Sovereign debt sustainability, the carbon budget and climate damages

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Table of Contents

Research question

- Two contemporaneous challenges: managing the risk of growing public indebtedness and dealing with the consequences of climate change.
  - $\Rightarrow$ consequences of climate damages on public debt sustainability?
  - $\Rightarrow$ consequences of transition costs on public debt sustainability?
- These climate-related issues have entered into policy discussions
  - $\Rightarrow$ revision of European budgetary rules
  - $\Rightarrow$ revision of IMF Public Debt Sustainability Framework
- First academic paper to address this critical issue by estimating national *fiscal* (or *debt*) *limits* in advanced economies under the Paris Agreement's carbon constraints, while taking into account:
  - the economic costs of reducing carbon emissions,
  - climate damages,
  - the degree of political coordination in the transition.
- At the intersection of two literature domains:
  - macro-financial research on fiscal limits and debt sustainability,
  - macro-climate research on the economic costs of environmental policies and climate change.

Scarce Literature on the Impact of Climate Change on Sovereign Debt Sustainability

- Emerging research links climate change economics with fiscal policies, highlighting how climate change and mitigation efforts impact government finances.
- Consequences of climate damages:
  - Climate vulnerability leads to higher sovereign borrowing costs, particularly in high-risk and developing countries (Beirne, Renzhi, and Volz, 2021; Cevik and Jalles, 2022).
  - Stronger institutions in emerging markets can mitigate the negative impact of temperature on sovereign bond performance (Boehm, 2022).
- Fewer studies examine the consequences of transition policies:
  - Transition policies towards low-carbon economies can lower borrowing costs (Battiston and Monasterolo, 2020; Collender et al., 2023). Need for climate-smart investments to avoid credit downgrades and fiscal strains (Klusak et al., 2023; Zenios, 2022).
  - Important challenges for high-debt countries (IMF, 2023 and Seghini and Dees, 2024 use dynamic general equilibrium models to analyze how different mitigation policies –e.g., carbon taxes, public investments– impact GDP, public debt, and default risks)
- Established vital link between climate change costs and public debt sustainability $\longrightarrow$ need for integrated fiscal and environmental strategies, and further research on incorporating climate considerations into sovereign debt sustainability models.

- No default as long as: debt-to-GDP $\leq$ **fiscal limit**

  $\Longrightarrow$ Involuntary default framework

- Climate-related challenges affect both sides of this inequality: this paper concentrates on the impact on fiscal limits through the growth channel.

- Fiscal Limit: the maximum debt-to-GDP ratio a government can accumulate without losing its repayment credibility.

- Main determinants: *growth rate*, risk-free interest rate, future potential primary surpluses.

Main Results

- Transition scenario
  - $\Longrightarrow$ In the short term, fiscal limits are initially lower due to abatement costs, highlighting sustainability issues related to specific transition challenges for countries like Italy and France.
  - $\Longrightarrow$ If the transition is successfully coordinated at a global level, fiscal limits converge to higher and stable levels.
- vs Business-as-usual/Uncoordinated Transition
  - $\Longrightarrow$ Climate policies initially lower fiscal limits compared to BAU scenarios.
  - $\Longrightarrow$ If the transition globally fails or is not undertaken at all (BAU), growth rates are impacted by increasingly severe climate damages $\Rightarrow$ plunging fiscal limits.
- Policy Implication: importance of coordinated, prompt transition policies to mitigate climate impacts, safeguard fiscal sustainability, and support the financing of a green economic transition.

Integrating a model for fiscal limits with climate considerations I

- Extension of the model by Collard, Habib, and Rochet, 2015, incorporating a reduced-form growth rate function related to carbon emissions:

$$b_t^M = \max_{d_t} b(d_t) = \max_{d_t} \frac{d_t}{R(d_t)} = \max_{d_t} \frac{d_t}{R}\left[1 - \mathrm{PD}(d_t)\right] \quad \text{(risk-neutral investors)}$$

$$\text{Default if: } g_{t+1} \equiv \frac{\eta(E_{t+1})}{\eta(E_t)} e^{\mu_0 + \epsilon_{t+1}} < \frac{d_t}{\alpha + b_{t+1}^M}, \quad \text{where} \quad \epsilon_j \sim_{i.i.d.} N(0, \sigma_0^2)$$

  d: face value of debt-to-GDP, b: govt. borrowing-to-GDP, α: maximum primary surplus,
  PD: prob. of default, R: gross risk-free rate, g: gross GDP growth rate,
  μ_0 and σ_0: “green” post-transition growth rate and volatility, E: carbon emissions.

  ▸ Development

- The abatement cost function $\eta(\cdot)$ is adapted and calibrated for 31 advanced economies by referencing the OECD’s empirical results in developing the ”Environmentally Adjusted Multifactor Productivity” (Cárdenas Rodríguez, Haščič, and Souchier, 2018):

$$\eta(E_t) = E_t^\beta = e_t \bar{E}^\beta \approx \left[(c + e_t)\bar{E}\right]^\beta \tag{1}$$

  β: short-term abatement cost parameter, c: CCS parameter, $\bar{E}$: national carbon budget

  ▸ Development

Integrating a model for fiscal limits with climate considerations II

- Maximum sustainable borrowing (MSB):

$$b_t^M = \max_{d_t} \frac{d_t}{R}\left[1 - F(x_t)\right] = \frac{\gamma e^{\mu_0}}{R}(\alpha + b_{t+1}^M)\frac{\eta(E_{t+1})}{\eta(E_t)} = \frac{\alpha}{\eta(E_t)}\sum_{j=1}^{+\infty}\left(\frac{\gamma e^{\mu_0}}{R}\right)^j \eta(E_{t+j}) \tag{2}$$

$$\text{where} \quad \gamma \equiv \max_x x[1 - F(x)] = x_M[1 - F(x_M)],$$

$$x_t \equiv \frac{d_t}{[\alpha + b_{t+1}^M]e^{\mu_0}\frac{\eta(E_{t+1})}{\eta(E_t)}}$$

$F(\cdot)$: c.d.f. of the log-normally i.i.d. random shock $\exp(\epsilon)$,
γ: constant borrowing factor (net of growth)

- Fiscal limit/ maximum sustainable debt (MSD):

$$d_t^M = x_M(\alpha + b_{t+1}^M)e^{\mu_0}\frac{\eta(E_{t+1})}{\eta(E_t)} \equiv \frac{R}{1 - F(x_M)}b_t^M. \tag{3}$$

Data

Country	μ	σ	μ_0	σ_0	β	Debt/GDP$_{2020}$	MPS(α)	NDC 2021-25 (E_0)	CB 2026 ($\bar{E}_1$)
France	1.57	1.48	1.88	1.43	6.4	115.2	3.65	2.035	7.329
Italy	0.73	1.94	1.03	1.68	10.1	155.3	6.55	1.880	6.769

Table: Columns 1-5 (%), based on Cárdenas Rodríguez, Haščič, and Souchier, 2018 (period 1990-2013): average GDP growth rate (μ), its volatility (σ), average "green" GDP growth rate adjusted for pollution increase/reduction (μ_0), and its volatility (σ_0), and the short-term abatement cost parameter (β).
Columns 6-7 (%), IMF data: historical maximum primary surplus ($\alpha = \max_t \frac{s_t}{Y_t}$) and debt-to-GDP in 2020.

