Sovereign debt sustainability, the carbon budget and climate damages*

Caterina Seghini [1]

[1]Swiss Finance Institute, Université de Genève.

August 15, 2024

Abstract

To what extent could the necessity to address climate change threaten sovereign debt sustainability and reduce fiscal space? Mitigation efforts and increasing temperatures imply economic costs that reduce countries' growth rates, respectively in the short and long term. This can make the repayment of sovereign debt more difficult. In this paper, I assess the impact of the costly reduction of greenhouse gas (GHG) emissions on debt limits (the maximum government debt-GDP ratios that can be sustained without risk of default). Different scenarios, both consistent and inconsistent with the carbon budget constraints of the Paris Agreement, are analyzed for advanced economies to quantify how their debt limits are affected by abatement costs and climate damages. For some countries, such as Italy, mitigation efforts are able to push government debt into the unsustainable territory. Moreover, the role of coordination in transition policies among countries is assessed as a key determinant of sovereign debt sustainability. The evidence shows that failing to enforce a slowdown in emissions at a global level, and to stabilize climate damages, causes debt limits to plunge in the long term for all countries, even for the few that are implementing the transition. On the contrary, if the green transition is coordinated globally, debt limits converge to stable and higher levels, despite an initial and temporary decrease due to the negative impact of emission reductions on GDP growth rates. The evidence presented indicates that it is significantly more beneficial for countries to collaboratively and promptly transition towards mitigating climate impacts on growth and fiscal space. This will support sustainable public debt and the potential to finance the greening of our economies.

Keywords: Sovereign Debt, Fiscal Limits, Climate Change, Mitigation Policies.

JEL classification: E63, H63, O44, Q54.

---

[*] Email: caterina.seghini@unige.ch. I am grateful to Jean-Charles Rochet, Tony Berrada, Ugo Panizza, Philippe Bacchetta, Eric Jondeau, Katheline Schubert, Stéphane Dees, Stavros Zenios, Alain Naef, Ernst Maug and other discussants and participants at the CEPR Paris Symposium 2023, 13th PhD student Workshop on International Macroeconomics, 1st Verona Early Career Workshop in Economics, 4th EENR International Conference, DebtCon7, 28th ICMAIF, SFI Research Days 2024, PSE-CEPR Policy Forum 2024, 72nd AFSE Congress and QCGBF Conference 2024 for valuable suggestions.

1 Introduction

Ensuring the sustainability of public finances and addressing the climate change emergency are two primary concerns most governments are simultaneously facing. The Intergovernmental Panel on Climate Change (IPCC) has been continuously recalling the need of respecting a global carbon budget that keeps global warming below 2, or even 1.5, degrees Celsius over preindustrial levels, requiring immediate and effective action. Against the background of substantial amounts of sovereign debt worldwide, the green transition involves economic costs, which might cause difficulties for highly indebted countries in ensuring the repayment of currently outstanding debts. On the other hand, failing to successfully achieve this structural change to a green production system at a global level will lead to increasing climate damages and continuously diminishing growth rates in the medium and long term. Two fundamental questions are then addressed in this study: Do the commitments made by advanced economies under the Paris Agreement threaten the sustainability of their public debts? Is the alternative of collectively following a business-as-usual path a better option for public finance? I will show in this paper that while mitigation costs can push some highly indebted countries into unsustainable territory, failing to coordinate and keep global temperatures under control will certainly result in default on current debt levels for nearly all the economies studied here.

This study addresses this critical issue by estimating national *fiscal* (or *debt*) *limits*, while taking into account the economic costs of reducing carbon emissions and of climate damages. A *fiscal limit* refers to the maximum amount of debt-to-GDP that a government is allowed to accumulate without impairing the credibility of honoring its repayment. This concept is fundamental for determining the so-called *fiscal space* (that is the distance between the fiscal limit and the actual debt-to-GDP ratio, Ghosh et al., 2013) and the probability of defaulting on its current debt.

Traditionally in the literature, fiscal limits depend on risk-free interest rates, primary surpluses and economic growth. I will show here that the negative impacts of climate-related challenges on economic growth reduce fiscal limits and fiscal space, posing a threat to public debt sustainability.

Fiscal limits and probabilities of defaults are estimated by extending the model proposed by Collard, Habib, and Rochet (2015) with a reduced-form growth rate function in terms of greenhouse gas (GHG) emissions. Abatement costs are defined as the impact of a reduction in emissions on GDP growth rates, and calibrated for each country by using the results of the OECD study constructing the "Environmentally Adjusted Multifactor Productivity" indicator (Cárdenas Rodríguez et al., 2018)[1]. Fiscal limits are studied here for 31 advanced economies, which both are analysed in Cárdenas Rodríguez et al. (2018), and submitted their plans for climate action under the Paris Agreement, known as "Nationally Determined Contributions" (NDCs).

---

[1] around which several sensitivity analyses are also conducted

Following the climate economic literature, various scenarios are first proposed, with different assumptions on the magnitude of short- and long-term abatement costs. Some countries, such as Greece, Japan, and Portugal, face general debt sustainability issues, independently from the transition. For other nations, like Italy and France, these problems emerge specifically in the context of the transition when higher abatement costs are assumed. In general, the path of fiscal limits consistent with maximizing sovereign debt sustainability and respecting the carbon budget is characterized by: a long-term stationary level which depends on the green growth rate remaining after the transition; an increase over time towards this long-term level from an initially lower debt limit, which is affected by short-term abatement costs.

Secondly, the role of alternative government objectives is explored, under the constraint of respecting a national carbon budget: maximizing current debt sustainability or maximizing welfare. The second objective entails a faster mitigation effort in order to keep more resources under the constraint available for the future.

Finally, the role of climate damages, which depend on global cumulative emissions, is analyzed, highlighting the importance of political coordination among countries in the greening effort. The results show that, at the beginning of the transition, due to mitigation costs, the fiscal limit in the coordinated policy scenario is generally lower than in a business-as-usual scenario (where emissions uncontrollably increase and cause worsening climate damages). Nevertheless, by 2080 or even sooner, the trade-off leans positively, for all countries, towards a coordinated green transition. Indeed, failing to enforce a slow-down in emissions at a global level would lead to increasing climate damages and, thus, falling economic growth rates and fiscal limits, entailing serious debt sustainability problems in the long term for all advanced countries, even for the few ones actuating the transition. On the contrary, a coordinated successful transition would stabilize climate damages[2] and fiscal limits in the long-term. From the evidence that will be presented, it results as beneficial for countries to collaboratively and promptly transition towards mitigating climate impacts on growth and fiscal spaces. This will support sustainable public debt and the potential to finance the greening of our economies.

This paper combines two strands of literature: the macro-financial literature on sovereign debt sustainability, and the macro-climate literature on environmental sustainability, aiming to estimate the economic costs of transition policies and climate change.[3]

Regarding the first strand, models for fiscal limits, as in Collard, Habib, and Rochet (2015) and Collard et al. (2022), are conceived for advanced economies, for which monetary finance is in principle excluded and public debt is denominated in local currency. It is also assumed that defaults are involuntary or "excusable" (Grossman and Huyck, 1988), which refers to the situation where a country is

---

[2] Climate damages would still be present in a scenario of 2° or even 1.5°C, but they will be stabilized to a given level, which would mean a lower GDP in levels, but a stable growth rate

[3] For a more extended literature review on the joint challenges of public debt sustainability and climate-related costs, refer to Seghini (2024).

not able to borrow enough on the market in order to service its due debt repayments. It is then "forced" to fail by market investors, in line with the evidence on sovereign crises in advanced economies (Yeyati and Panizza, 2011, Bolton et al., 2022). This modeling approach therefore excludes any strategic type of default (as introduced by Eaton and Gersovitz, 1981).[4] Furthermore, the current model, by following Collard, Habib, and Rochet (2015), defines the fiscal limit as the debt-to-GDP ratio which maximizes government borrowing available for repayment of outstanding debt. A great part of this literature otherwise estimates fiscal limits as the present value of future maximum primary surpluses (Bi 2012, Bi and Leeper 2013, Tanner, 2013, Pallara and Renne, 2023 and forthcoming). Finally, the concept of fiscal limit is also considered as a key determinant of the probability of default on sovereign debt in the dynamic stochastic general equilibrium literature, to study the macroeconomic consequences of high-risk public debt (Corsetti et al., 2013, Batini et al., 2016, Darracq et al., 2016). The second strand of literature - the macro-climate literature - intends to quantify the impact of climate and transition risks on economic growth rates, a significant factor for fiscal limits. This literature, given the novelty and complexity of the subject, shows that such economic costs are surrounded by great uncertainty. In general, empirically these costs are estimated to be modest (e.g. Metcalf and Stock, 2020 and forthcoming), with the great caveat, though, of taking as reference a period where mitigation efforts have been quite low, and surely not at the levels necessary to respect the Paris agreements.[5] These papers also usually focus on a particular policy instrument and a subset of economic sectors. Given the willingness to stay general in this paper regarding the transition policy mix, my model is calibrated using the estimation results of Cárdenas Rodríguez et al. (2018). Regarding climate damages, I resort to the literature on analytical Integrated Assessment Models (IAM),[6] and choose the exponential damage function of Dietz and Venmans (2019), for its good fit with temperature-emissions data.[7]

The first contribution of this paper is to model fiscal limits while taking into account the impact of climate change and mitigation costs. Whereas some research has been conducted about the impact of adaption to climate change on primary surpluses (e.g. Barrage 2020, 2023), the literature about the implications of the transition and climate damages for public debt sustainability remains scarce (Battison and Monasterolo 2020, Zenios 2022, IMF Fiscal Monitor October 2023, Seghini and Dees 2024, and empirical analyses by Beirne et al. 2021, Boehm 2022 and Collender et al. 2023). Among this emerging literature this paper is however the first, to my knowledge, to propose a structural model that explains and quantifies the relationship between climate-related costs and fiscal limits. The second main contribution of this paper is the evaluation of the critical role of international coordination in transition policies on sovereign debt sustainability. The evidence presented here demonstrates that

---

[4] Some recent examples are Aguiar et al. (2022), Hatchondo et al. (2022).

[5] More recently, higher values have been estimated, e.g. Dees (2020).

[6] Such as Golosov et al. (2014), and the following literature.

[7] Alternative notable damage functions are defined in Nordhaus (2014) and Weitzman (2012)

without enforcing a global slowdown in emissions and stabilizing climate damages, long-term debt limits decline for all countries, even those actively implementing transition measures. Conversely, if the green transition is globally coordinated, debt limits stabilize at higher levels despite an initial temporary decline caused by the negative impact of emission reductions on GDP growth rates. The findings strongly suggest that a collaborative and prompt transition towards mitigating climate impacts is significantly more beneficial for countries.

Section 2 of the paper introduces the general model for fiscal limits with abatement costs in the growth function. Section 3 details the growth function employed in the simulations, the fiscal limit in the green net-zero economy, and the maximization problems. Section 4 describes the data used to calibrate the country-specific parameters in our analysis and Section 5 shows the results. Section 6 introduces climate damages and the relevance of globally coordinating the transition, in order to guarantee public debt sustainability and ample fiscal spaces. Section 7 concludes.

2 Modeling debt sustainability, growth and carbon emissions

This section introduces the model used in this paper to study the interaction between environmental and fiscal sustainability. The concept of the fiscal limit employed here is the debt-to-GDP ratio that maximizes government borrowing available for the repayment of outstanding debt. This value represents the maximum sustainable debt (MSD). The framework, which provides measures of maximum sustainable borrowing (MSB) and maximum sustainable debt (MSD), as proposed by Collard, Habib, and Rochet (2015), is extended here to capture their dependence on the path of present and future carbon emissions. For now, climate damages are ignored (they will be introduced in Section 6), and only abatement costs are incorporated into the model.

2.1 Incorporating emissions into a fiscal limits model

As in the original model, 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, with Y_t representing current GDP.[8] Default at t occurs if:

$$D_t - \alpha Y_t > b_t^M Y_t \Longleftrightarrow \frac{D_t}{Y_t} > \alpha + b_t^M \tag{1}$$

---

[8] For the sake of tractability, debt is assumed to be completely rolled over every period. This is in particular needed when the fiscal limit is defined as the value maximizing government borrowing, by balancing the face value of debt and its probability of default. Some notable papers which address the issue of debt sustainability with long-term debt are Hatchondo and Martinez (2009), Chatterjee and Eyigungor (2012), Bacchetta et al. (2018), Lorenzoni and Werning (2019).

where α represents the maximum primary surplus (MPS) with respect to GDP, that the government can extract from the private sector.[9] The maximum primary surplus α adds to the maximum sustainable borrowing (MSB) b_t^M to constitute the resources available for repaying the outstanding debt-to-GDP. Given $B_t^M \equiv b_t^M Y_t$, the MSB is defined by:

$$b_t^M = \max_{d_t} b(d_t) = \max_{d_t} \frac{d_t}{R(d_t)} \tag{2}$$

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.[10] The fiscal limit, or MSD, is the debt-to-GDP d_t which maximizes the borrowing proceeds $b(d_t)$, thereby achieving the maximum sustainable borrowing MSB.[11] For simplicity, as in Collard, Habib, and Rochet (2015), it will be assumed zero recovery in default, and a constant gross risk-free rate R.[12] Assuming competitive financial markets and risk-neutral investors, the return promised on government bonds $R(d_t)$ satisfies:

$$R(d_t)\,(1 - \mathsf{PD}(d_t)) = R \tag{3}$$

The remainder of this section extends the traditional model by Collard, Habib, and Rochet (2015) by incorporating an additional constraint for the government on carbon emissions, namely a "carbon budget". The probability of default PD will be indirectly affected, through the consequences of this constraint on the growth rate. In order to observe this channel, let rewrite the condition of default (1), at $t+1$, in terms of the gross growth rate:

$$D_{t+1} \equiv d_t Y_t > (\alpha + b_{t+1}^M) Y_{t+1} \Longleftrightarrow g_{t+1} = \frac{Y_{t+1}}{Y_t} < \frac{d_t}{\alpha + b_{t+1}^M} \tag{4}$$

I introduce here a general formulation of the stochastic GDP growth rate, in terms of carbon emissions:

$$g_{t+1} = \mathrm{H}_{t+1}(\{E_{t|t-1}\}) e^{\mu_0 + \varepsilon_{t+1}}, \text{ where } \varepsilon_j \sim_{i.i.d.} N(0, \sigma_0^2) \quad \forall j \tag{5}$$

The component $\mathrm{H}_{t+1}(\{E_{t|t-1}\})$ represents the contribution of the emissions path $\{E_{t|t-1}\}$ to the economic growth rate. μ_0 and σ_0 are the average growth rate and volatility of a net-zero economy that

---

[9] The MPS α can be thought as the level of primary surplus (net taxation) which maximizes the Laffer curve. It is assumed to be constant, as in Tanner (2013), where it is defined as the level of "maximum feasible primary surplus that citizens can tolerate." Tanner (2013) then recovers, from the level of MPS, a value for the maximum sustainable debt (MSD), which satisfies a stabilization rule. The approach adopted by Collard, Habib, and Rochet (2015) is similar: they look for the maximum debt level for which sustainability and stability are guaranteed.

