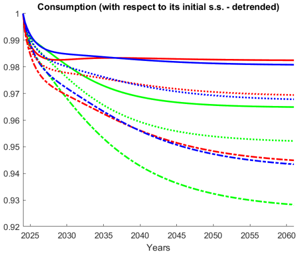
Appendix – The impact of climate damages II

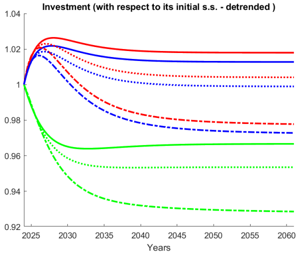
▸ Damage Functions



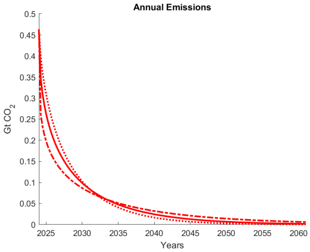


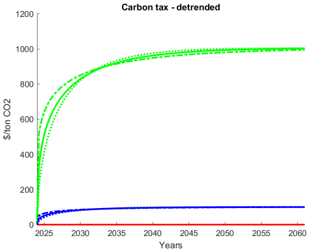


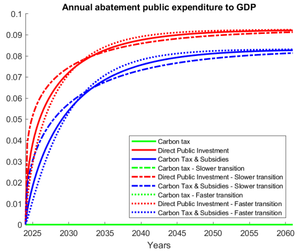


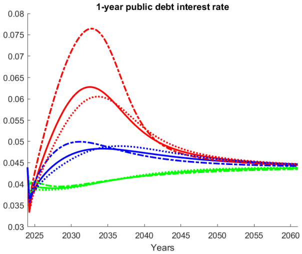


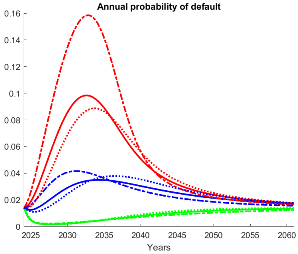
Appendix – Speed of the Transition



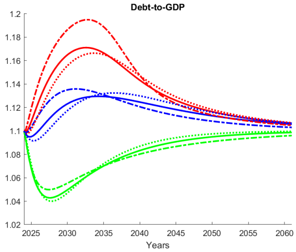


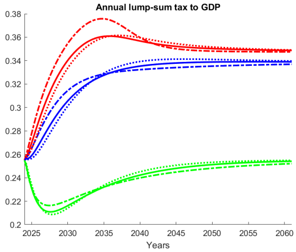


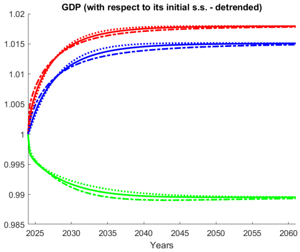


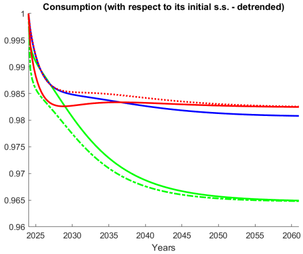


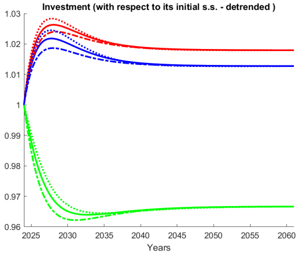
Appendix – Speed of the transition



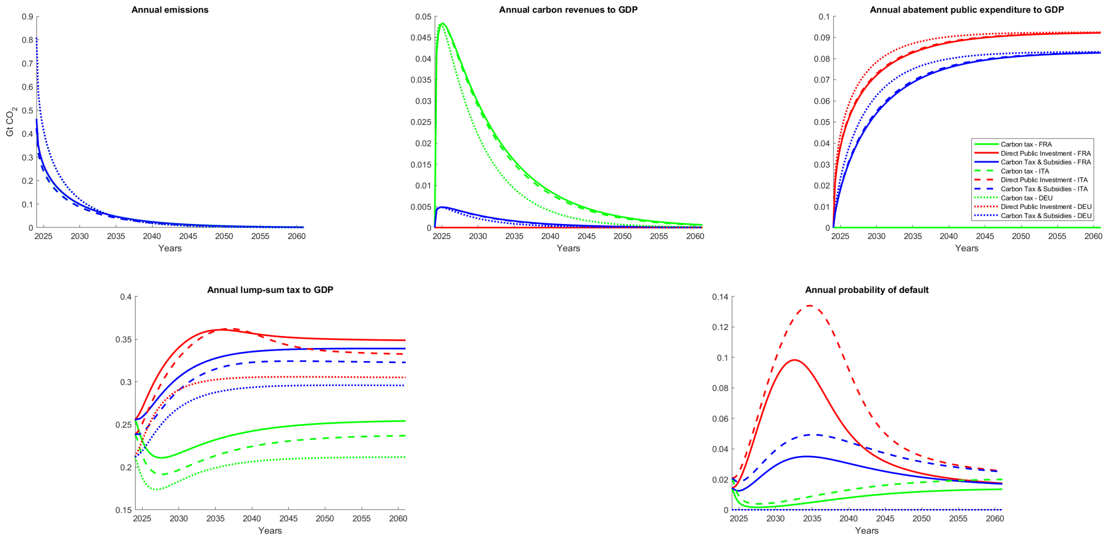








Appendix – Initial debt-to-GDP levels



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Appendix – Spillover mechanism