Columns 8-9 ($GtCO_2$): based on EU "National Determined Contribution" and IPCC 2°C-67% prob. scenario global carbon budget 2020 (1150 $GtCO_2$) on a per-capita basis.

5-year period, $r = R - 1 = 2.44\%$, $c = 1\%$.

▸ r calib ▸ c calib

▸ Other countries

$$\max_{\{E_t\}} b_0^M \quad \text{s.t.} \quad \sum_{t=1}^{+\infty} E_t \leq \bar{E}_1, \quad E_t \geq 0 \tag{4}$$

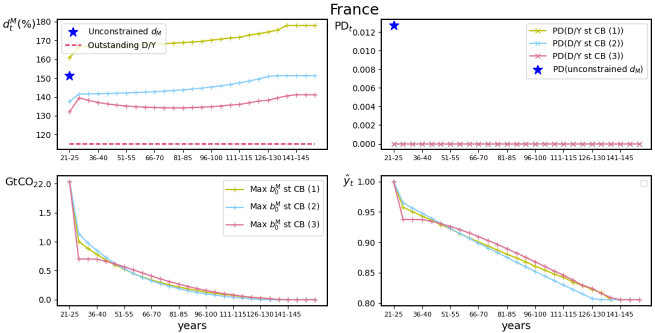
▸ Fiscal limits in the transition – OECD countries

Three long-term scenarios on the green growth rate:

(1) optimistic: $\mu_0 \neq \mu$, $\sigma_0 \neq \sigma$;

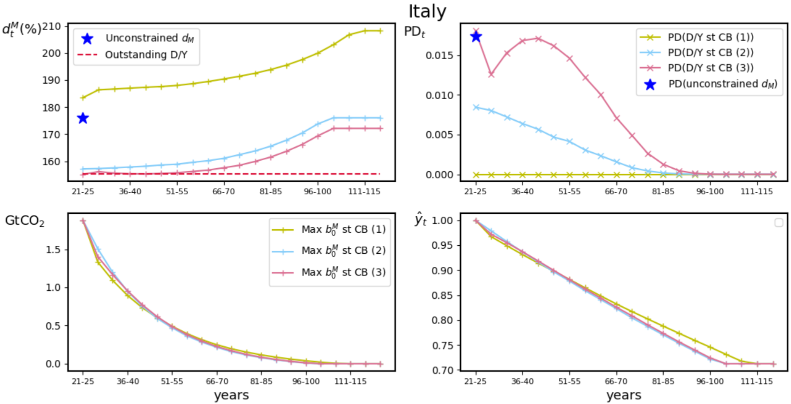
(2) parallel hypothesis (PL): $\mu_0 = \mu$, $\sigma_0 = \sigma$;

(3) pessimistic: $\mu_0 = \mu[1 - m(E_t)]$, where $m(E_t) = \sqrt{\theta \sum_1^t e_t}$, $\theta = 0.0121$.[a]

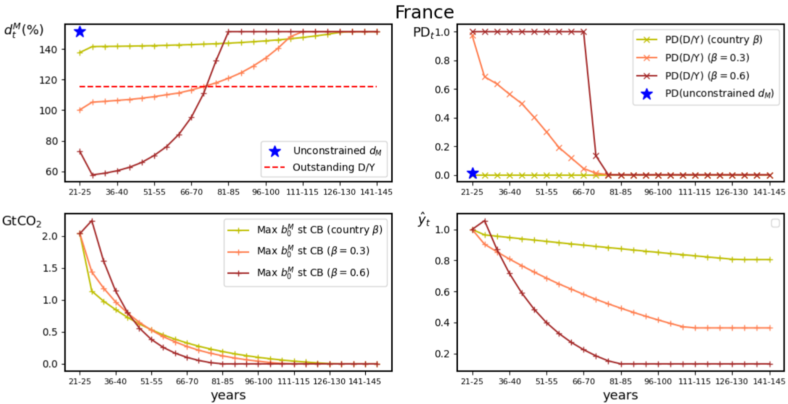


[a] Ratio of success rate of clean over dirty technology: calibrated as the product of the ratio of number of citations per patent (1.43 as in Dechezlepretre, Martin, and Mohnen, 2017) and the inverse of the ratio of pass-through years (5/8 as in Perrons, Jaffe, and Le, 2021)
$\Longrightarrow$ success rate of green over dirty technology = 89%
$\Longrightarrow \mu_0 = \mu(1 - 11\%)$, at the end of the transition $\Longrightarrow$ $\theta = 0.0121$.

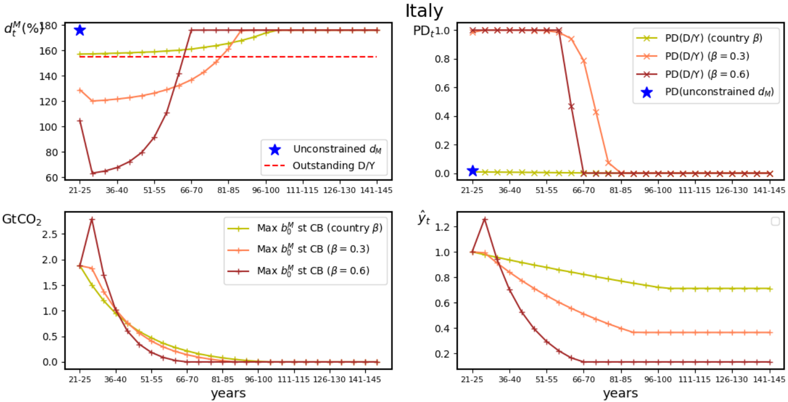
⇒ Long-term green growth prospects: Italian sustainability at risk?



Higher values of β imply unsustainable debt for Italy and France. PL scenario. I



Higher values of β imply unsustainable debt for Italy and France. PL scenario. II

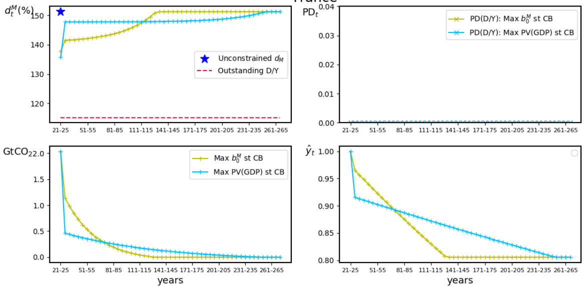


$$\max_{\{E_t\}} \sum_{t=0}^{+\infty} \frac{\mathbb{E}_0[Y_t]}{R^t} = \frac{Y_0}{\eta(E_0)} \sum_{t=0}^{+\infty} \left(\frac{\bar{g}}{R}\right)^t \eta(E_t) \quad \text{s.t.} \quad \sum_{t=1}^{+\infty} E_t \leq \bar{E}_1, E_t \geq 0 \tag{5}$$

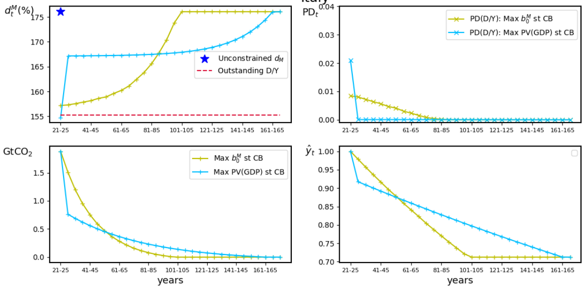
$\bar{g} = e^{\mu_0 + 1/2\sigma_0^2}$: expected green gross growth rate. $\gamma e^{\mu_0} < \bar{g}$

$\Rightarrow$ Maximizing welfare under the carbon budget, instead of the current MSB, leads to an initial faster transition, to save carbon budget for the future. PL scenario.