[10] Collard, Habib, and Rochet (2015) show how this maximization is equivalent to finding the debt level which minimizes the average interest rate on government bonds: $d_M = \arg\min_d \frac{R_t(d)}{d}$. The solution to the problem is the one which equates the marginal interest rate with the average interest rate: $R'(d_M) = \frac{R(d_M)}{d_M}$.

[11] Fiscal limit: $d_t^M := \arg\max_{d_t} b(d_t) = \arg\max_{d_t} \frac{d_t}{R(d_t)}$.

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

does not rely on emissions. Carbon compensation in the short-term is ruled out ($E_{t|t-1} \geq 0, \forall t$) and the time subscript indicates that the amount of carbon emissions $E_{t|t-1}$, exploited at t, is indeed decided at $t-1$, 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. Indeed, in the following, I will assume a period of 5 years, which also corresponds to the average maturity of US outstanding debt, and for the sake of simplicity, I will refer to $E_{t|t-1}$ as E_t.
Rewriting the default condition as follows, by also making explicit the dependence from the emissions path $\{E_t\}$:

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

and by making use of equivalence (3), the MSB (2) can be redefined, given a path for carbon emissions $\{E_t\}$, as:

$$b^M_t(\{E_t\}) = \max_{d_t} \frac{d_t}{R}[1 - \mathrm{PD}(d_t, \{E_t\})] = \max_{d_t} \frac{d_t}{R}\left[1 - F\left(\frac{d_t}{[\alpha + b^M_{t+1}(\{E_t\})]e^{\mu_0}\mathrm{H}_{t+1}(\{E_t\})}\right)\right] \tag{6}$$

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

Calling the critical shock (the minimum shock's realization necessary to avoid default),[13]

$$x_{t+1} \equiv \frac{d_t}{[\alpha + b^M_{t+1}(\{E_t\})]e^{\mu_0}\mathrm{H}_{t+1}(\{E_t\})}, \tag{7}$$

and the constant borrowing factor (net of growth)[14]

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

the MSB can be rewritten as:

$$b^M_t(\{E_t\}) = \frac{\gamma e^{\mu_0}}{R}[\alpha + b^M_{t+1}(\{E_t\})]\mathrm{H}_{t+1}(\{E_t\}). \tag{8}$$

In the following, this most general version of the function $\mathrm{H}(\cdot)$, in terms of the emission path, will take a more specific form, depending only on current and next-period emissions.

---

[13] Check also the original paper by Collard, Habib and Rochet (2015).

[14] Assuming that the emission path only affects the average growth rate and not volatility ensures that the borrowing factor, net of growth, remains constant, as in the original model. I have also explored alternative formulations that affect volatility, resulting in a more complex computational solution of the model. Nonetheless, given the uncertainty regarding the consequences of transition policies on volatility, I have chosen to leave this analysis out of this paper, reserving it for future, more in-depth research.

2.2 Emissions and growth

In Appendix A.1, the growth function assumed in (5) is extensively motivated and further defined using the existing empirical literature on climate economics. In particular the function $\mathrm{H}(\cdot)$ and the green growth parameters μ_0 and σ_0 are defined and calibrated using the results of the OECD paper by Cárdenas Rodríguez et al. (2018), which constructs the novel "Environmentally Adjusted Multifactor Productivity" indicator. Their estimation exercise does not focus on specific policy instruments, economic sectors, or types of emissions, ensuring the generality of results needed for my analysis.

Given that our main goal is to study the fiscal sustainability of transition paths that lead to net zero emissions, it is appropriate to define the growth function as:

$$g_{t+1} \simeq e^{\mu_0+\varepsilon_{t+1}} \left(\frac{c+e_{t+1}}{c+e_t} \right)^{\beta}, \text{ where } \ \varepsilon_j \sim_{i.i.d.} N(0, \sigma_0^2) \ \ \forall j \tag{9}$$

and μ_0, σ_0 and β are calibrated for each country, by following Cárdenas Rodríguez et al. (2018). They obtain $\beta < 1$ for every country and every type of emission, with significant results only for carbon dioxide and methane. In this paper, the parameter β is calibrated as the weighted average (over emission types) of the elasticity of output to GHG emissions expressed in CO_2-equivalent. It can be interpreted as the short-term abatement cost for each country, as a higher value indicates a greater dependence on carbon emissions and the need for more significant efforts to decarbonize.

The paremeter c represents the percentage of emissions over the country's carbon budget $\bar{E}_1$, that will be possible to recapture by the CCS (carbon capture and storage) technologies which are currently developing, and therefore can still be sustained in a green economy with net zero emissions. This value is assumed to be 1% of the global carbon budget, as at the beginning of 2026. CCS technology capacity was, in 2021, around 41Mt CO2 per year, or 205Mt CO2 over 5 years (our assumed period length). They are projected to develop to a capacity of 230Mt CO2 per year by 2030, which amounts over 5 years, to around 0.1% of our benchmark global carbon budget in 2021 (1116 Gt CO2, as illustrated below). 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 the following results, the transition is generally slow, and never achieved before 2050, therefore, we can safely assume a value of $c = 1\%$ with respect to the 2026 carbon budget $\bar{E}_1$. Globally, this would amount to around 1.8 Gt CO_2 per year, which is way below the assumptions of various IPCC scenarios (AR 6 Synthesis Report, 2023). Nonetheless, in Appendix D.1, the results of a comparative analysis for lower values are reported.[15] The parameter

---

[15] Notice that the role of c becomes most relevant in the last period of the transition, where, since $e_j = 0$, $\forall j > T$, we have:

$$g_{T+1} = e^{\mu_0+\varepsilon_{t+1}} \left(\frac{1}{1+ae_T} \right)^{\beta}, \text{ where } \ a = 1/c.$$

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_T. It follows that governments will tend to postpone more and to reduce the level of emissions in this is taken as constant for the sake of simplicity.

In the following, I will then adopt:

$$\mathrm{H}_{t+1}(\{E_t\}) := \frac{\eta(E_{t+1})}{\eta(E_t)} := \left[\frac{(c+e_{t+1})\bar{E}_1}{(c+e_t)\bar{E}_1}\right]^{\beta} = \left(\frac{c+e_{t+1}}{c+e_t}\right)^{\beta}.$$

This specification of the function $\mathrm{H}(\cdot)$ also finds additional interpretations in light of the research by Dietz and Venmans (2019). Their model represents a further justification of the reduced-form growth function in terms of emission employed in this paper, as discussed in Appendix A.2.

3 Fiscal limits, emissions' abatement and the carbon budget

In this section, I incorporate the two elements introduced in section 2: the fiscal limit measure and the growth rate as a function of green growth and emissions. I introduce, then, the concepts of carbon budget, "green" fiscal limit, debt sustainability and the maximization problems which underline the results of this paper.

3.1 The maximum sustainable debt under the carbon budget

By adopting the growth functional form in terms of emissions (31), assumed in the previous section, the MSB (8) can be rewritten as:[16]

$$b_t^M = \frac{\gamma e^{\mu_0}}{R}(\alpha + b_{t+1}^M)\frac{\eta(E_{t+1})}{\eta(E_t)}, \text{ where } \eta(E_t) = (c\bar{E} + E_t)^{\beta} = [(c+e_t)\bar{E}]^{\beta} \tag{10}$$

The MSB equation can be represented in two other additional ways. First, by iterating we get:

$$\begin{aligned} b_t^M &= \alpha \sum_{j=1}^{+\infty}\left(\frac{\gamma e^{\mu_0}}{R}\right)^{j}\prod_{l=0}^{j-1}\frac{\eta(E_{t+l+1})}{\eta(E_{t+l})} && (11)\\ &= \underbrace{\alpha\frac{\gamma e^{\mu_0}}{R}\frac{\eta(E_{t+1})}{\eta(E_t)}}_{b_S^M(\{E_t\})}\underbrace{\sum_{j=1}^{+\infty}\left(\frac{\gamma e^{\mu_0}}{R}\right)^{j-1}\prod_{l=1}^{j-1}\frac{\eta(E_{t+l+1})}{\eta(E_{t+l})}}_{\Gamma_{\{E_t\}}} && (12)\end{aligned}$$

where the latter formulation is aligned with the standard model by Collard, Habib, and Rochet (2015). The first component $b_S^M(\{E_t\})$ is the maximum static borrowing[17], and $\Gamma_{\{E_t\}}$ is the borrowing multiplier, which measures the "increase in present borrowing made possible by infinitely repeated reliance

---

final period. This results in smoothness of the optimal transition in our framework, when governments aim to maximize current sustainability, as introduced in Section 3.

[16] We drop also the explicit dependence of MSB from the path of emissions $\{E_t\}$.

[17] the MSB if borrowing were not possible in the subsequent period.

on future borrowing", given a feasible path $\{E_t\}$. The product $\gamma e^{\mu_0}\frac{\eta(E_{t+1})}{\eta(E_t)}$ represents the total borrowing factor, including the growth rate contribution.
Alternatively, the product in (11) can be simplified into $\prod_{l=0}^{j-1}\frac{\eta(E_{t+l+1})}{\eta(E_{t+l})}=\frac{\eta(E_{t+j})}{\eta(E_t)}$, in order to get:

$$b_t^M=\frac{\alpha}{\eta(E_t)}\sum_{j=1}^{+\infty}\left(\frac{\gamma e^{\mu_0}}{R}\right)^j\eta(E_{t+j}) \tag{13}$$

This second form is the most convenient, since it highlights the dependence of current MSB both on E_t, which is assumed to be predetermined (as explained before), and on the sequence of future carbon emissions.

Given (7), the maximum sustainable debt (MSD) corresponds to :

$$d_t^M=x_M(\alpha+b_{t+1}^M)e^{\mu_0}\frac{\eta(E_{t+1})}{\eta(E_t)}\equiv\frac{R}{1-F(x_M)}b_t^M. \tag{14}$$

This represents the fiscal limit in period t: the maximum face value the debt issued in period t can have to remain sustainable. This value will be compared with current debt-to-GDP levels to determine their sustainability.

The carbon budget. Each economy also has a total available carbon budget that the government must respect:

$$\sum_{j=0}^{+\infty}E_j\leq\bar{E}_0 \tag{15}$$

The imposition of this constraint captures the political commitments signed under the Paris Agreement and implicitly reflects the willingness to avoid the adverse effects of climate change generated by the use of carbon emissions. For now, the negative economic impact of climate change, which has been the focus of recent advances in environmental economics through the modeling of the so-called "damages function," is ignored. Potentially, an increasing consumption of emissions could guarantee higher economic growth in the short term but decrease it in the long run due to the depletion of the country's natural resources and a higher frequency of climate disasters. The willingness and necessity of avoiding these adverse effects are simply captured, for now, by imposing the carbon budget, as in Gollier (2022). In Section 6, I will explicitly introduce economic climate damages by employing the damage function by Dietz and Venmans (2019), both in the green transition scenario and in alternative business-as-usual scenarios.

At time t, the environmental constraint rewrites as:

$$\sum_{j=t}^{+\infty}E_j\leq\bar{E}_t \tag{16}$$

where $\bar{E}_t = \bar{E}_0 - \sum_{j=0}^{t-1} E_j$ is the remaining carbon budget.

Debt sustainability. Here, as in the standard model by 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 $b_t^M \leq \tau(b_{t+1}^M)$ $\forall t$". Furthermore, Collard, Habib, and Rochet (2015) look for a debt level that is stable, and thus, "more properly described as sustainable". Here, the same approach is adopted. Therefore, in order to ensure convergence of the MSB to a finite value, the following condition must be satisfied:

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

There must exist a time j after period t, when we are measuring the MSB b_t^M, such that the total borrowing factor (the product of the borrowing factor net of growth γ and the gross growth rate $g_l = e^{\mu_0} \frac{\eta(E_l)}{\eta(E_{l-1})}$) is lower than the gross risk-free interest rate R. This condition 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.

3.2 The MSD of the green economy

The framework introduced here can provide an answer to a first crucial question: What will be the fiscal limit (MSD) of a country after successfully completing the green transition? This represents the limit towards which its economy will tend in the long run, given the necessity of respecting the carbon budget. This green economy will be characterized by the feasible path $\{E_t\}$: $E_j = 0$, $\forall j \geq t$, and by the green growth rate $g_{t+1}^G = e^{\mu_0 + \varepsilon_{j+1}}$, $\forall j \geq t$. In this case, the MSB becomes:

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

Equivalently to the standard analysis by Collard, Habib, and Rochet (2015), by iterating, we get:

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

The product γe^{μ_0} represents the "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. In the green economy where $E_j = 0$, $\forall j \geq t$, and it is assumed $\gamma e^{\mu_0} < R$ (always respected in data range of this paper), the MSB capacity is finite and equal to:

$$b_{M,G} \equiv \frac{\alpha \gamma e^{\mu_0}}{R - \gamma e^{\mu_0}}. \tag{17}$$

The function τ is then a contraction that has the unique fixed point $b_{M,G}$.[18] This represents the "green MSB," or the borrowing capacity of the green economy, towards which the government will converge at the end of the transition. Using (7), the green fiscal limit (MSD) is described by:

$$d_{M,G} \equiv (\alpha + b_{M,G}) x_M e^{\mu_0}. \tag{18}$$

The probability of default for a given level of debt d, in the green economy, can be found through:

$$\mathsf{PD}_{M,G}(d) \equiv F\left(\frac{d}{[\alpha + b_{M,G}]e^{\mu_0}}\right) = \Phi\left(\frac{\ln(d) - \ln(\alpha + b_{M,G}) - \mu_0}{\sigma}\right) \tag{19}$$

where Φ represents the standard normal c.d.f.