By following Burriel et al., 2020, we modify equation (16) as follows:

$$R_t = \frac{1}{q_t^k \mathbb{E}_t\left[\lambda_{t+1}\right]} \left\{ \mathbb{E}_t\left[\lambda_{t+1} R_{t+1}^k\right] + (1-\delta)\mathbb{E}_t\left[\lambda_{t+1} q_{t+1}^k (1 - \omega_q f \vartheta_t \mathrm{PD}_{t+1})\right] \right\}, \tag{56}$$

where we calibrate $\omega_q = 0.5$.

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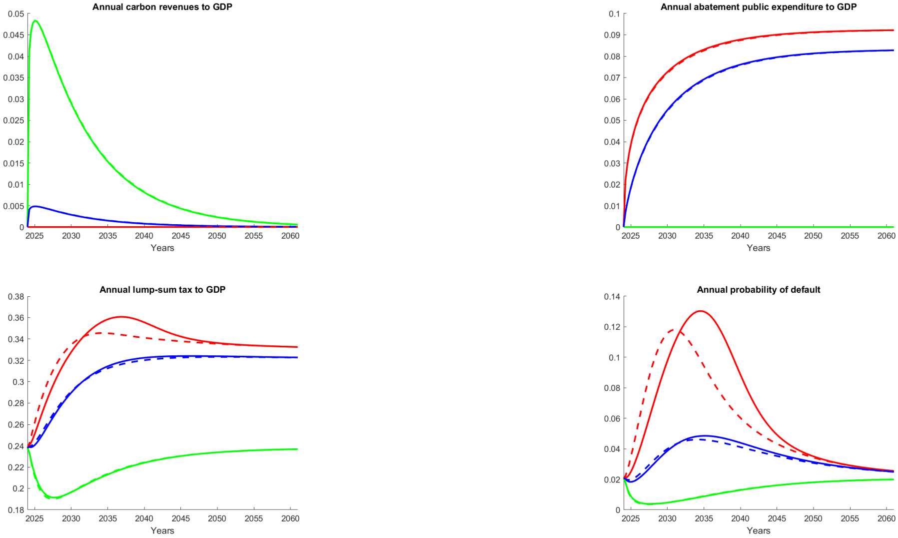
Appendix – Financial spillover of high public debt risk to private financing conditions



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Social planner's problem: committed choice of θ_t in order to maximize welfare, defined as the present discounted value of utility:

$$\max_{\theta_t} V_t = \left(\ln C_t - \mu_L \frac{L_t^{1+\sigma_l}}{1+\sigma_l} \right) + \beta \mathbb{E}_t V_{t+1}, \tag{57}$$

subject to all the equations describing the competitive equilibrium.

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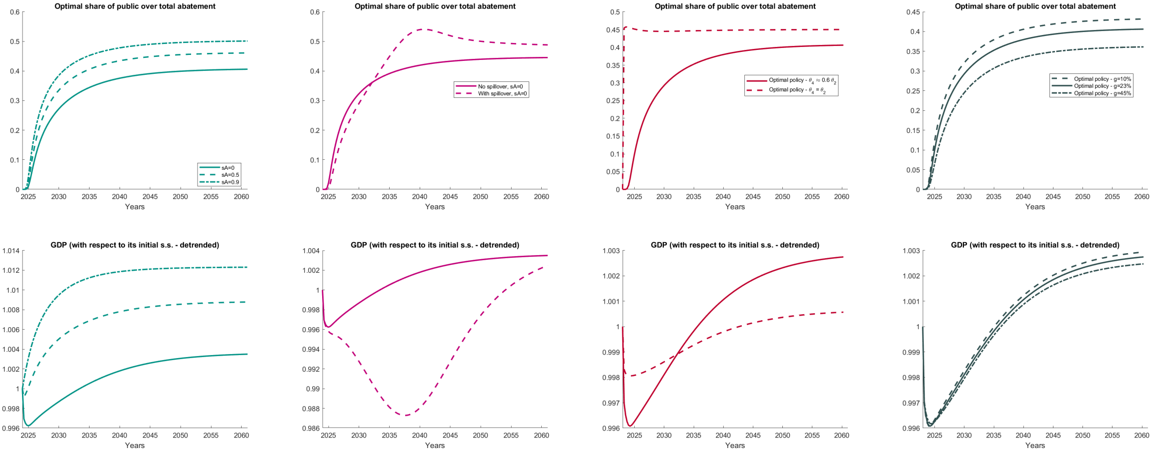
Appendix – Optimal share of public over total abatement



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