France



Italy



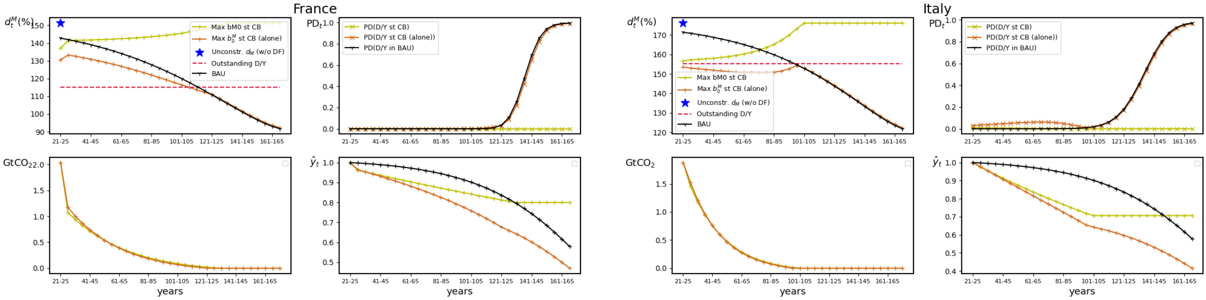
Climate damages and the need for global coordination

Climate damages are introduced through the exponential function proposed by Dietz and Venmans, 2019 Dietz and Venmans, 2019:

$$D(T_t) = \exp\left(-\frac{\rho}{2}T_t^2\right), \text{ where } T_t = \zeta C_t. \tag{6}$$

T_t: global average temperature increase, C_t: global cumulative emissions since 1850

$\Rightarrow$ A globally coordinated transition (light green) stabilizes climate damages and growth, then avoiding the plummeting fiscal limits of a business-as-usual scenario (black) or a “solitary” transition (orange). PL scenario.



▸ US ▸ Shift period

The case of Italy: the need for an efficient and coordinated transition

	2021-25					2101-105		
TRANSITION	COORDINATED			SOLITARY	BAU	COORDINATED	SOLITARY	BAU
green growth	optimistic	parallel	pessimistic	parallel		parallel		
$\beta = 0.101$	183.48	**156.61-157.18**	155.19	**153.52**	**171.35**	**176.05**	**153.05**	**152.80**
$\beta = 0.3$		128.99				176.05		

Table: The Italian fiscal limit amidst the transition. $r = 2.44\%$. Written in red the scenarios where debt-to-GDP is higher than the fiscal limit ($d_t = 155.3\% > d_t^M$). Colored cells highlight the benchmark scenario ($\beta = 0.101$, PL) for different degrees of political coordination in the transition (coordinated/solitary/BAU). In the green cell for 2021-25, the first value accounts for climate damages in the 2°C scenario, while the second ignores them.

Concluding remarks

- During the early stages of the transition, fiscal limits are lower than their long-term *stationary* values, assuming a globally successful transition scenario (2°C).

  High emissions' abatement costs can push countries like Italy and France from sustainable to unsustainable current debt-to-GDP ratios.

- A coordinated transition initially results in lower fiscal limits than in a BAU scenario, due to the negative impact of emission cuts on GDP growth.

  However, by 2080, these coordinated actions prove more advantageous for all countries than in a BAU or uncoordinated transition scenario, where fiscal limits continue to plunge and currently outstanding debt-to-GDP becomes unsustainable for many countries.

$\Rightarrow$ **Coordinated and costly efficient efforts are needed to stabilize climate damages, economic growth and fiscal limits**, supporting sustainable public debt and the green transition financing.

Further Research

- Climate damages and volatility
- Is the maximum primary surplus affected by transition policies?
- Endogenous fiscal limits into dynamic general equilibrium models with carbon emissions and abatement costs

Appendix – Model development I

The government issues one-period bonds $B_t \equiv b_t Y_t$ every period, with a face value $D_{t+1} \equiv d_t Y_t$ to be repaid at the beginning of the next period. Default at t occurs if:

$$D_t - \alpha Y_t > b_t^M Y_t \iff \frac{D_t}{Y_t} > \alpha + b_t^M \tag{7}$$

$B_t^M \equiv b_t^M Y_t$ denotes the MSB, defined by:

$$b_t^M = \max_{d_t} b(d_t) = \max_{d_t} \frac{d_t}{R(d_t)} \tag{8}$$

where $b(d_t)$ are the borrowing proceeds with respect to GDP, from issuing one-period debt with a face value d_t with respect to GDP.

For simplicity, ass. zero recovery in default, and a constant gross risk-free rate R.[1] Assuming competitive financial markets and risk-neutral investors:

$$R(d_t)\left(1 - \mathrm{PD}(d_t)\right) = R \tag{9}$$

Back to Model

Appendix – Model development II

Let rewrite the default condition (7), at $t+1$, in terms of the gross growth rate:

$$D_{t+1} \equiv d_t Y_t > (\alpha + b^M_{t+1}) Y_{t+1} \iff g_{t+1} = \frac{Y_{t+1}}{Y_t} < \frac{d_t}{\alpha + b^M_{t+1}} \tag{10}$$

Stochastic growth rate in terms of carbon emissions:

$$g_{t+1} = \eta_{t+1}(\{E_{t|t-1}\}) e^{\mu_0 + \epsilon_{t+1}}, \text{ where } \epsilon_j \sim_{i.i.d.} N(0, \sigma_0^2) \quad \forall j \tag{11}$$

- $\eta_{t+1}(\{E_{t|t-1}\})$: cost function which depends on the transition path.
- μ_0: growth rate of a net-zero economy.
- Carbon compensation in the short-term is ruled out ($E_{t|t-1} \geq 0, \forall t$).
- Carbon emissions $E_{t|t-1}$, exploited at t, is decided at $t-1$,[2] capturing the so called "carbon lock-in" phenomenon, and the commitment of countries in the Paris Agreement of updating their National Determined Contributions (NDCs) every five years.
  (assume a period of 5 years = average maturity of US outstanding debt).

Back to Model

Given

$$g_{t+1} \equiv e^{\mu_0+\epsilon_{t+1}}\eta_{t+1}(\{E_t\}) < \frac{d_t}{\alpha + b^M_{t+1}(\{E_t\})} \iff e^{\epsilon_{t+1}} < \frac{d_t}{[\alpha + b^M_{t+1}(\{E_t\})]e^{\mu_0}\eta_{t+1}(\{E_t\})}$$

+ (9) $\Longrightarrow$ MSB (8), given a path for carbon emissions $\{E_t\}$:

$$b^M_t(\{E_t\}) = \max_{d_t} \frac{d_t}{R}[1 - \mathrm{PD}(d_t, \{E_t\})] = \max_{d_t} \frac{d_t}{R}\left[1 - F\left(\frac{d_t}{[\alpha + b^M_{t+1}(\{E_t\})]e^{\mu_0}\eta_{t+1}(\{E_t\})}\right)\right] \tag{12}$$

where $F(\cdot)$ is the c.d.f. of the lognormally i.i.d. random shock $\exp(\epsilon)$.