3.3 The government's maximization problems

This section introduces the two maximization problems of current debt sustainability and "welfare" (or the present value of future GDPs), which underlie the results presented in Section 5. Further details are available in Appendix B.

3.3.1 Maximizing the current MSB under the carbon budget.

A government constrained by the need to respect a national carbon budget might aim to maximize the MSB of the current period to ensure the repayment of the current outstanding debt-to-GDP d_{t-1}. For current political decisions, especially for countries facing fiscal challenges, this value is crucial, along with its relative MSD: this represents the maximum achievable fiscal limit of the country under the constraint of the impending transition. For simplicity, let me call the initial period $t = 0$, which will represent the current NDC cycle 2021-25. The MSB in an initial period $t = 0$ is:

$$\begin{aligned} b_0^M &= \frac{\gamma e^{\mu_0}}{R}(\alpha + b_1^M)\frac{\eta(E_1)}{\eta(E_0)} \\ &= \frac{\alpha}{\eta(E_0)} \sum_{t=1}^{+\infty} \left(\frac{\gamma e^{\mu_0}}{R}\right)^t \eta(E_t) \end{aligned} \tag{20}$$

The debt sustainability maximization problem, given an initial level of emissions E_0, is expressed as:

$$\max_{\{E_t\}} \; b_0^M = \frac{\alpha}{\eta(E_0)} \sum_{t=1}^{+\infty} \left(\frac{\gamma e^{\mu_0}}{R}\right)^t \eta(E_t) \tag{21}$$

$$\text{s.t.} \; \sum_{t=1}^{+\infty} E_t \leq \bar{E}_1 \tag{22}$$

$$E_t \geq 0 \tag{23}$$

---

[18] If it was $\gamma e^{\mu_0} > R$, any borrowing $b > 0$ would be sustainable.

By solving this problem, we find the emissions path $\{E_t\}$ that maximizes the MSB in $t = 0$, and the consequent fiscal limits along the transition.

3.3.2 Maximizing "welfare" under the carbon budget

The previous maximization problem will be compared to the transition path a benevolent social planner would undertake, by ignoring the constrain of an outstanding debt to be repaid. The benevolent social planner would maximize the summation of the present value of expected future GDP (which is taken as a representation of social welfare), where the latter, in period t, is:

$$\begin{aligned}\mathbb{E}_0[Y_t] &= Y_0 e^{t\mu_0}\mathbb{E}_0\left[\prod_{j=1}^{t} e^{\varepsilon_j}\right]\frac{\eta(E_t)}{\eta(E_0)} \\ &= Y_0 e^{t\mu_0}\prod_{j=1}^{t}\mathbb{E}_0\left[e^{\varepsilon_j}\right]\frac{\eta(E_t)}{\eta(E_0)} = \frac{Y_0}{\eta(E_0)}e^{t(\mu_0+1/2\sigma_0^2)}\eta(E_t) \\ \text{where} \quad & \eta(E_t) = (c\bar{E}_1 + E_t)^{\beta}\end{aligned}$$

given that $\exp(\varepsilon_j)$ is assumed to be i.i.d. and lognormal. The welfare maximization writes as:

$$\max_{\{E_t\}} \sum_{t=0}^{+\infty}\frac{\mathbb{E}_0[Y_t]}{R^t} = \frac{Y_0}{\eta(E_0)}\sum_{t=0}^{+\infty}\left(\frac{\bar{g}}{R}\right)^t \eta(E_t) \tag{24}$$

$$\text{s.t.} \quad \sum_{t=1}^{+\infty} E_t \leq \bar{E}_1 \tag{25}$$

$$E_t \geq 0 \tag{26}$$

by defining $\bar{g} = e^{\mu_0 + 1/2\sigma_0^2}$, as the expected green growth rate.

4 Data and Calibration

This section presents the data used for the calibration of the model for 31 advanced economies. The analysis is restricted to these OECD countries due to data limitation on two aspects: countries that signed the Paris Agreement and submitted their plans for climate action, known as "Nationally Determined Contributions" (NDCs); countries studied in the OECD paper that constructs the Environmentally Adjusted Multifactor Productivity indicator, from which we take estimates of countries' β (representing the short-term abatement cost parameter).

Period length and risk-free interest rate The period length for repaying outstanding government debt is set to 5 years, matching the average maturity of outstanding US government debt in 2020.[19]

---

[19] Since we are considering zero-coupon bonds, using duration would be more appropriate. This would be around 5.5 years, as shown by Andreolli 2021 (JMP). We take 5 years for the sake of simplicity.

The risk-free interest rate $r \equiv R - 1$ is chosen to match the real yield on the United States five-year Treasury Bond over the period 2003–2020.[20] The maximum value of the annual return over this period is 2.44% (2006). The average annual returns over 2003-2013 and 2003-2020 are 0.76% and 0.5%, respectively. CBO (Congressional Budget Office) projections[21] predict an increase in real interest rates over the next decades compared to the current unprecedented low rates scenario. Given the long-run horizon of this paper, the maximum value over the available data period of 2.44% is taken as the benchmark. Additionally, a comparative analysis is conducted for higher and lower values: 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.[22]

The maximum primary surplus is taken to match the national historical maximum primary surplus: $\alpha = \max_t \frac{s_t}{Y_t}$, where s_t is the annual primary surplus, (source IMF). A lower value indicates a worse situation for the fiscal sustainability of the country, called “fiscal fatigue". From the IMF datasets, I also take values of debt-to-GDP in 2020 for the 31 countries in my analysis. The data are reported in the last two columns of Table 1.

GDP growth rate and the abatement cost β. I take the mean and volatility of the growth rate from OECD data: the first four columns in Table 1 represent, respectively, for each country the historical average μ of the GDP growth rate and its volatility σ, and the average green GDP growth rate (adjusted for pollution abatement) μ_0 and volatility σ_0, from Cárdenas Rodríguez et al. (2018, reference period 1990-2013). Notice that for most countries, μ_0 is higher than μ (and σ_0 is lower than σ). This is because these countries actually reduced their emissions over the reference period. In the first analysis, I will assume that μ_0 corresponds to the long-term green growth rate, after pollution abatements have been completed. However, this assumption might be too optimistic. Therefore, I will also analyze scenarios where μ_0 and σ_0 are equal to μ and σ (the "parallel hypothesis"), or where μ_0 is lower than μ.

The fifth column lists the β coefficient, which is equivalent to the elasticity of output with respect to emissions and represents the abatement short-term cost parameter. This value is an average of the elasticities that are significant in the OECD study by Cárdenas Rodríguez et al. (2018) for CO_2 and CH_4 (methane), weighted by the average relevance of each type of emission over the national total emissions during the period 1990-2013 (to be consistent with the OECD reference period).[23] The average weights over time are presented in Table 2 for each country, along with their standard

---

[20] The selected period is due to data limitation: data.nasdaq.com.

[21] Gamber, 2020

[22] 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.

[23] Data source: ourworldindata.org/greenhouse-gas-emissions, based on emissions data from Jones et al., *National contributions to climate change due to historical emissions of carbon dioxide, methane and nitrous oxide [Data set]*, In Scientific Data (2023.1), Zenodo

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

Table 1: Summary of Economic Indicators. Columns 1-4, based on Cárdenas Rodríguez et al., 2018 (reference 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). Columns 5-6, IMF data: historical maximum primary surplus ($\alpha = \max_t \frac{s_t}{Y_t}$) and debt-to-GDP in 2020.

deviations. Appendix C presents robustness results for β, using the share of each type of emission over the national total emissions in 2013 and 2020 as weights. Except for a few countries, these percentages have generally been stable over time. For the Netherlands, where data are missing, the average across countries is used to calibrate β. Notice that, following the OECD results, $\beta_i \leq 0.165$ for every country. This is in line with the existing empirical literature, such as Känzig (2023), Känzig and Konradt (2023), and Metcalf and Stock (2020, forthcoming). They estimate that the negative effect of climate policies on the level and growth of economic output is generally quite modest and/or not significant. The adverse impact is more substantial for emission trading systems than for carbon taxes, and it becomes lower or might even turn positive in the presence of revenue recycling. In general, these results are consistent with the estimates derived from computable general equilibrium models. For example, in the E3 model by Goulder and Hafstead (2018), a $40 per ton carbon tax for the United States starting in 2020 and rising at 5 percent real annually would reduce annual emissions

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%

Table 2: Mean and standard deviation of carbon dioxide (CO_2) and methane (CH_4) percentages over total emissions.

by 40% and GDP by only 1.5% in 2035. Notice, however, that the focus of this paper is on the relationship between the growth rates of emissions and GDP, and we aim to maintain generality in terms of the carbon policies enacted by individual countries. This is why I do not directly resort to the results of this empirical and theoretical literature on carbon pricing to calibrate the function $\eta(\cdot)$. Instead, I employ the OECD results by Cárdenas Rodríguez et al. (2018), which directly estimate the impact of emissions reduction on GDP growth.

The modeling approach of the relationship between growth and emissions proposed in this paper is not unique in the literature; for example, it has been derived by Dietz and Venmans (2019), as discussed in Appendix A.2. Notice that their calibration would align with an even lower short-term abatement cost. Nonetheless, given the uncertainty around the costs of the transition and the policy choices regarding its implementation, I will show a sensitivity analysis for a higher β. This choice is also based on the observation that existing empirical estimates are based on mitigation efforts not aligned with the needs of a complete net-zero transition. It is also worth recalling that β only captures the short-term cost of the transition. A value for μ_0 lower than μ would potentially capture its long-term cost, due, for example, to a lower rate of development of a green economy compared to a dirty economy, as represented in the pessimistic scenario (3) introduced in Section 5.

Global carbon budget, National Determined Contributions and national carbon budgets. Referring to the IPCC (2023) estimates[24] for the remaining global carbon budget in 2020, I select the 2°C over pre-industrial levels scenario with 67% probability, which corresponds to a carbon budget of 1150 Gt of CO_2 emissions. To estimate the national carbon budgets, I follow Gollier (2022) by dividing this global budget per capita among the countries. Given a global population in 2021 of 7794 million people and a global level of carbon emissions of around 34 Gt CO_2e in 2020, the remaining budget for 2021 onwards of 1116 Gt CO_2e is divided as depicted in Table 1. Beyond the ethical reason for adopting this rule, this choice is also due to a lack of clear national benchmarks in the political spectrum. Indeed, how much each country should contribute to the fight against climate change by reducing emissions is notably the subject of a long-standing debate. Nonetheless, the commitment to keeping global average temperatures below 2°C over pre-industrial levels (and pursuing efforts to limit the increase even further to 1.5°C) has become legally binding with the Paris Agreement, adopted in 2015 and entered into force in 2016. Therefore, this carbon budget is taken seriously and rightly assumed as a hard constraint in this paper.

Also notice that in equation (5), emissions were introduced as $E_{t|t-1}$ to capture that the amount of emissions in period t is decided at $t-1$, reflecting the so-called "carbon lock-in" phenomenon. This phenomenon is mainly due to technological and political constraints. Regarding political constraints, it is important to note that, under the Paris Agreement, countries must submit their nationally determined contributions (NDCs) according to a 5-year cycle.[25] From the current NDCs submitted by "the Parties,"[26] I extrapolated the emissions targets for the first cycle, 2021-2025. These targets will be taken as given in the following simulations of the model, as the initial 5-year emissions value E_0 (second column to the right in Tables 4 and 5). Recalling that the national carbon budget writes as:

$$\sum_{j=0}^{+\infty} E_j \leq \bar{E}_0 \quad \text{or} \quad \sum_{j=1}^{+\infty} E_j \leq \bar{E}_1, \quad \text{where} \quad \bar{E}_1 = \bar{E}_0 - E_0,$$

we would have that the carbon budget in 2021 $\bar{E}_0$ and in 2026 $\bar{E}_1$ respectively correspond to the last columns of Tables 3 and 4/5.

To extrapolate the emissions targets, reference emissions for the NDCs' mitigation objectives are taken from the OECD dataset as the GHG emissions including LULUCF (Land Use, Land Use Changes and Forests).[27] Countries which stated explicitly a 2025 target in their NDCs are highlighted

---

[24] P. 29, Table SPM.2 in IPCC (2023).

[25] https://unfccc.int/NDCREG

[26] As of the beginning of 2023.

[27] Except for the NDCs of Canada, Norway and Switzerland, for which emissions in the reference year are clearly defined as excluding LULUCF.

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

Table 3: National carbon budgets from 2021 onward (3rd column), based on a per capita criterion (1st and 2nd columns).

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 4: NDCs 2021-2025 (E_0) and national carbon budgets from 2026 onward ($\bar{E}_1$).
According to NDCs (submitted by 2023): reference year (col.1), emissions in the reference year (col.2, GHG emissions including LULUCF, OECD data), emissions in 2020 (col.3, GHG emissions including LULUCF, OECD data), emissions target for 2030 (col.4), cumulative emissions target for 2030 if available (col.5), emissions target for 2025 (col.6, in green if stated, in black if extrapolated through linear reduction from 2020), estimated target as cumulative emissions E_0 over the NDC cycle 2021-2025 (col.7), and consequent carbon budgets from 2026 onwards (col.8, based on Table 3). "Em" stands for "Emissions", reported in Gt of CO_2.

in green. Countries with an explicit cumulative objective (for 2030) are highlighted in red. All other countries defined the NDC objective in terms of annual emissions in 2030. I estimated their 2025 objective, and thus the cumulative emissions during the first cycle (2021-2025) by assuming a linear

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

Table 5: EU – NDCs 2021-2025 (E_0) and national carbon budgets from 2026 onward ($\bar{E}_1$). Based on last row of Table 4 on a per-capita basis. "Em" stands for "Emissions", reported in Gt of CO_2.

reduction rule from 2020 emissions' levels. For the EU countries in Table 5, the NDC is unique: their 2021-2025 objectives and the remaining carbon budgets are defined on a per-capita basis according to the EU NDC, whose information is reported at the bottom of Table 4. The MSB and the present value of future GDPs, will be maximized under the constraint represented by the carbon budgets $\bar{E}_1$, for 2026 onward, reported in Tables 4 and 5.[28]

5 Results

This section presents the results for the maximization problem of current debt sustainability introduced in Section 3.3.1. First, I will analyze the consequences of the transition for the fiscal limits of advanced economies under three long-term scenarios for the green growth rate:

(1) optimistic: $\mu_0 \neq \mu$, $\sigma_0 \neq \sigma$, as reported in Table 1;[29]

---

[28] Iceland will be ignored in the following analysis, because of the negativity of its budget constraint. The reason is geological, and coming from the methane release of the melting permafrost in its lands.

[29] The characterization of this scenario as "optimistic" reflects the observation that for the majority of countries $\mu_0 > \mu$, in the OECD study. This is also implied by the fact that these countries decreased their emissions over the observation period 1990-2013. The denomination as "optimistic" also intend to reflects the dimensionality curse of estimations of short-term and long-term abatement costs based on historical data (the abatement effort of the past is only a small part of what would be needed to respect the Paris Agreement). For few countries, such as Australia, New Zealand and Spain, μ_0 is lower than μ. This second small group of advanced economies didn't reduce their emissions over the observation

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

(3) pessimistic:[30] $\mu_0 = \mu[1 - m(E_t)]$, where $m(E_t)$ is decreasing in E_t, and when $E_t = 0$, μ_0 is reduced by a certain fraction (which will be calibrated to 11%, as explained below) with respect to μ. It is convenient to define the function m in terms of relative emissions:

$$m(e_t) = \sqrt{\theta \sum_1^t e_t}. \tag{27}$$

The parameters α and β are calibrated for each country as in Table 1.

The parallel hypothesis scenario (2) is consistent with the evidence provided by Metcalf and Stock (2020 and forthcoming), and with the classical assumptions of computable general equilibrium (CGE) models (such as Goulder et al., 2019), where the long-run stationary growth rate is only determined by fundamentals, that would remain unaffected by temporary transition policies. The pessimistic scenario (3) can be interpreted using the theoretical framework by Acemoglu et al. (2012) of directed endogenous technological progress: a lower long-run growth rate of the green economy would result from a lower success rate in innovation in the green sector compared to the dirty sector. The higher growth rate of the dirty sector would be achieved in a laissez-faire scenario, potentially leading to an environmental disaster (note that climate economic damages are ignored for now and will be introduced in Section 6). Conversely, the optimistic scenario (1) aligns with the opposite situation, where innovation is more frequently successful in the green sectors. Evidence in this regard is mixed. Knowledge spillovers, measured through the number of patent citations, appear to be higher for clean technologies, as shown by Dechezleprêtre et al. (2021, 2017) and Perrons et al. (2021). Nonetheless, the latter paper also shows that the pass-through delay of green innovations from scientific discovery to actual implementation is higher than for dirty innovations. I take the ratio of success rate of clean over dirty technology as the product of the ratio of their number of citations per patent (1.43 according to Dechezleprêtre and al. (2017)) and the inverse of the ratio of the pass-through years (5/8 according to Perrons et al. (2021). This results in a success rate of green technology equal to 89% of the success rate of dirty technology. Therefore, we assume $\mu_0 = \mu(1 - 11\%)$ at the end of the transition. Based on these considerations, equation (27) is calibrated for scenario (3) with a value of $\theta = 0.0121$.

5.1 Abatement costs and fiscal limits

Table 6 lists, for each country, the values for the optimistic (1), parallel-hypothesis (2), and pessimistic (3) scenarios of the stationary debt limit at the end of the transition, d_M, and the initial debt limit under

---

period.

[30] When maximizing the MSB under this long-term scenario, we add a monotonicity constraint in emissions over time and we assume the carbon budget to hold in equality. These assumptions are needed to avoid unrealistic paths in emissions' reductions. Notice that when these constraints are imposed for the other two scenarios, our results remain unchanged.

the carbon budget constraint, d_0^{M*}, when the risk-free real interest rate is at 2.44%.[31] Tables A3 and A4 in Appendix, show, respectively, the results for a 3% and 1.88% interest rate. As expected, initial values are lower than the respective stationary values.[32]

Country	Green d_M			d_0^{M*} st cb			D/Y
	(1)	(2)-*chr*	(3)	(1)	(2)	(3)	
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

Table 6: Debt sustainability in advanced countries in the transition. $r = 2.44\%$. d_M: the debt limit in the green economy. d_0^{M*} st cb: the debt limit consistent with the carbon budget. In red, countries that have general debt sustainability problems (D/Y$>d_M$); in brown, countries for which this issue appears only in the context of performing the transition (D/Y$>d_0^{M*}$ st cb).

Countries that have general debt sustainability problems, such as Greece, Japan and Portugal, are highlighted in red. As well known, Japan's situation is particular, as its high debt level is largely held domestically by its citizens and the Bank of Japan (BoJ), providing insulation against market volatility

---

[31] Table A2 includes also the MSB values. Under the scenario (2), the stationary MSB and MSD are equivalent to the classical measure in Collard, Habib, and Rochet (2015). In the following graphs, this value will be represented by a blue star.

[32] Except for very few cases in scenario (3): this anomaly comes from computational limitations, that prevent studying a true infinite horizon, and from the fact that for Australia, Austria, Ireland, Norway and Poland, the maximization of current sustainability leads to dividing the carbon budget in very small pieces among all the available years. This result appears only for Norway and Poland when $r = 3\%$.

and international financial pressures. Japan's monetary policy, including measures like quantitative easing, has been crucial in managing its debt levels. These policies have kept interest rates low, reducing the cost of debt servicing. Nonetheless, concerns about the long-term sustainability of such high debt levels remain, especially if domestic savings decline or if there are shifts in market confidence. Regarding the US debt ceiling ($31.4 trillion, suspended in June 2023 until January 2025), which corresponded to 134% of GDP in 2021, it can be noted that this is always below the MSD reported in these results. It can be argued that the ceiling would be more appropriately defined as a percentage of GDP rather than in US dollars. Given that GDP historically increases over time, the resulting debt ceiling-to-GDP ratio would continuously decrease if the ceiling were not systematically politically re-discussed and increased every few years. Let me remind that the current study remains agnostic regarding the evolution of actual debt-to-GDP ratios. Nonetheless, it is reasonable to expect that they will need to rise to cope with the green transition and/or climate damages.[33] The risk is that not only would they surpass the official debt ceilings, but also MSD levels that would entail a truly higher probability of default.

In table 6, sustainability issues arise due to transition costs only for two countries, Italy and Lithuania, highlighted in brown, in their pessimistic scenario.[34] Figure 1 plots the results of the debt sustainability maximization problem introduced in Section 3.3.1 for some of the countries in our dataset,[35] for $r = 2.44\%$ and the alternative three long-term scenarios. The four pictures for each country shows: the optimizing transition path in $GtCO_2$ (bottom left), the corresponding normalized detrended GDP (bottom right), the debt limit (top left) and the probability of default of outstanding debt-to-GDP (top right). Each point shows their respective values for a 5-year period, starting from the current NDC cycle 2021-2025, for which we take the level of emissions as given in Tables 4 and 5. First, the pessimistic scenario (3) entails lower stationary green fiscal limits in the long term than both the parallel hypothesis (2) and the optimistic scenario (1). Given the recursive nature of the fiscal limit measure, this relationship –$(3) < (2) < (1)$– is closely reflected in the initial debt limits at the beginning of the transition. Secondly, for countries with a lower abatement cost β (such as France, the United Kingdom, and Portugal), the drop in optimal emissions in period 1 (2026-2030) compared to period 0 (2021-2025) is more substantial than for other countries that depend more on emissions (higher β). In this regard, Figure 2 shows a sensitivity analysis for higher values of β (0.3 and 0.6) in the parallel hypothesis scenario (2) for Italy, France, and the United States. For these countries, a higher abatement cost $\beta = 0.3$ implies a shift from a sustainable to an unsustainable current debt-to-GDP ratio (depicted as a dashed red flat line). Confirming the previous intuition, a higher β implies a faster transition, with an initial overshooting if $\beta = 0.6$, for countries with a sufficiently large carbon budget.

---

[33] On the basis of this observation, I take the debt-to-GDP of the pandemic year 2020 as a reasonable benchmark, despite the slight reduction in public indebtedness in subsequent years.

[34] France also shows sustainability problems in the transition if the risk-free interest rate were at 3%. See Table A3.

[35] For space reasons, the dynamic results for only few notable countries are shown. Results for all countries and scenarios are available upon request to the author.

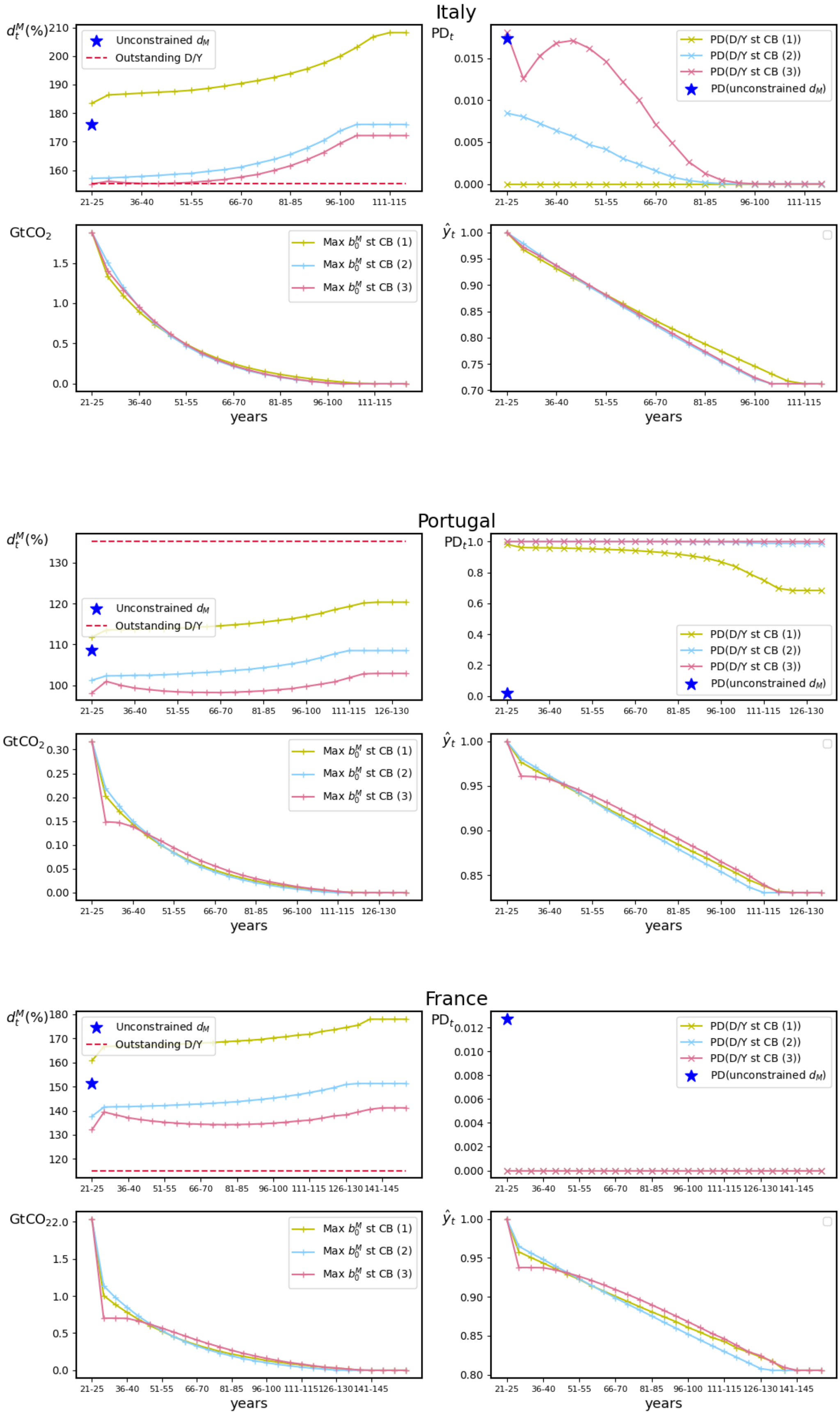

Figure 1: Comparison of the impact on debt sustainability of different scenarios for the long-term green growth rate. $r = 2.44\%$. Plots for the fiscal limit d_t^M, the annual probability of default PD_t (1.0 is 100%) of 2020 debt-to-GDP ratios (outstanding D/Y, assumed to remain constant), the emissions path expressed in GtCO$_2$ maximizing the current maximum sustainable borrowing b_0^M under the carbon budget, and the normalized detrended GDP $\hat{y}_t$. Scenarios: (1) optimistic, (2) parallel hypothesis, (3) pessimistic.