Calling the critical shock (the minimum shock's realization necessary to avoid default),

$$x_{t+1} \equiv \frac{d_t}{[\alpha + b^M_{t+1}(\{E_t\})]e^{\mu_0}\eta_{t+1}(\{E_t\})}, \tag{13}$$

and the constant borrowing factor (net of growth)

$$\gamma \equiv \max_x x[1 - F(x)] = x_M[1 - F(x_M)],$$

Back to Model

the MSB can be rewritten as:

$$b_t^M(\{E_t\}) = \frac{\gamma e^{\mu_0}}{R}[\alpha + b_{t+1}^M(\{E_t\})]\eta_{t+1}(\{E_t\}) \tag{14}$$

or, given our specific abatement cost function:

$$b_t^M = \frac{\gamma e^{\mu_0}}{R}(\alpha + b_{t+1}^M)\frac{\eta(E_{t+1})}{\eta(E_t)}, \text{ where } \eta(E_t) = (c\bar{E} + E_t)^{\beta} = [(c + e_t)\bar{E}]^{\beta} \tag{15}$$

By iterating we get:

$$b_t^M = \alpha \sum_{j=1}^{+\infty}\left(\frac{\gamma e^{\mu_0}}{R}\right)^j \prod_{l=0}^{j-1}\frac{\eta(E_{t+l+1})}{\eta(E_{t+l})} = \frac{\alpha}{\eta(E_t)}\sum_{j=1}^{+\infty}\left(\frac{\gamma e^{\mu_0}}{R}\right)^j \eta(E_{t+j}) \tag{16}$$

The product $\gamma e^{\mu_0}\frac{\eta(E_{t+1})}{\eta(E_t)}$ represents the total borrowing factor, including the growth rate contribution. Given (13), the MSD corresponds to :

$$d_t^M = x_M(\alpha + b_{t+1}^M)e^{\mu_0}\frac{\eta(E_{t+1})}{\eta(E_t)} \equiv \frac{R}{1 - F(x_M)}b_t^M. \tag{17}$$

Back to Model

[1] Together with neither renegotiation nor bail-out, and an independent central bank that resists possible government demand to inflate debt away.

[2] for simplicity, I will refer to $E_{t|t-1}$ as E_t.

Appendix – Public Debt Sustainability

As in Collard, Habib, and Rochet (2015), debt is defined as sustainable if the sequence b_t^M is bounded: "$b > 0$ is sustainable if and only if there exists a bounded sequence of borrowings $(b_t^M)_t$ such that $b_0^M = b$ and $b_t^M \leq \tau(b_{t+1}^M)\ \forall t$".

A stable debt level can be "more properly described as sustainable": in order to have convergence of the MSB to a finite value, the following condition has to be satisfied:

$$\exists j > t \text{ s.t. } \gamma e^{\mu_0} \frac{\eta(E_l)}{\eta(E_{l-1})} < R, \forall l \geq j.$$

This is ensured when imposing a carbon budget (given that this constraint will lead to zero emissions in the medium/long term) if $\gamma e^{\mu_0} < R$, which is always quantitatively verified in the data range of this paper.

Back to Model

$$b_t^{M,G} = \frac{\gamma e^{\mu_0}}{R}(\alpha + b_{t+1}^M) \equiv \tau(b_{t+1}^M).$$

By iterating:

$$b_t^{M,G} = \frac{\alpha\gamma e^{\mu_0}}{R}\Gamma_G, \text{ where } \Gamma_G = \left[1 + \frac{\gamma e^{\mu_0}}{R} + \left(\frac{\gamma e^{\mu_0}}{R}\right)^2 + \dots\right].$$

γe^{μ_0}: "green" borrowing factor.

- When $\gamma e^{\mu_0} < R$, the series converges to a finite borrowing multiplier $\Gamma_G = \frac{1}{1 - \frac{\gamma e^{\mu_0}}{R}}$.
- When $\gamma e^{\mu_0} \geq R$, the series diverges, and Γ_G is infinite.

$\Longrightarrow$ In the green economy where $E_j = 0, \ \forall j \geq t$, and $\gamma e^{\mu_0} < R$, the MSB is finite and equal to:

$$b_{M,G} \equiv \frac{\alpha\gamma e^{\mu_0}}{R - \gamma e^{\mu_0}} \tag{18}$$

and the function τ is a contraction that has the unique fixed point $b_{M,G}$.[3]

Back to Model

[3] In the case $\gamma e^{\mu_0} > R$, any borrowing $b > 0$ would be sustainable.

The growth function (11) is calibrated on the basis of the results of Cárdenas Rodríguez, Haščič, and Souchier, 2018, who construct the novel EAMFP indicator.

- From the transformation function:

$$H(Y, E, L, K, S, t) \geq 1,$$

  Y: desirable output of the economy (GDP); E the undesirable output (carbon emissions): L, K and S: labour, produced capital and natural capital, respectively

$$\implies \quad \dot{Y}_{i,t} = a_i + \delta_t + \rho_i \dot{X}_{it} + \sum \beta_{ji} \dot{E}_{jit} + \epsilon_{it}. \tag{19}$$

  $\dot{Y}_{i,t}$: net GDP growth rate of country i; $\dot{X}_{i,t}$: elasticity-weighted growth rate of inputs; $\dot{E}_{jit}$ growth rate of each type j of GHG emissions;[4] δ_t: time dummies; ϵ_{it}: normally distributed error term; a_i: environmentally adjusted productivity growth.

- The coefficients relate to the elasticities of the transformation function with respect to desirable and undesirable outputs:

$$\rho_i = -\frac{1}{\epsilon_{HYi}}; \quad \beta_{ji} = \rho_i \epsilon_{HEji} = -\frac{\epsilon_{HEji}}{\epsilon_{HYi}} \equiv \epsilon_{YEji}$$

  where the latter is the elasticity of output with respect to emissions of type j, for country i.

Back to Model

- I use the historical average (for the data range 1990-2013 in Cárdenas Rodríguez, Haščič, and Souchier, 2018) of equation (19), for calibrating $\eta(\cdot)$ and the parameters μ, σ, μ_0, and σ_0, for each country:

$$\underbrace{\mathbb{E}[\dot{Y}_{i,t}]}_{\mu_i} = \underbrace{a_i + \mathbb{E}[\delta_t] + \rho_i \mathbb{E}[\dot{X}_{it}]}_{\mu_{0,i}} + \sum \beta_{ji} \mathbb{E}[\dot{E}_{jit}]$$

For simplicity, it is assumed that the total contribution of the different elements in $\mu_{0,i}$ would not be affected by changes in the growth rate of carbon emissions.

$$\implies \quad \mu_i = \mu_{0,i} + \beta_i \dot{E}_{it} \tag{20}$$

given $\sum_j \beta_{ji} \dot{E}_{jit} = \sum_j \beta_{ji} w_{ji} \dot{E}_{it} = \beta_i \dot{E}_{it}$; w_{ji}: weight (assumed constant) of emissions of type j of country i over its total emissions. Data

$$\implies \quad g_{i,t+1} = e^{\mu_i + \epsilon_{i,t+1}} = e^{\mu_{0,i} + \beta_i \dot{E}_{it} + \epsilon_{i,t+1}} = e^{\mu_{0,i} + \epsilon_{i,t+1}} \left(\frac{E_{i,t+1}}{E_{i,t}} \right)^{\beta_i} = e^{\mu_{0,i} + \epsilon_{i,t+1}} \left(\frac{e_{i,t+1}}{e_{i,t}} \right)^{\beta_i},$$

$\left(\frac{E_{i,t+1}}{E_{i,t}} \right)^{\beta_i}$: generalized η-term defined above; $e_{i,t} \equiv E_{i,t}/\bar{E}_{i,1}$: emissions' share with respect to $\bar{E}_{i,1}$.

Back to Model

Appendix – Abatement cost function III

- Main goal: study the fiscal sustainability of transition to net zero

$$\Longrightarrow \quad g_{i,t+1} = e^{\mu_{0,i}+\epsilon_{i,t+1}} \left(\frac{c + e_{i,t+1}}{c + e_{i,t}} \right)^{\beta_i}, \tag{21}$$

c: percentage of emissions over the country's carbon budget $\bar{E}_{i,1}$, that will be possible to recapture by CCS (carbon capture and storage) technologies $\Rightarrow$ assumed fixed for simplicity.

- Benchmark: $c = 1\%$
  - $\Rightarrow$ CCS technology capacity was, in 2021, around 41Mt CO2 per year.
  - $\Rightarrow$ Projected to develop to 230Mt CO2 per year by 2030: over 5 years, around 0.1% of benchmark global carbon budget in 2021 (1116 Gt CO2).
  - $\Rightarrow$ The realized growth rate would be of 85%. At this rate, a capacity of 1% of the carbon budget would be achieved before 2050. In my results, the transition is generally slow, and never achieved before 2050.
  - $\Rightarrow$ We can safely assume a value of $c = 1\%$ with respect to the 2026 carbon budget $\bar{E}_{i,1}$: globally, around 1.8 Gt CO_2 per year $\Longleftrightarrow$ way below the assumptions of various IPCC scenarios (AR 6 Synthesis Report, 2023)!

Back to Model

Back to Data

- Notice that the role of c becomes most relevant in the last period of the transition, where, since $e_{i,j} = 0, \forall j > T$:

$$g_{i,T+1} = e^{\mu_{0,i}+\epsilon_{i,t+1}} \left(\frac{1}{1 + ae_{i,T}} \right)^{\beta_i}, \text{ where } a = 1/c.$$

A higher value of a, or lower value of c, means that the last transition period's growth rate is more depressed, for the same value of $e_{i,T} \implies$ Governments will tend to postpone more and to reduce the level of emissions in this final period.

Back to Model

Sensitivity analysis

[4] $\dot{x}_{i,t} = \ln(x_{i,t}) - \ln(x_{i,t-1})$, for every variable x.

Appendix – Risk-free rate calibration

- 5 years: average maturity of outstanding US government debt in 2020.
- r chosen to match the real yield on US 5-year Treasury Bond over 2003–2020 (selected period due to data limitation: data.nasdaq.com). $\Longrightarrow$ Maximum value of annual return over this period: 2.44% (2006). Its average over 2003-2013 and 2003-2020: respectively 0.76%, and 0.5%.
- CBO (Congressional Budget Office) predicts an increase in real interest rates over the next decades. Given our long-run horizon, we take as benchmark 2.44%.
- Comparative analysis for: 3%, to represent the possible increase of interest rates to the high values of the past; and 1.88% to align with the CBO's projections for mid-century.[5]

▸ Back to Data

[5] I assume a term premium between 5-year yield and 10-year yields of 45 percentage points, its average over the past two decades for inflation-linked treasury bonds.

Appendix – Data: CO_2 and CH_4 shares over total emissions.

▸ Back to Model Appendix

Country	CO2 mean	CO2 std	CH4 mean	CH4 std
Australia	59.87%	8.88%	25.18%	7.85%
Austria	68.14%	15.60%	25.85%	12.69%
Belgium	79.57%	4.36%	16.64%	4.45%
Canada	83.55%	2.70%	12.38%	1.90%
Czech Republic	69.06%	13.32%	27.27%	13.98%
Denmark	70.12%	5.51%	21.48%	5.42%
Estonia	76.54%	7.24%	16.62%	4.66%
Finland	71.29%	10.34%	21.46%	7.66%
France	58.69%	11.22%	35.19%	14.02%
Germany	77.22%	9.72%	18.76%	9.33%
Greece	61.81%	10.99%	30.46%	9.86%
Hungary	59.69%	11.84%	33.90%	15.30%
Iceland	68.37%	16.92%	18.71%	7.80%
Ireland	24.89%	23.13%	65.81%	28.95%
Italy	62.11%	15.91%	31.10%	15.00%
Japan	78.32%	13.53%	16.71%	10.86%
Latvia	64.50%	9.80%	27.08%	7.67%
Lithuania	66.29%	6.18%	24.05%	6.00%
Luxembourg	42.86%	44.60%	43.21%	33.55%
Netherlands	–	–	–	–
New Zealand	56.91%	20.49%	30.62%	15.45%
Norway	67.11%	6.53%	24.00%	4.71%
Poland	63.83%	10.29%	31.07%	9.56%
Portugal	52.21%	14.35%	40.49%	14.04%
Slovak Republic	75.78%	8.54%	20.13%	8.85%
Slovenia	62.98%	9.38%	31.89%	9.24%
Spain	64.14%	10.83%	27.93%	10.55%
Sweden	77.37%	4.88%	16.05%	2.97%
Switzerland	67.96%	12.22%	25.90%	11.25%
Turkey	45.85%	22.35%	42.48%	21.58%
United Kingdom	76.50%	3.61%	20.07%	4.29%
United States	84.37%	3.54%	11.85%	2.75%
average	65.74%	11.90%	26.91%	10.72%