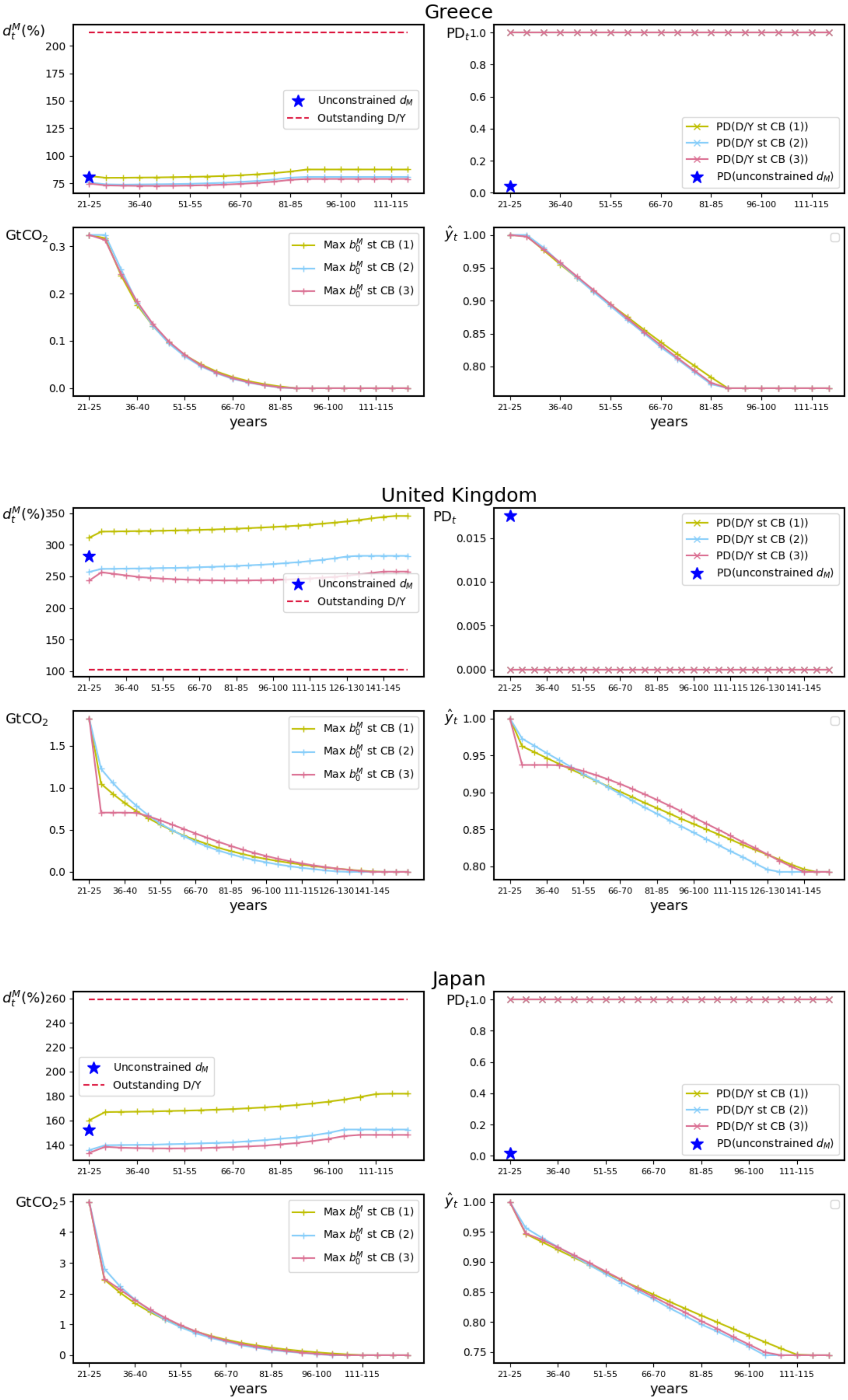

Figure 1: Comparison of the impact on debt sustainability of different scenarios for the long-term green growth rate. $r = 2.44\%$. (cont.)

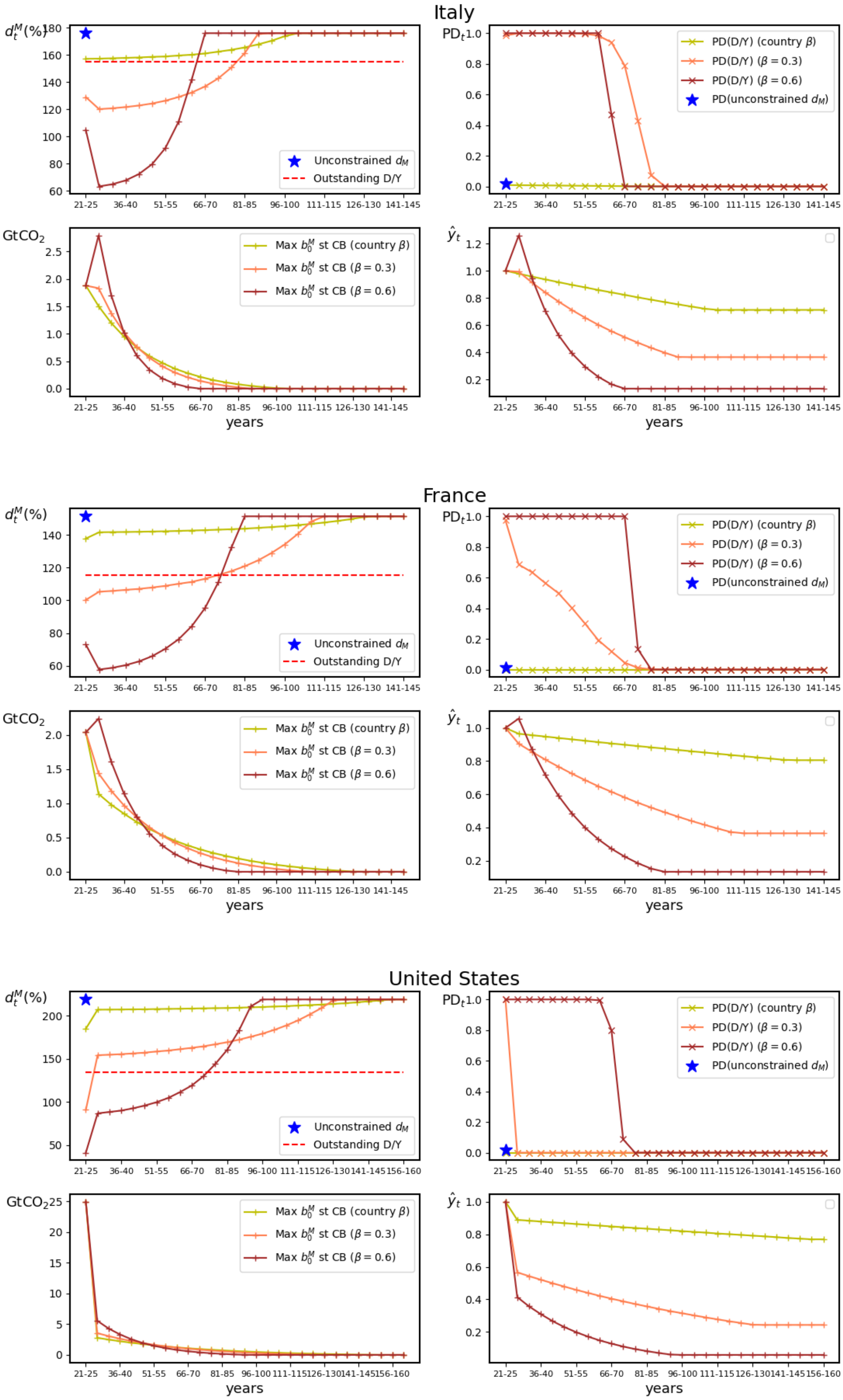

Figure 2: Sensitivity analysis for higher values of β. $r = 2.44\%$, parallel hypothesis scenario. Plots for the fiscal limit d_t^M, the annual probability of default PD$_t$ (1.0 is 100%) of 2020 debt-to-GDP ratios (outstanding D/Y, assumed to remain constant), the emissions path expressed in GtCO$_2$ maximizing the current maximum sustainable borrowing b_0^M under the carbon budget, and the normalized detrended GDP $\hat{y}_t$. Country βs are reported in Table 1.

The consequent convergence to the stationary MSD is faster but passes through very adverse levels of fiscal limit. The value 0.6 represents the disruptive cost of a "disordered transition" scenario. Despite this value hopefully having a low likelihood, this evidence points towards the importance of carefully quantifying current and future abatement costs and managing them efficiently to avoid impairing debt sustainability in the short term, making financing the transition an unfeasible task. In these and the following graphs, the blue star represents the traditional fiscal limit measure of Collard, Habib, and Rochet (2015), which does not take into account the role of climate-related costs. Also, in Appendix D.1, Figure A1 shows sensitivity analysis for lower values of the recapture parameter c.

5.2 Current debt sustainability versus "welfare" maximization

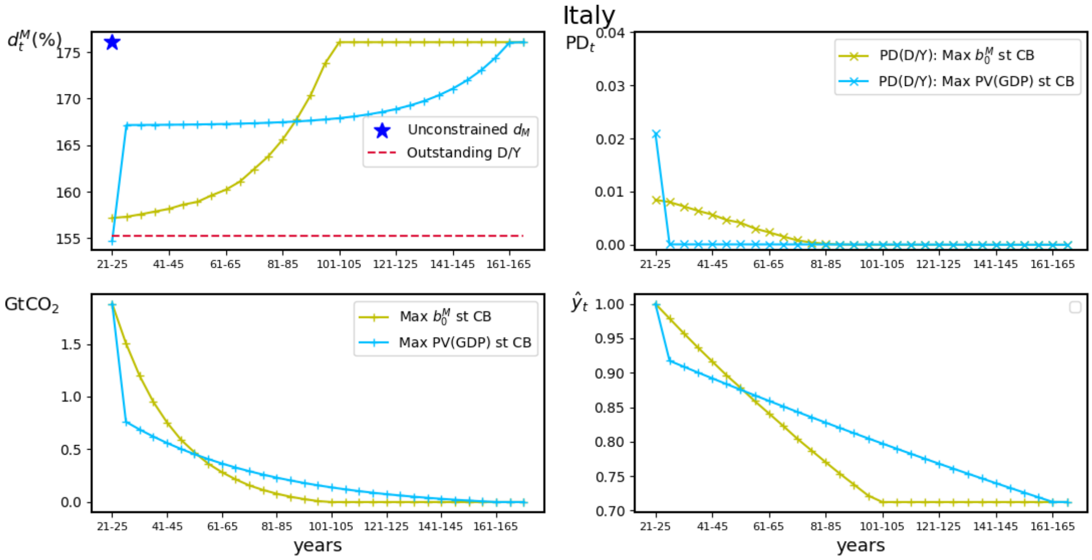

Figure 3: Maximizing under the carbon budget the current maximum sustainable borrowing versus welfare maximization. $r = 2.44\%$, parallel hypothesis scenario. Plots for the fiscal limit d_t^M, the annual probability of default PD_t (1.0 is 100%) of 2020 debt-to-GDP ratios (outstanding D/Y, assumed to remain constant), the emissions path expressed in GtCO$_2$ maximizing the current maximum sustainable borrowing b_0^M or welfare (the present value of future GDPs, PV(GDP)) under the carbon budget, and the normalized detrended GDP $\hat{y}_t$.

In this section, the results of performing the debt sustainability maximization problem of Section 3.3.1 are compared with the outcomes of maximizing the present value of expected future GDP, as outlined in Section 3.3.2. Instead of evaluating the minimum probability of default of current debt-to-GDP levels, this second problem aims to represent the desire of a benevolent social planner (or an altruistic government) to maximize "social welfare." This objective leads to a very fast initial decarbonization in the first period, leaving a significant fraction of the remaining carbon budget available for the future. A benevolent social planner maximizing welfare would prefer to perform most of the green transition of the economy as quickly as possible, leaving the possibility of emitting for future generations.

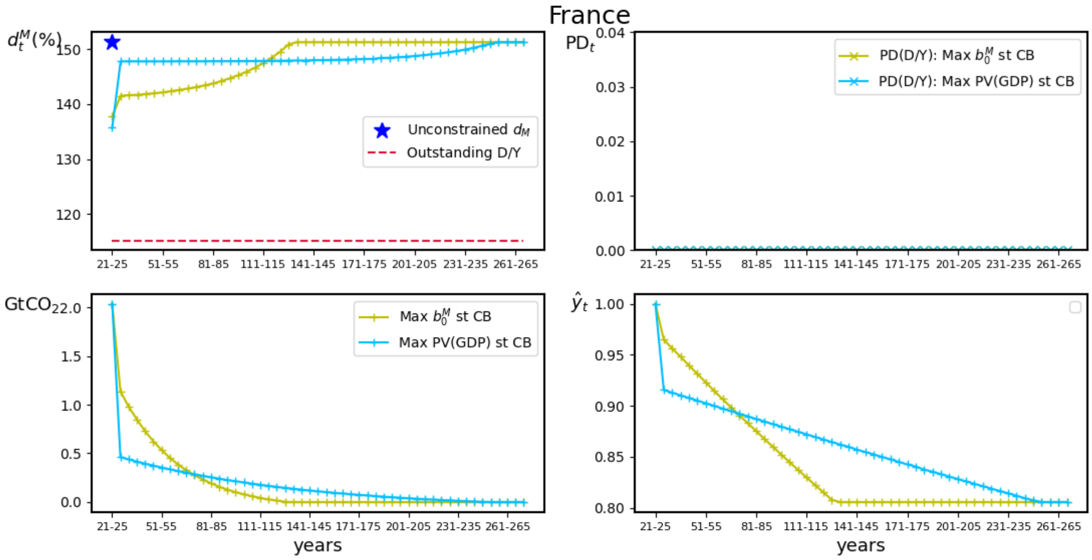

Figure 3: Maximizing under the carbon budget the current maximum sustainable borrowing versus welfare maximization. $r = 2.44\%$, parallel hypothesis scenario.

The resulting initial debt limit is lower, but its subsequent levels are higher, with a slower convergence to the stationary fiscal limit. The probabilities of default remain generally unaffected. Of course, the desire to perform a fast transition would encounter, in a more sophisticated depiction of the economic system, a fundamental feasibility constraint. These results, however, highlight how different objectives can entail different choices of transition paths under the same carbon budget, implying different values and dynamics for national fiscal limits.

6 Introducing climate damages and the need for global coordination

Until now, we have overlooked a fundamental aspect of the transition: its primary motivation of reducing climate damages. Their economic impact is captured in the economic-climate literature through the so-called "damage function." I follow Dietz and Venmans (2019) (DV in the following) and assume it to be exponential in temperature, which is linear in cumulative emissions:

$$D(T_t) = \exp\left(-\frac{\rho}{2}T_t^2\right), \text{ where } T_t = \zeta C_t. \tag{28}$$

T_t represents the global average temperature increase, with respect to pre-industrial levels, and C_t global cumulative emissions since 1850. The parameters ρ and ζ are calibrated by taking their central value in DV: $\rho = 0.01$, and $\zeta = 0.000480$.[36] The time delay from cumulative emissions to temperature

---

[36] In this analysis I employed a global damage function. In future extensions of this work, the parameter ρ could potentially be adapted locally. Nonetheless, further research in the literature needs to be conducted in order to provide

is assumed to be negligible, following the evidence provided by DV.