Back to Data

Country	μ	σ	μ_0	σ_0	β	Debt/GDP$_{2020}$	MPS(α)
Australia	3.29	1.08	3.14	1.01	0.067	57.8	4.15
Austria	1.90	1.77	2.20	1.75	0.022	83.2	3.32
Belgium	1.80	1.53	2.07	1.48	0.074	112.8	6.84
Canada	2.36	1.88	2.38	1.78	0.036	117.8	10.05
Czech Republic	2.55	2.96	3.24	2.57	0.165	37.7	2.14
Denmark	1.48	2.16	1.62	2.09	0.040	42.1	11.62
Estonia	4.51	6.40	4.59	5.98	0.077	19.0	3.36
Finland	1.77	3.76	2.00	3.72	0.033	69.0	9.63
France	1.57	1.48	1.88	1.43	0.064	115.2	3.65
Germany	1.44	2.18	2.13	2.19	0.092	68.7	4.34
Greece	1.01	4.24	1.09	3.83	0.079	211.9	4.37
Hungary	1.76	2.86	2.26	2.55	0.116	80.0	7.84
Iceland	2.68	3.57	2.71	3.49	0.032	77.4	8.48
Ireland	4.62	4.40	4.66	4.22	0.063	58.4	6.72
Italy	0.73	1.94	1.03	1.68	0.101	155.3	6.55
Japan	0.93	2.06	1.34	1.90	0.080	259.0	5.53
Latvia	4.59	6.55	4.82	6.44	0.086	43.3	1.70
Lithuania	4.58	5.89	4.81	5.12	0.131	46.6	1.63
Luxembourg	3.68	3.42	3.97	3.24	0.133	24.8	4.44
Netherlands	1.99	2.12	2.39	2.14	0.077	52.8	5.62
New Zealand	2.63	2.23	2.54	2.18	0.034	43.1	7.53
Norway	2.48	1.69	2.67	1.54	0.027	46.8	20.57
Poland	3.69	2.98	3.76	3. 00	0.015	57.4	3.62
Portugal	1.53	2.29	1.61	2.02	0.055	135.2	3.47
Slovak Republic	4.15	3.42	4.39	3.30	0.102	59.7	0.23
Slovenia	2.53	3.50	2.67	3.13	0.108	79.8	2.54
Spain	2.04	2.36	1.96	2.13	0.072	120.0	4.01
Sweden	2.04	2.70	2.32	2.62	0.066	39.6	7.05
Switzerland	1.55	1.64	1.78	1.65	0.089	42.4	3.44
Turkey	4.01	4.90	2.90	4.03	0.110	39.5	7.03
United Kingdom	2.02	1.51	2.09	1.50	0.042	102.6	6.65
United States	1.77	1.37	1.84	1.24	0.043	134.2	3.93

App. – Data: National carbon budgets from 2021 onward, per capita criterion

Back to Data

Country	Total population 2021 (Mln)	Percentage over global population	National Carbon budget ($GtCO_2e$)
Australia	25.8	0.33%	3.694
Austria	9.0	0.12%	1.289
Belgium	11.6	0.15%	1.661
Canada	38.1	0.49%	5.455
Czech Republic	10.7	0.14%	1.532
Denmark	5.8	0.07%	0.830
Estonia	1.3	0.02%	0.186
Finland	5.5	0.07%	0.788
France	65.4	0.84%	9.364
Germany	83.9	1.08%	12.013
Greece	10.4	0.13%	1.489
Hungary	9.6	0.12%	1.375
Iceland	0.3	0.00%	0.043
Ireland	5.0	0.06%	0.716
Italy	60.4	0.77%	8.648
Japan	126.0	1.62%	18.042
Latvia	1.9	0.02%	0.272
Lithuania	2.7	0.03%	0.387
Luxembourg	0.04	0.001%	0.006
Netherlands	17.2	0.22%	2.463
New Zealand	4.9	0.06%	0.702
Norway	5.5	0.07%	0.788
Poland	37.8	0.48%	5.412
Portugal	10.2	0.13%	1.461
Slovak Republic	5.5	0.07%	0.788
Slovenia	2.1	0.03%	0.301
Spain	46.7	0.60%	6.687
Sweden	10.2	0.13%	1.461
Switzerland	8.7	0.11%	1.246
United Kingdom	68.2	0.88%	9.765
United States	332.9	4.27%	47.667

App. – Data: NDCs 2021-2025 (E_0) and national carbon budgets from 2026 ($\bar{E}_1$)

Back to Data

Country	Ref. year	Ref. Em	Em 2020	2030 target	Em 2021–30	2025 target	Em 2021–25: estimated target	CB 2026
Australia	2005	0.621	0.498	0.354	4.381		2.191	1.504
Canada	2005	0.739	0.672	0.425		0.549	2.967	2.488
Iceland	1990	0.013	0.013	0.006		0.010	0.056	-0.013
Japan	2013	1.408	1.096	0.760		0.928	4.977	13.065
New Zealand	2005	0.086	0.055	0.043	0.571		0.286	0.416
Norway	1990	0.052	0.029	0.025		0.027	0.138	0.649
Switzerland	1990	0.054	0.042	0.027		0.035	0.189	1.057
United Kingdom	1990	0.810	0.409	0.259		0.334	1.822	7.943
United States	2005	6.635	5.222	3.251		4.844	24.98	22.69
EU	1990	4.632	3.081	2.085		2.583	13.911	50.093

Table: “Em”: “Emissions”, reported in Gt of CO_2. According to NDCs (submitted by 2023):

1. reference year,
2. emissions in the reference year (GHG emissions including LULUCF, OECD data),
3. emissions in 2020 (GHG emissions including LULUCF, OECD data),
4. emissions target for 2030,
5. cumulative emissions target for 2030 if available,
6. emissions target for 2025 (in green if stated, in black if extrapolated through linear reduction from 2020),
7. estimated target as cumulative emissions E_0 over the NDC cycle 2021-2025,
8. consequent carbon budgets from 2026 onwards (based on Table 32).

App. – Data: EU, NDCs 2021-2025 (E_0) and national carbon budgets from 2026 ($\bar{E}_1$)

Back to Data

EU Country	Em 2021–2025: estimated target	CB 2026 onwards
Austria	0.280	1.009
Belgium	0.361	1.300
Czech Republic	0.333	1.199
Denmark	0.181	0.650
Estonia	0.040	0.146
Finland	0.171	0.616
France	2.035	7.329
Germany	2.611	9.402
Greece	0.324	1.165
Hungary	0.299	1.076
Ireland	0.156	0.560
Italy	1.880	6.769
Latvia	0.059	0.213
Lithuania	0.084	0.303
Luxembourg	0.001	0.004
Netherlands	0.535	1.928
Poland	1.176	4.236
Portugal	0.317	1.143
Slovak Republic	0.171	0.616
Slovenia	0.065	0.235
Spain	1.453	5.233
Sweden	0.317	1.143

Appendix – Debt sustainability in the transition. $r = 2.44\%$.

Back to Main Presentation

Country	Green d_M (1)	(2)-*chr*	(3)	d_O^{M*} st cb (1)	(2)	(3)	D/Y
Australia	896.47	1031.30	568.35	680.93	779.85	592.45	57.80
Austria	162.83	140.75	129.35	157.22	136.22	130.29	83.20
Belgium	357.46	306.99	282.14	317.05	274.50	260.88	112.80
Canada	532.28	500.19	444.12	477.20	449.15	420.75	117.80
Czech Republic	122.04	77.80	70.56	93.01	62.62	59.32	37.70
Denmark	395.43	370.42	351.65	375.01	351.98	341.39	42.10
Estonia	116.28	103.97	90.16	105.36	94.84	87.66	19.00
Finland	245.50	229.20	218.40	236.79	221.45	215.53	69.00
France	177.91	151.26	141.17	160.73	137.69	132.08	115.20
Germany	173.22	135.84	129.21	151.92	121.14	117.68	68.70
Greece	87.47	80.71	78.89	81.50	75.59	74.68	211.90
Hungary	290.92	225.66	213.32	248.67	197.24	191.11	80.00
Ireland	404.25	368.51	291.36	362.78	332.11	292.69	58.40
Italy	208.18	176.05	172.14	183.48	157.18	155.19	155.30
Japan	181.92	152.56	148.18	160.11	135.72	133.45	259.00
Latvia	57.60	52.33	45.31	51.66	47.24	43.62	43.30
Lithuania	76.66	57.30	48.78	62.95	48.45	44.33	46.60
Luxembourg	277.52	220.78	184.83	221.97	180.48	162.84	24.80
Netherlands	254.62	217.01	200.05	226.62	194.88	185.71	52.80
New Zealand	360.12	367.39	322.79	331.31	337.83	315.40	43.10
Norway	1475.18	1202.54	1042.05	1411.74	1155.26	1085.08	46.80
Poland	225.23	219.19	177.54	219.51	213.67	200.98	57.40
Portugal	120.33	108.47	102.87	111.80	101.22	98.12	135.20
Slovak Republic	18.37	14.66	11.50	15.15	12.28	10.67	59.70
Slovenia	91.80	79.36	72.87	79.45	69.52	66.25	79.80
Spain	152.77	145.75	134.66	138.30	132.28	126.26	120.00
Sweden	262.10	231.60	215.38	239.39	212.83	204.00	39.60
Switzerland	146.22	133.48	125.14	133.24	122.35	117.73	42.40
Turkey	217.35	255.52	220.51	186.90	217.03	199.72	39.50
United Kingdom	345.71	282.47	257.56	311.22	257.03	243.27	102.60
United States	242.97	219.13	190.97	204.42	185.10	170.88	134.20

Appendix – Debt sustainability in the transition. $r = 3\%$.

Back to Results

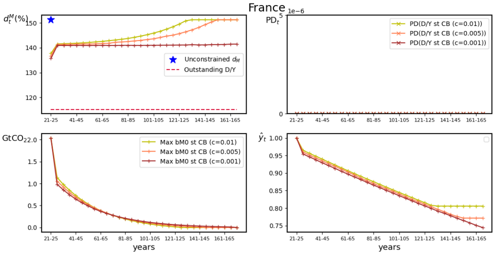
Country	Green b_M (1)	Green b_M (2)-*chr*	Green b_M (3)	Max b_O^M st cb (1)	Max b_O^M st cb (2)	Max b_O^M st cb (3)	Green d_M (1)	Green d_M (2)-*chr*	Green d_M (3)	d_O^{M*} st cb (1)	d_O^{M*} st cb (2)	d_O^{M*} st cb (3)	D/Y
Australia	379.41	405.54	295.02	296.14	315.68	272.84	443.5	474.32	345.05	346.17	369.21	319.11	57.8
Austria	112.42	99.69	92.86	108.95	96.8	93.15	132.36	117.39	109.35	128.27	114	109.7	83.2
Belgium	244.35	215.77	201.14	219.6	195.23	187.29	286.88	253.47	236.28	257.82	229.34	220.01	112.8
Canada	362.02	344.02	312.08	326.62	310.8	294.27	426.31	405.56	367.9	384.63	366.4	346.91	117.8
Czech Republic	81.22	55.83	51.32	63.86	45.97	43.93	96.44	66.58	61.21	75.84	54.82	52.39	37.7
Denmark	288.7	272.65	260.55	275.22	260.37	253.62	341.13	322.39	308.08	325.21	307.86	299.89	42.1
Estonia	81.33	73.4	64.68	74.42	67.56	63.06	100.73	91.42	80.56	92.17	84.15	78.55	19
Finland	182.63	171.62	164.3	176.75	166.35	162.39	219.77	206.63	197.81	212.7	200.28	195.52	69
France	123.3	107.79	101.71	112.61	99.08	95.74	144.69	126.57	119.43	132.16	116.34	112.41	115.2
Germany	123.45	100.2	95.91	109.75	90.38	88.17	145.99	118.51	113.43	129.79	106.89	104.28	68.7
Greece	66.49	61.46	60.18	62.38	57.93	57.3	80.11	74.44	72.89	75.16	70.15	69.4	211.9
Hungary	208.94	167.1	158.99	181.5	148.02	144.04	248.07	199.08	189.41	215.49	176.34	171.6	80
Ireland	261.98	243.02	200.53	237.99	221.52	199.32	317.15	294.86	243.31	288.1	268.78	241.84	58.4
Italy	153.97	132.54	129.92	137.42	119.66	118.34	181.14	156.36	153.27	161.67	141.16	139.61	155.3
Japan	133.67	114.39	111.47	118.86	102.68	101.19	157.61	135.12	131.67	140.15	121.29	119.53	259
Latvia	40.18	36.89	32.47	36.43	33.64	31.38	50.08	46.06	40.53	45.4	41.99	39.17	43.3
Lithuania	51.64	40.03	34.78	43.32	34.43	31.91	63.23	49.52	43.03	53.05	42.6	39.48	46.6
Luxembourg	179.96	149.8	129.34	147.82	125.27	115.28	215.35	179.61	155.07	176.9	150.2	138.21	24.8
Netherlands	177.75	155.54	145.12	160.17	141.23	135.65	210.11	183.81	171.5	189.33	166.9	160.31	52.8
New Zealand	248.88	252.87	227.3	230.27	233.86	220.59	294.34	299.2	268.94	272.32	276.71	261.01	43.1
Norway	938.91	801.95	715.5	903.94	774.46	730.3	1103.04	943.43	841.73	1061.96	911.1	859.14	46.8
Poland	146.53	143.49	121.27	143.22	140.28	133.38	174.84	171.17	144.67	170.89	167.34	159.11	57.4
Portugal	87.69	79.95	76.32	82.07	75.11	73.13	103.53	94.66	90.37	96.89	88.93	86.58	135.2
Slovak Republic	11.21	9.45	7.79	9.47	8.08	7.23	13.42	11.33	9.35	11.33	9.69	8.67	59.7
Slovenia	65.82	57.8	53.63	57.81	51.31	49.23	78.66	69.38	64.37	69.08	61.58	59.08	79.8
Spain	109.71	105.18	98.26	100.32	96.4	92.68	129.67	124.62	116.42	118.58	114.21	109.81	120
Sweden	188.08	168.97	158.6	173.36	156.57	151	223.46	200.93	188.6	205.97	186.18	179.56	39.6
Switzerland	103.63	96	90.88	95.72	89.12	86.33	121.88	112.89	106.87	112.58	104.81	101.52	42.4
Turkey	157.64	179.7	158.14	137.35	154.9	144.32	190.41	219.42	193.1	165.91	189.13	176.22	39.5
United Kingdom	235.86	199.67	184.76	215.1	183.74	175.58	277.95	235.6	218.01	253.48	216.8	207.17	102.6
United States	160.05	147.49	132.06	136.16	125.89	118.03	188.28	173.68	155.51	160.18	148.24	138.99	134.2

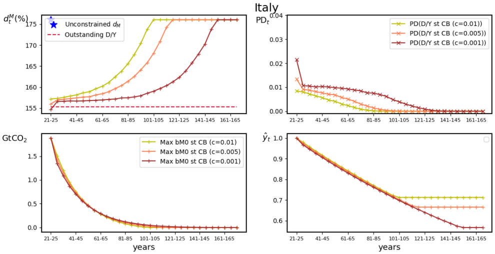
Appendix – Debt sustainability in the transition. $r = 1.88\%$.