By adding the damage function, the GDP growth rate becomes:

$$g_{i,t+1} = e^{\mu_{0,i}+\varepsilon_{i,t+1}-\frac{\rho}{2}[(\zeta C_{t+1})^2-(\zeta C_t)^2]} \left(\frac{c+e_{i,t+1}}{c+e_{i,t}}\right)^{\beta_i} \tag{29}$$

Notice that the damage function is global, and thus, C_t represent global cumulative emissions. In the coordinated transition scenario, it is assumed that each country, when selecting its own transition path, will automatically set the path for the global economy, through, for example, political bargaining efforts, or carbon border adjustment mechanisms. Therefore, when analysing country i, global cumulative emissions are defined as $C_t = C_{2020} + \frac{\bar{E}_0^G}{\bar{E}_{i,0}} C_{i,t}$, where $\bar{E}_0^G$ and $\bar{E}_{i,0}$ are respectively the global and the national carbon budget from 2021 onward. Cumulative emissions until 2020, C_{2020}, are estimated to have been 3336 Gt CO2. National cumulative emissions at time t are defined as: $C_{i,t} = \sum_0^t E_{i,t}$, where period 0 represents the period 2021-2025.

6.1 Results: the impact of climate damages

We are now able to properly compare the coordinated transition paths with a business-as-usual scenario, where national and global emissions continue to develop over time as historically. In this case, the growth rate and volatility of countries are set respectively to their historical averages μ_i and σ_i, whereas the annual growth rate of global emissions is set to its average from 1990 to 2020, as 1.126%.

When the damage function is added to the growth function, the trade-off that countries face with respect to climate issues becomes evident, underscoring the importance of political coordination among countries in the greening effort. Figure 4 shows the dynamic results for France, Italy, and the US. Initially, due to mitigation costs, the fiscal limit in the coordinated policy scenario (light green line) is lower than in the business-as-usual (BAU) scenario. However, in the long term, the BAU scenario (black lines) always reaches a very high probability of default. For most countries, the trade-off between mitigation and unmanaged climate costs for the level of the fiscal limit shifts in favor of a coordinated global transition (light green lines) very rapidly, within the first 5-10 years of our analysis, and for all countries before 2080. The precise period of the shift is reported in Table A5 for each country. In general, countries with higher β tend to change the sign of the trade-off later.

The orange lines depict the fiscal limit when the considered country is the only one respecting its fair carbon budget ("solitary" transition), while the rest of the world continues on the business-as-usual path. As expected, this converges to the black line, except for countries such as the US, whose population and emissions constitute a significant share of global population and emissions.

---

this granularity to the exponential (and other) damage function(s) at the country level.

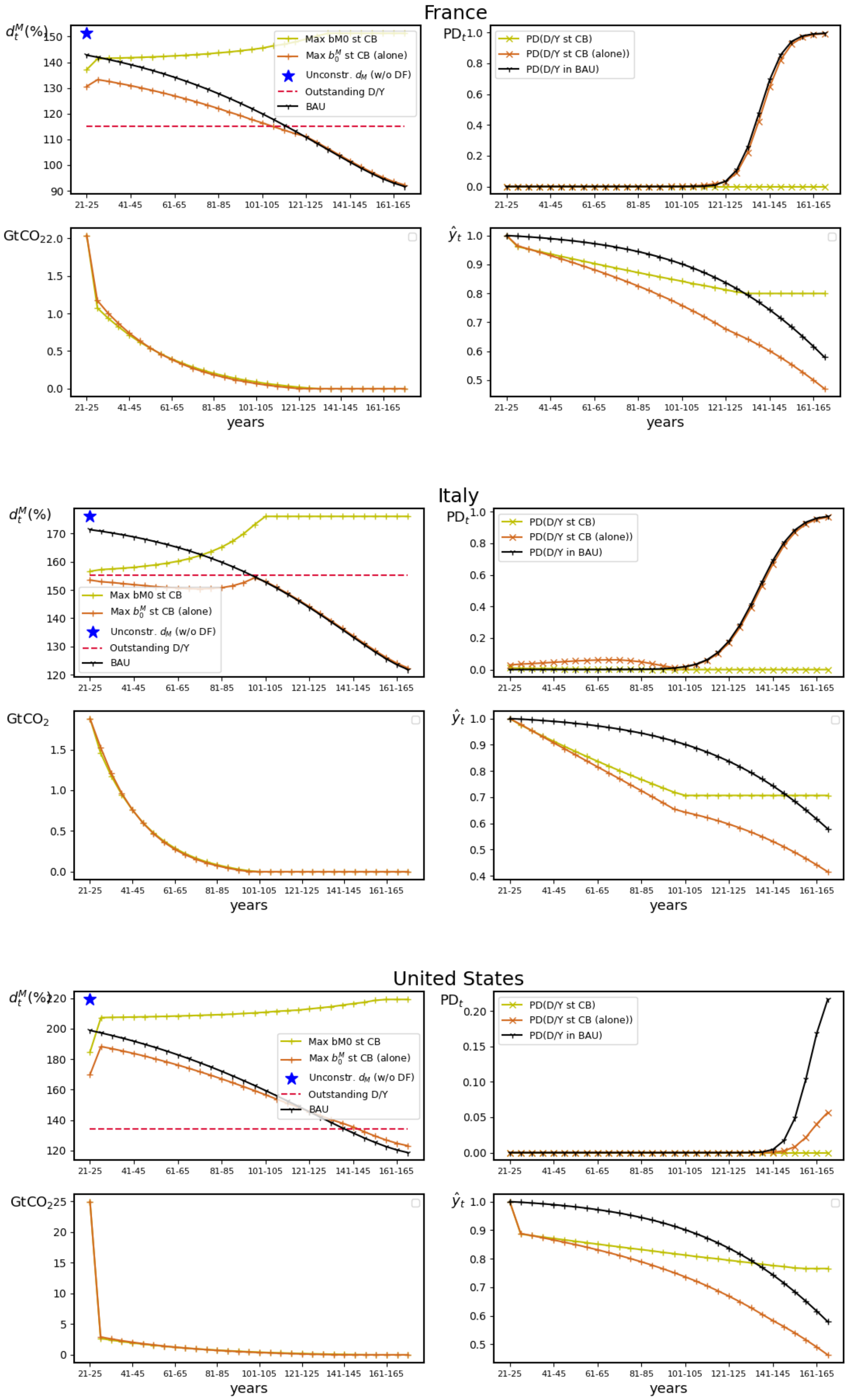

Figure 4: Debt sustainability in a coordinated transition (light green), a "solitary" transition (orange) and a global business-as-usual scenario (black). $r = 2.44\%$, parallel hypothesis scenario. Plots for the fiscal limit d_t^M, the annual probability of default PD$_t$ (1.0 is 100%) of 2020 debt-to-GDP ratios (outstanding D/Y, assumed to remain constant), the emissions path expressed in GtCO$_2$ maximizing the current maximum sustainable borrowing b_0^M under the carbon budget, and the normalized detrended GDP $\hat{y}_t$.

This "solitary" transition scenario shows that failing to enforce a global slowdown in emissions leads to increasing climate damages, falling economic growth rates (the detrended output in the bottom right panels continuously decrease), and declining fiscal limits, resulting in serious long-term debt sustainability problems for all advanced countries. Conversely, a successful coordinated transition (light green line) would stabilize climate damages and fiscal limits in the long term. This stabilization would support sustainable public debt and the potential to finance the greening of economies. This evidence demonstrates that international coordination in transition policies is crucial for mitigating the negative impacts of climate damages on GDP growth rates and maintaining higher long-term debt limits. A collaborative and prompt transition towards mitigating climate impacts is significantly more beneficial for countries, ensuring fiscal stability and sustainable economic growth.

Notice that the probability of default rises only when the current debt-to-GDP ratio exceeds the fiscal limit. Except for countries with particularly fragile fiscal situations, such as Japan or Greece, this occurs in the business-as-usual scenario towards the end of this century or in the next for most countries. Nonetheless, the depicted probabilities of default refer to current debt-to-GDP ratios. Given the substantial costs that unmanaged climate damages would impose on public finances, we might expect debt-to-GDP ratios to increase over the next decades in the business-as-usual scenario. This might also be true in a globally successful transition, depending on the policy mix between carbon taxes and public investment implemented by each country, as shown in Seghini and Dees (2024). The question of the joint analysis of the evolution of debt-to-GDP ratios and fiscal limits in alternative mitigation scenarios pertains to the research agenda following this paper.[37]

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

We are now able to give an answer to the two fundamental questions posed in the Introduction of this paper: Do the commitments made by advanced economies under the Paris Agreement threaten the sustainability of their public debts? Is the alternative of collectively following a business-as-usual path a better option for public finance? Table 7 summarizes the key findings of the paper for Italy, showing the values of Italian fiscal limits in the first NDC cycle (2021-25) and at the beginning of the next century (2101-2105). Scenarios where the initial debt-to-GDP of 155.30% (its value in 2020) exceeds the fiscal limit ($d_t > d_t^M$) are highlighted in red. The benchmark scenario ($\beta = 0.101$ and parallel hypothesis for the green growth distribution) for different degrees of political coordination in the transition (coordinated/solitary/BAU) is highlighted with colored cells. It is evident that the solitary transition scenario is always unviable. The BAU scenario, though initially sustainable, becomes unsustainable in the long term. The only consistently viable scenario from a fiscal sustainability perspective is the coordinated one. In the green cell for 2021-25, two very close values are reported. The

---

[37] This needs both a more sophisticated macro-climate economic model and, as a more complex issue, a compatible endogenous fiscal limit model.

	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 7: 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.

first value, 156.61%, accounts for climate damages in the 2°C scenario, while the second, 157.18%, ignores them (as in Section 5). The proximity of these values confirms that political coordination can eliminate the fiscal sustainability costs of climate change. However, extreme caution is necessary to ensure an economically efficient transition to keep abatement costs low. A higher mitigation cost (β) would pose significant fiscal sustainability challenges and prevent reaching the high long-term debt limit of a coordinated scenario. Thus, the only viable option for guaranteeing the sustainability of the Italian public debt is achieving global coordination in the transition effort and finding the most efficient way to mitigate emissions to maintain effective yet minimal abatement costs. The same conclusion applies to the French case, shown in Appendix D.3.

7 Conclusions

This paper underscores the dual imperative of maintaining sovereign debt sustainability while addressing climate change. By integrating climate-related costs and the commitments of the Paris Agreement into fiscal sustainability models, we highlight the significant impact of carbon budget constraints and climate damages on fiscal limits.

Our findings reveal that carbon budget constraints notably reduce fiscal limits in the short term, temporarily increasing default risks for highly indebted countries. Conversely, failing to address climate change exacerbates fiscal risks in the long term, leading to continuously diminishing growth rates and fiscal limits. Importantly, scenarios involving coordinated global transitions to a green economy show more favorable and stable fiscal outcomes compared to isolated efforts or business-as-usual approaches.

The Italian case exemplifies these dynamics: under a coordinated transition, Italy's fiscal limits are more viable despite the initial costs. However, a lack of global coordination or a failed transition results in significantly reduced fiscal limits and increased default risks in the long run. This illustrates the broader finding that coordinated international efforts are crucial for all countries to maintain fiscal sustainability.

The evidence strongly supports the need for swift, globally coordinated climate action to keep temperatures and climate damages under control, and mitigate their economic and fiscal impacts. For advanced economies, national or regional policies alone are insufficient; global cooperation is essential to prevent deterioration in public debt sustainability and ensure sufficient fiscal space for financing the green transition.

Future research should focus on integrating more detailed economic policy mixes, such as carbon pricing, subsidies, direct public investments, and adaptation, into fiscal limits models. The objective would be to obtain a framework where the debt limit and the debt-to-GDP ratio are both endogenously determined from a common transition scenario. One direction could be to model the environmental economic aspects using a general equilibrium model. However, a more sophisticated endogenous fiscal limit model would be necessary to ensure consistency with a more complex and micro-founded growth rate function.

In conclusion, the transition to a green economy, while challenging and costly, is imperative for maintaining long-term fiscal sustainability. Coordinated international efforts are crucial to managing the economic impacts of climate change and securing sustainable growth for future generations.

References

Acemoglu, Daron, Philippe Aghion, Leonardo Bursztyn, and David Hemous. “The Environment and Directed Technical Change”. *American Economic Review* 102, no. 1 (Feb. 2012): 131–66.

Aguiar, Mark, Satyajit Chatterjee, Harold Cole, and Zachary Stangebye. “Self-Fulfilling Debt Crises, Revisited”. *Journal of Political Economy* 130, no. 5 (May 2022): 1147–1183.

Bacchetta, Philippe, Elena Perazzi, and Eric van Wincoop. “Self-fulfilling debt crises: What can monetary policy do?” *Journal of International Economics* 110 (2018): 119–134.

Barrage, Lint. “The Fiscal Costs of Climate Change”. *AEA Papers and Proceedings* 110 (2020): 107–112.

— . *The Fiscal Costs of Climate Change in the United States*. Tech. rep. WP 23/380. CER-ETH, 2023.

Batini, Nicoletta, Giovanni Melina, and Stefania Villa. *Fiscal Buffers, Private Debt, and Stagnation: The Good, the Bad and the Ugly*. IMF Working Papers 2016/104. International Monetary Fund, May 2016.

Battiston, Stefano, and Irene Monasterolo. “The Climate Spread of Corporate and Sovereign Bonds”. SSRN Working Paper (July 2020).

Beirne, John, Nuobu Renzhi, and Ulrich Volz. “Feeling the heat: Climate risks and the cost of sovereign borrowing”. *International Review of Economics Finance* 76 (2021): 920–936.

Bi, Huixin. “Sovereign default risk premia, fiscal limits, and fiscal policy”. *European Economic Review* 56, no. 3 (2012): 389–410.

Bi, Huixin, and Eric M. Leeper. *Analyzing Fiscal Sustainability*. Staff Working Papers 13-27. Bank of Canada, 2013.

Boehm, H. “Physical climate change and the sovereign risk of emerging economies”. *Economic Structures* 11 (2022): 31.

Bolton, Patrick, Mitu Gulati, and Ugo Panizza. *Sovereign Debt Puzzles*. IHEID Working Papers 27-2022. Economics Section, The Graduate Institute of International Studies, Dec. 2022.

Cárdenas Rodríguez, Miguel, Ivan Haščič, and Martin Souchier. “Environmentally Adjusted Multifactor Productivity: Methodology and Empirical Results for OECD and G20 Countries”. *Ecological Economics* 153 (2018): 147–160.

Chatterjee, Satyajit, and Burcu Eyigungor. “Maturity, Indebtedness, and Default Risk”. *American Economic Review* 102, no. 6 (May 2012): 2674–99.

Collard, Fabrice, Michel Habib, Ugo Panizza, and Jean-Charles Rochet. *Debt Sustainability with Involuntary Default*. CEPR Discussion Papers 17357. C.E.P.R. Discussion Papers, 2022.

Collard, Fabrice, Michel Habib, and Jean-Charles Rochet. "Sovereign Debt Sustainability In Advanced Economies". *Journal of the European Economic Association* 13, no. 3 (2015): 381–420.

Collender, Sierra, Baoqing Gan, Christina S. Nikitopoulos, Kylie-Anne Richards, and Laura Ryan. "Climate transition risk in sovereign bond markets". *Global Finance Journal* 57 (2023): 100868.

Corsetti, Giancarlo, Keith Kuester, André Meier, and Gernot J. Müller. "Sovereign Risk, Fiscal Policy, and Macroeconomic Stability". *The Economic Journal* 123, no. 566 (2013): F99–F132.

Darracq Pariès, Matthieu, Pascal Jacquinot, and Niki Papadopoulou. *Parsing financial fragmentation in the euro area: a multi-country DSGE perspective*. Working Paper Series 1891. European Central Bank, Apr. 2016.

Dechezlepretre, Antoine, Ralf Martin, and Myra Mohnen. *Knowledge Spillovers from clean and dirty technologies*. GRI Working Papers 135. Grantham Research Institute on Climate Change and the Environment, Oct. 2017.

Dechezleprêtre, Antoine, Cal B. Muckley, and Parvati Neelakantan. "Is firm-level clean or dirty innovation valued more?" *The European Journal of Finance* 27 (2021): 31–61.

Dées, Stéphane. "Assessing the Role of Institutions in Limiting the Environmental Externalities of Economic Growth". *Environmental and Resource Economics* 76 (2020): 429–445.

Dietz, Simon, and Frank Venmans. "Cumulative carbon emissions and economic policy: In search of general principles". *Journal of Environmental Economics and Management* 96 (2019): 108–129.

Eaton, Jonathan, and Mark Gersovitz. "Debt with Potential Repudiation: Theoretical and Empirical Analysis". *The Review of Economic Studies* 48, no. 2 (1981): 289–309.

Gamber, Edward. *The Historical Decline in Real Interest Rates and Its Implications for CBO's Projections*. CBO Working Paper. Congressional Budget Office, 2020.

Ghosh, Atish R., Jun I. Kim, Enrique G. Mendoza, Jonathan D. Ostry, and Mahvash S. Qureshi. "Fiscal Fatigue, Fiscal Space and Debt Sustainability in Advanced Economies". *The Economic Journal* 123, no. 566 (2013): F4–F30.

Gollier, Christian. *The cost-efficiency carbon pricing puzzle*. TSE Working Papers 18-952. Toulouse School of Economics (TSE), 2022.

Golosov, Mikhail, John Hassler, Per Krusell, and Aleh Tsyvinski. "Optimal Taxes on Fossil Fuel in General Equilibrium". *Econometrica* 82, no. 1 (Jan. 2014): 41–88.

Goulder, Lawrence H., and Marc A. C. Hafstead. *Confronting the Climate Challenge: U.S. Policy Options*. Columbia University Press, 2018.

Goulder, Lawrence H., Marc A.C. Hafstead, GyuRim Kim, and Xianling Long. “Impacts of a carbon tax across US household income groups: What are the equity-efficiency trade-offs?” *Journal of Public Economics* 175 (2019): 44–64.

Grossman, Herschel I., and John B. Van Huyck. “Sovereign Debt as a Contingent Claim: Excusable Default, Repudiation, and Reputation”. *The American Economic Review* 78, no. 5 (1988): 1088–1097.

Hatchondo, Juan Carlos, and Leonardo Martinez. “Long-duration bonds and sovereign defaults”. *Journal of International Economics* 79, no. 1 (2009): 117–125.

Hatchondo, Juan Carlos, Leonardo Martinez, and Francisco Roch. “Fiscal Rules and the Sovereign Default Premium”. *American Economic Journal: Macroeconomics* 14, no. 4 (Oct. 2022): 244–73.

International Monetary Fund. Fiscal Affairs Dept. *Fiscal Monitor, October 2023: Climate Crossroads: Fiscal Policies in a Warming World*. Vol. 2023. 002. International Monetary Fund, 2023.

IPCC. “Climate Change 2023: Synthesis Report”. In *Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]*. 35–115. IPCC, Geneva, Switzerland, 2023.

— . “Summary for Policymakers”. In *Climate Change 2021 – The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, 3–32. Cambridge University Press, 2023.

Känzig, Diego R. *The Unequal Economic Consequences of Carbon Pricing*. Working Paper, Working Paper Series 31221. National Bureau of Economic Research, May 2023.

Känzig, Diego R, and Maximilian Konradt. *Climate Policy and the Economy: Evidence from Europe’s Carbon Pricing Initiatives*. Working Paper, Working Paper Series 31260. National Bureau of Economic Research, May 2023.

Lorenzoni, Guido, and Iván Werning. “Slow Moving Debt Crises”. *American Economic Review* 109, no. 9 (Sept. 2019): 3229–63.

Metcalf, Gilbert E., and James H. Stock. “The Macroeconomic Impact of Europe’s Carbon Taxes”. *American Economic Journal: Macroeconomics* (forthcoming).

Nordhaus, William. *A question of balance: Weighing the options on global warming policies*. Yale University Press, 2014.

Perrons, Robert K., Adam B. Jaffe, and Trinh Le. “Linking scientific research and energy innovation: A comparison of clean and dirty technologies”. *Energy Research Social Science* 78 (2021): 102122.

Renne, Jean-Paul, and Kevin Pallara. “Fiscal Fatigue, Fiscal Limits and Sovereign Credit Spreads”. *Proceedings of Paris December 2019 Finance Meeting EUROFIDAI - ESSEC* (July 2023).

— . “Fiscal Limits and the pricing of Eurobonds”. *Management Science* (forthcoming).

Seghini, Caterina. *Climate and Sovereign Debt Sustainability: A Literature Review*. SSRN Working Paper, Mar. 2024.

Seghini, Caterina, and Stéphane Dees. *The Green Transition and Public Finances*. SSRN Working Paper, Jan. 2024.

Stock, James H., and Gilbert E. Metcalf. “Measuring the Macroeconomic Impact of Carbon Taxes”. *American Economic Review* 110, no. May (2020): 101–06.

Tanner, Evan C. *Fiscal Sustainability: A 21st Century Guide for the Perplexed*. IMF Working Papers 2013/089. International Monetary Fund, Apr. 2013.

Weitzman, Martin L. “GHG Targets as Insurance Against Catastrophic Climate Damages”. *Journal of Public Economic Theory* 14, no. 2 (2012): 221–244.

Yeyati, Eduardo Levy, and Ugo Panizza. “The elusive costs of sovereign defaults”. *Journal of Development Economics* 94, no. 1 (2011): 95–105.

Zenios, Stavros A. “The risks from climate change to sovereign debt”. *Climatic Change* 172, no. 3 (June 2022): 1–19.

Appendix

A The model

A.1 Emissions and growth – extended

In this section, the growth function assumed in (5) is motivated and further defined using the existing empirical literature on climate economics. In particular the function H$(\cdot)$ and the green growth parameters μ_0 and σ_0 are defined and calibrated using the results of the OECD paper by Cárdenas Rodríguez et al. (2018), which constructs the novel "Environmentally Adjusted Multifactor Productivity" indicator. Their estimation exercise does not focus on specific policy instruments, economic sectors, or types of emissions, ensuring the generality of results needed for my analysis. Here, I show the relationship between the present model, particularly the growth function in (5), and the estimation equation in Cárdenas Rodríguez et al. (2018).

From the transformation function

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

where Y denotes the desirable output of the economy (GDP), E the undesirable output (carbon emissions), and L, K and S, labour, produced capital and natural capital, respectively, they define the following linear regression equation:

$$\dot{Y}_{i,t} = a_i + \delta_t + \rho_i \dot{X}_{it} + \sum \beta_{hi} \dot{E}_{hit} + \varepsilon_{it}. \tag{30}$$

$\dot{Y}_{i,t}$ is the net GDP growth rate of country i, $\dot{X}_{i,t}$ its elasticity-weighted growth rate of inputs and $\dot{E}_{hit}$ the growth rate of each type h of GHG emissions (e.g., carbon dioxide, methane).[38] δ_t are time dummies, and ε_{it} a normally distributed error term. a_i represents environmentally adjusted productivity growth. The coefficients relate to the elasticities of the transformation function with respect to desirable and undesirable outputs as follows:

$$\rho_i = -\frac{1}{\varepsilon_{\Theta Y i}}; \quad \beta_{hi} = \rho_i \varepsilon_{\Theta E h i} = -\frac{\varepsilon_{\Theta E h i}}{\varepsilon_{\Theta Y i}} \equiv \varepsilon_{Y E h i}$$

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

I use the historical average (for the data range in the OECD anaylsis, 1990-2013) of equation (30),

---

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

for calibrating our function $\mathrm{H}(\cdot)$ and the parameters $\mu_i, \sigma_i, \mu_{0,i}$, and $\sigma_{0,i}$, for each country i:

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

For simplicity, it is assumed that the total sum of the different elements in $\mu_{0,i}$ would not be affected by changes in the growth rate of carbon emissions. Therefore, the historical net growth rate μ_i can be split into a "green" growth rate $\mu_{0,i}$ and the contribution of emissions. I also rewrite this latter term as: $\sum_h \beta_{hi}\dot{E}_{hit} = \sum_h \beta_{hi} w_{hi} \dot{E}_{it} = \beta_i \dot{E}_{it}$, where w_{hi} represents the weight (assumed constant) of emissions of type h of country i over its total emissions. How these weights are calibrated in the present analysis will be explained in Section 4. Notice that, by following the OECD results, $\beta_i < 1$ for every country. This parameter represents the weighted average (over emission types) of the elasticity of output to GHG emissions expressed in CO_2-equivalent. By recalling the expression for the gross growth rate in Collard, Habib, and Rochet (2015) (for country i), we can write:

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

where $\left(\frac{E_{i,t+1}}{E_{i,t}}\right)^{\beta_i}$ represents the generalized H-term defined above, and $e_{i,t} \equiv E_{i,t}/\bar{E}_{i,1}$ are the current emissions' share with respect to $\bar{E}_{i,1}$: the national carbon budget for country i in the first period. The parameter β_i can be interpreted as the short-term abatement cost for country i, as a higher value indicates a greater dependence on carbon emissions and the need for more significant efforts to decarbonize.

Given that our main goal is to study the fiscal sustainability of transition paths that lead to net zero emissions, it is appropriate to transform the previous equation as follows:

$$g_{i,t+1} \simeq e^{\mu_{0,i} + \varepsilon_{i,t+1}} \left(\frac{c + e_{i,t+1}}{c + e_{i,t}} \right)^{\beta_i}, \tag{31}$$

where c is the percentage of emissions over the country's carbon budget $\bar{E}_{i,1}$, that will be possible to recapture by the CCS (carbon capture and storage) technologies which are currently developing, and therefore can still be sustained in a green economy with net zero emissions.

A.2 Comparison with other models

It can be shown that the i.i.d. growth function $g_{t+1} \equiv e^{\mu + \varepsilon_{t+1}}$ in the Collard, Habib, and Rochet (2015) framework is compatible with a stochastic Solow model, with a Cobb-Douglas production function with labor L and capital K as inputs, and technological progress Z_t (labor-intensive).[39] Emissions can

---

[39] These results are available upon request.

then be introduced as an additional input to this model, as in Dietz and Venmans (2019). Total output becomes:

$$Y_t = e^{z_t} K_t^{\kappa} (Z_t L_t)^{1-\kappa} \eta_{DV}(E_t) D(T_t) = e^{\zeta_t} \hat{k}_t^{\kappa} Z_t L_t \eta_{DV}(E_t) D(T_t)$$

where z_t is a technological shock, κ the share of capital in production and $\hat{k}_t \equiv \frac{K_t}{Z_t L_t}$ capital per effective labor . Dietz and Venmans (2019) also impose:

$$\eta_{DV}(E_t) = \exp\left(\phi E_t - \frac{\varphi}{2} E_t^2\right)$$
$$D(T_t) = \exp\left(-\frac{\rho}{2} T_t^2\right), \text{ where } T_t = \zeta C_t$$

where C_t are global cumulative emissions. Notice that this function η is concave in emissions, as assumed in this paper. By assuming that $\hat{k}_t$ is already close to the steady state, which will be achieved at the end of the transition when emissions are zero, their growth rate writes approximately as:

$$g_{i,t+1} \approx \exp[\mu_{0,i} + \varepsilon_{i,t+1} - \frac{\rho}{2}[(\zeta C_{t+1})^2 - (\zeta C_t)^2] + \phi(E_{t+1} - E_t) - \frac{\varphi}{2}(E_{t+1}^2 - E_t^2)]$$

Notice that following DV, we can interpret $\frac{\eta'_{DV}(E_t)}{\eta_{DV}(E_t)}$ as the MAC (marginal abatement cost) function. Whereas DV have: $\frac{\eta'_{DV}(E_t)}{\eta_{DV}(E_t)} = \phi - \varphi E_t$, which is decreasing in E_t, in the current model, the MAC function becomes:

$$\frac{\eta'(E_t)}{\eta(E_t)} = \frac{\beta}{c\bar{E}_0 + E_t},$$

also decreasing in emissions. Therefore, following DV, we can give an exact interpretation to η, and in principle open the path to implementing different MAC functions, and study their impact on fiscal limits. This is left for future research.