Back to Results

Country	Green b_M			Max b_o^M st cb			Green d_M			d_o^{M*} st cb			D/Y
	(1)	(2)-*chr*	(3)	(1)	(2)	(3)	(1)	(2)-*chr*	(3)	(1)	(2)	(3)	
Australia	∞	∞	1549.25	∞	∞	2322.6	∞	∞	1715.6	∞	∞	2571.98	57.8
Austria	191.67	158.91	143.03	184.23	153.17	145.94	213.66	177.18	159.48	205.36	170.78	162.72	83.2
Belgium	431.19	353.06	317.3	376.23	311.19	291.53	479.3	392.68	352.91	418.21	346.11	324.24	112.8
Canada	642.4	590.51	506.29	571.39	526.3	488.83	716.25	659.11	565.1	637.08	587.44	545.61	117.8
Czech Republic	149.58	83.42	74.21	109.56	65.38	61.16	168.17	94.19	83.79	123.17	73.83	69.06	37.7
Denmark	423.04	391.1	367.89	398.75	369.49	356.29	473.27	437.84	411.85	446.1	413.65	398.86	42.1
Estonia	118	102.74	87.17	105.71	92.76	84.62	138.36	121.16	102.8	123.95	109.39	99.79	19
Finland	245.13	226.66	214.69	235.52	218.19	211.56	279.3	258.37	244.73	268.34	248.72	241.16	69
France	209.9	170.41	156.41	187.11	153.32	145.49	233.23	189.44	173.88	207.9	170.45	161.74	115.2
Germany	191.64	142.91	134.76	165.38	125.78	121.48	214.58	160.03	150.91	185.17	140.85	136.03	68.7
Greece	84.71	77.1	75.2	78.34	71.71	70.73	96.63	88.41	86.23	89.37	82.22	81.11	211.9
Hungary	315.04	232.08	217.48	264.2	199.77	192.45	354.13	261.79	245.31	296.98	225.34	217.08	80
Ireland	492.45	432.4	318.66	435.15	384.17	333.89	564.43	496.73	366.07	498.75	441.32	383.56	58.4
Italy	221	181.19	176.58	191.95	159.74	157.35	246.17	202.39	197.23	213.81	178.42	175.76	155.3
Japan	193.83	157.4	152.21	168.58	138.6	135.87	216.39	176.04	170.23	188.2	155.01	151.96	259
Latvia	57.78	51.54	43.66	51.18	45.98	41.9	68.19	60.91	51.6	60.4	54.35	49.53	43.3
Lithuania	84.7	58.39	48.32	67.79	48.41	43.5	98.2	68.4	56.6	78.59	56.7	50.95	46.6
Luxembourg	349.05	254.85	203.09	269.78	202.58	177.21	395.49	289.3	230.54	305.67	229.96	201.17	24.8
Netherlands	291.26	238.44	215.94	255.38	211.35	199.1	325.97	266.79	241.61	285.81	236.48	222.77	52.8
New Zealand	418.2	428.96	363.31	382.1	391.7	363.41	468.26	480.55	407.01	427.84	438.81	407.11	43.1
Norway	2036.03	1507.44	1240.65	1933	1438.56	1334.99	2264.71	1679.05	1381.89	2150.1	1602.33	1486.97	46.8
Poland	283.91	273.27	205.41	275.67	265.44	243.58	320.75	308.66	232.01	311.44	299.81	275.12	57.4
Portugal	129.35	113.94	107.08	119.15	105.5	101.65	144.59	127.73	120.04	133.19	118.27	113.95	135.2
Slovak Republic	26.19	18.54	13.29	20.9	15.12	12.58	29.69	21.05	15.09	23.69	17.17	14.28	59.7
Slovenia	98.08	82.03	74.27	83.42	70.77	66.82	110.97	93.21	84.39	94.39	80.42	75.93	79.8
Spain	167.31	157.52	143.22	149.65	141.33	133.5	187.24	176.71	160.66	167.47	158.54	149.76	120
Sweden	283.7	244.25	224.19	256.33	222.28	211.27	319.13	274.99	252.41	288.35	250.25	237.86	39.6
Switzerland	165.46	147.72	136.51	148.3	133.35	127.09	184.25	164.47	151.99	165.14	148.47	141.51	42.4
Turkey	222.59	266.3	223.54	188.53	222.32	201.06	254.56	307.86	258.42	215.61	257.01	232.44	39.5
United Kingdom	414.21	318.28	283.73	366.91	285.72	266.58	462.15	355.58	316.98	409.38	319.2	297.82	102.6
United States	311.7	269.39	224.1	258.53	224.62	202.92	347.17	300.34	249.85	287.95	250.43	226.23	134.2

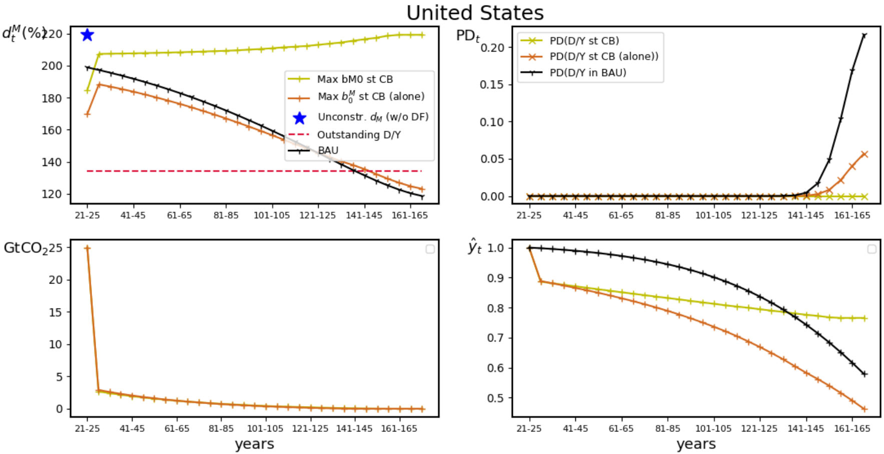
Appendix – Sensitivity analysis for the CCS parameter c. $r = 2.44\%$.





Back to abatement cost function

Appendix – US and the transition



Back to damage function

App. – When MSD in a successful global transition overcomes BAU scenario.

Back to DF

	Shift period
Australia	2021-25
Austria	2021-25
Belgium	2026-30
Canada	2026-30
Czech Republic	2076-80
Denmark	2026-30
Estonia	2061-65
Finland	2041-45
France	2026-30
Germany	2066-70
Greece	2071-75
Hungary	2076-80
Ireland	2026-30
Italy	2071-75
Japan	2061-65
Latvia	2066-70
Lithuania	2071-75
Luxembourg	2051-55
Netherlands	2041-45
New Zealand	2026-30
Norway	2021-25
Poland	2021-25
Portugal	2041-45
Slovak Republic	2026-30
Slovenia	2071-75
Spain	2046-50
Sweden	2051-55
Switzerland	2046-50
United Kingdom	2031-35
United States	2026-30

Appendix – Sovereign interest rates of current debt-to-GDP levels