B The government's maximization problems

B.1 Maximizing the current MSB under the carbon budget.

The maximization problem at $t = 0$, given an initial level of emissions E_0 is:

$$\max_{\{E_t\}} \; b_0^M = \frac{\alpha}{\eta(E_0)} \sum_{t=1}^{+\infty} \left(\frac{\gamma e^{\mu_0}}{R}\right)^t \eta(E_t) \tag{32}$$

$$\text{s.t.} \; \sum_{t=1}^{+\infty} E_t \leq \bar{E}_1 \tag{33}$$

$$E_t \geq 0 \tag{34}$$

aining carbon budget at time t with respect to a total budget $\bar{E}_0$: $\bar{E}_t \equiv \bar{E}_0 - \sum_{j=0}^{t-1} E_j$.

The associated Lagrangian is:

$$\mathscr{L} = \frac{\alpha}{\eta(E_0)} \sum_{t=1}^{+\infty} \left(\frac{\gamma e^{\mu_0}}{R}\right)^t \eta(E_t) - \lambda(\sum_{t=1}^{+\infty} E_t - \bar{E}_1) + \sum_{t=1}^{+\infty} \psi_t E_t$$

The FOC with respect to E_t is:

$$\begin{aligned}
\frac{\delta \mathscr{L}}{\delta E_t} &= \frac{\alpha}{\eta(E_0)} \left(\frac{\gamma e^{\mu_0}}{R}\right)^t \eta'(E_t) - \lambda + \psi_t = 0, \forall t > 0 \\
\Rightarrow \eta'(E_t) &= \frac{(\lambda - \psi_t)\eta(E_0)}{\alpha} \left(\frac{R}{\gamma e^{\mu_0}}\right)^t, \forall t > 0
\end{aligned}$$

For a higher period t, $\left(\frac{R}{\gamma e^{\mu_0}}\right)^t$ is higher, given that $\gamma e^{\mu_0} < R$. Therefore $\eta'(E_t)$ increases with time and, when $\beta < 1$ as in our standard scenario, E_t decreases:

$$\eta(E_t) = [c\bar{E}_1 + E_t]^\beta \implies \eta'(E_t) = \beta(c\bar{E}_1 + E_t)^{\beta-1}$$

Therefore:

$$\begin{aligned}
\beta(c\bar{E}_1 + E_t)^{\beta-1} &= \frac{(\lambda - \psi_t)\eta(E_0)}{\alpha} \left(\frac{R}{\gamma e^{\mu_0}}\right)^t \\
\implies E_t &= \left[\frac{\alpha\beta}{(\lambda - \psi_t)[c\bar{E}_1 + E_0]^\beta} \left(\frac{\gamma e^{\mu_0}}{R}\right)^t\right]^{1/(1-\beta)} - c\bar{E}_1 \qquad (35)
\end{aligned}$$

When $\beta < 1$ (in line with the OECD estimation results for ε_{YE}), since the condition $\gamma e^{\mu_0} < R$ holds, E_t decreases over time, as mentioned above. This guarantees a smooth transition path.[40][41]

B.2 Maximizing "welfare" under the carbon budget

The welfare maximization writes as

$$\max_{\{E_t\}} \sum_{t=0}^{+\infty} \frac{\mathbb{E}_0[Y_t]}{R^t} = \frac{Y_0}{\eta(E_0)} \sum_{t=0}^{+\infty} \left(\frac{\bar{g}}{R}\right)^t \eta(E_t) \qquad (36)$$

$$\text{s.t.} \sum_{t=1}^{+\infty} E_t \leq \bar{E}_1 \qquad (37)$$

$$E_t \geq 0 \qquad (38)$$

---

[40] If, instead $\beta > 1$, E_t has to increase over time under the maximization of current debt sustainability. This goes against the usual and reasonable planning of a green transition.

[41] The calculations to find a pseudo-analytical solution are available upon request to the author.

by defining $\bar{g} = e^{\mu_0 + 1/2\sigma_0^2}$, as the expected fundamental growth rate. The associated Lagrangian is:

$$\mathscr{L} = \frac{Y_0}{\eta(E_0)} \sum_{t=0}^{+\infty} \left(\frac{\bar{g}}{R}\right)^t \eta(E_t) - \varphi(\sum_{t=1}^{+\infty} E_t - \bar{E}_1) + \sum_{t=1}^{+\infty} \theta_t E_t$$

The FOC with respect to E_t is:

$$\begin{aligned}
\frac{\delta \mathscr{L}}{\delta E_t} &= \frac{Y_0}{\eta(E_0)} \left(\frac{\bar{g}}{R}\right)^t \eta'(E_t) - \varphi + \theta_t = 0, \forall t > 0 \\
\Rightarrow \eta'(E_t) &= \frac{(\varphi - \theta_t)\eta(E_0)}{Y_0} \left(\frac{R}{\bar{g}}\right)^t, \forall t > 0 \\
E_t &= \left[\frac{\beta Y_0}{(\varphi - \theta_t)(c\bar{E}_1 + E_0)^\beta} \left(\frac{\bar{g}}{R}\right)^t\right]^{1/(1-\beta)} - c\bar{E}_1 \qquad (39)
\end{aligned}$$

Let recall that, as demonstrated by Collard, Habib, and Rochet (2015), the total borrowing factor is lower than the average growth rate: $\gamma e^{\mu_0} < \bar{g}$. Therefore, we can expect emissions maximizing welfare to decrease slower than the emissions maximizing the current MSB, from an initial level:

$$E_1 = \left[\frac{\beta Y_0}{\varphi(c\bar{E}_1 + E_0)^\beta} \left(\frac{\bar{g}}{R}\right)\right]^{1/(1-\beta)} - c\bar{E}_0$$

by setting $\theta_1 = 0$ in the case initial emissions $E_1 > 0$.[42]

C Robustness analysis for the shares of CO2 and CH4 over total emissions, and the β.

The β coefficient is calibrated by taking the elasticities of output with respect to CO2 and CH4 estimated in Cárdenas Rodríguez et al. (2018). In the main results, the β is defined as a weighted average of these elasticities, where the weights are the average relevance of the type of emission over the national total emissions in the period 1990-2013 (the first and fourth columns in Table A1).[43] The table also shows the share of CO2 and CH4 over the national total emissions in 2013 and 2020, and the consequent βs alongside the main calibration used in the paper (seventh column). Except for some few countries, such as Luxembourg, New Zealand and Turkey, these percentages have been generally stable over time. For Netherlands, for which data are missing we take the average across countries to calibrate β.

---

[42] The calculations to find a pseudo-analytical solution of this second optimization problem are available upon request to the author.

[43] Data source: ourworldindata.com

Country	CO2 av$_{90-13}$	CO2$_{13}$	CO2$_{20}$	CH4 av$_{90-13}$	CH4$_{13}$	CH4$_{20}$	β	β_{13}	β_{20}
Australia	0.5987	0.696	0.6689	0.2518	0.2113	0.2119	0.0666	0.0763	0.0734
Austria	0.6814	0.7977	0.7993	0.2585	0.1532	0.1477	0.022	0.013	0.0126
Belgium	0.7957	0.7785	0.7766	0.1664	0.1512	0.1543	0.0738	0.0712	0.0714
Canada	0.8355	0.8033	0.8136	0.1238	0.1463	0.1276	0.0355	0.0339	0.0345
Czech Republic	0.6906	0.8183	0.8119	0.2727	0.1266	0.1284	0.1649	0.1547	0.154
Denmark	0.7012	0.7475	0.6712	0.2148	0.1673	0.2115	0.0402	0.0381	0.0389
Estonia	0.7654	0.7888	0.6709	0.1662	0.1567	0.2346	0.0767	0.0787	0.0694
Finland	0.7129	0.6533	0.6499	0.2146	0.2778	0.2662	0.033	0.0336	0.033
France	0.5869	0.7348	0.6975	0.3519	0.1793	0.2046	0.0643	0.0607	0.0602
Germany	0.7722	0.8755	0.8625	0.1876	0.0828	0.091	0.0925	0.0916	0.0912
Greece	0.6181	0.7949	0.7188	0.3046	0.1537	0.212	0.079	0.0959	0.0885
Hungary	0.5969	0.6895	0.7193	0.339	0.1837	0.1487	0.116	0.1163	0.1177
Iceland	0.6837	0.7975	0.7823	0.1871	0.1279	0.1382	0.0316	0.0292	0.0297
Ireland	0.2489	0.5019	0.4661	0.6581	0.3439	0.3728	0.0635	0.0532	0.0535
Italy	0.6211	0.8314	0.8141	0.311	0.1275	0.14	0.101	0.0904	0.0909
Japan	0.7832	0.9591	0.9545	0.1671	0.0254	0.0281	0.0804	0.066	0.0662
Latvia	0.645	0.6374	0.682	0.2708	0.2203	0.1851	0.0863	0.0867	0.0942
Lithuania	0.6629	0.6322	0.6112	0.2405	0.1734	0.1649	0.1314	0.1142	0.1098
Luxembourg	0.4286	0.9153	0.9007	0.4321	0.0549	0.0656	0.133	0.0281	0.0311
Netherlands							0.0768	0.0707	0.0707
New Zealand	0.5691	0.1679	0.2747	0.3062	0.6125	0.5229	0.034	0.068	0.058
Norway	0.6711	0.6221	0.6018	0.24	0.3249	0.3462	0.0274	0.0306	0.0312
Poland	0.6383	0.7348	0.7458	0.3107	0.1978	0.1825	0.0147	0.0169	0.0172
Portugal	0.5221	0.7616	0.7307	0.4049	0.1832	0.21	0.0553	0.0534	0.0535
Slovak Republic	0.7578	0.7818	0.751	0.2013	0.1482	0.1762	0.1019	0.0985	0.0984
Slovenia	0.6298	0.7948	0.7717	0.3189	0.1692	0.1828	0.1085	0.111	0.1098
Spain	0.6414	0.7801	0.7393	0.2793	0.1532	0.1822	0.0715	0.0581	0.0608
Sweden	0.7737	0.7199	0.7314	0.1605	0.1734	0.1789	0.0661	0.0627	0.0638
Switzerland	0.6796	0.8374	0.8067	0.259	0.1168	0.1397	0.0888	0.0799	0.0809
Turkey	0.4585	0.7132	0.7172	0.4248	0.1884	0.1849	0.1096	0.1705	0.1714
United Kingdom	0.765	0.8531	0.8072	0.2007	0.096	0.1229	0.0733	0.0765	0.0736
United States	0.8437	0.8461	0.835	0.1185	0.1109	0.1215	0.0558	0.0558	0.0553

Table A1: Share of CO2 and CH4 over total national emissions.

D Additional results

Country	Green b_M			Max b_0^M st cb			Green d_M			d_0^{M*} st cb			D/Y
	(1)	(2)-*chr*	(3)	(1)	(2)	(3)	(1)	(2)-*chr*	(3)	(1)	(2)	(3)	
Australia	788.12	906.13	499.36	598.63	685.19	520.54	896.47	1031.30	568.35	680.93	779.85	592.45	57.80
Austria	142.12	122.82	112.87	137.23	118.87	113.69	162.83	140.75	129.35	157.22	136.22	130.29	83.20
Belgium	312.88	268.56	246.81	277.51	240.13	228.22	357.46	306.99	282.14	317.05	274.50	260.88	112.80
Canada	464.49	436.02	387.14	416.43	391.53	366.77	532.28	500.19	444.12	477.20	449.15	420.75	117.80
Czech Republic	105.62	67.03	60.80	80.49	53.96	51.12	122.04	77.80	70.56	93.01	62.62	59.32	37.70
Denmark	343.90	321.94	305.62	326.14	305.91	296.70	395.43	370.42	351.65	375.01	351.98	341.39	42.10
Estonia	96.49	85.78	74.38	87.42	78.25	72.32	116.28	103.97	90.16	105.36	94.84	87.66	19.00
Finland	209.65	195.63	186.41	202.21	189.01	183.96	245.50	229.20	218.40	236.79	221.45	215.53	69.00
France	155.79	132.38	123.55	140.75	120.51	115.60	177.91	151.26	141.17	160.73	137.69	132.08	115.20
Germany	150.52	118.03	112.27	132.01	105.26	102.25	173.22	135.84	129.21	151.92	121.14	117.68	68.70
Greece	74.60	68.48	66.94	69.51	64.14	63.36	87.47	80.71	78.89	81.50	75.59	74.68	211.90
Hungary	251.81	194.65	184.00	215.23	170.13	164.85	290.92	225.66	213.32	248.67	197.24	191.11	80.00
Ireland	343.16	312.12	246.77	307.96	281.28	247.90	404.25	368.51	291.36	362.78	332.11	292.69	58.40
Italy	181.85	153.35	149.95	160.27	136.92	135.18	208.18	176.05	172.14	183.48	157.18	155.19	155.30
Japan	158.54	132.72	128.91	139.54	118.07	116.09	181.92	152.56	148.18	160.11	135.72	133.45	259.00
Latvia	47.49	43.08	37.30	42.60	38.88	35.91	57.60	52.33	45.31	51.66	47.24	43.62	43.30
Lithuania	64.34	47.60	40.52	52.84	40.25	36.82	76.66	57.30	48.78	62.95	48.45	44.33	46.60
Luxembourg	238.31	189.23	158.42	190.61	154.69	139.57	277.52	220.78	184.83	221.97	180.48	162.84	24.80
Netherlands	221.35	188.70	173.96	197.02	169.46	161.49	254.62	217.01	200.05	226.62	194.88	185.71	52.80
New Zealand	312.92	319.08	280.35	287.89	293.41	273.93	360.12	367.39	322.79	331.31	337.83	315.40	43.10
Norway	1290.37	1050.44	910.25	1234.88	1009.14	947.84	1475.18	1202.54	1042.05	1411.74	1155.26	1085.08	46.80
Poland	193.97	188.81	152.94	189.04	184.06	173.13	225.23	219.19	177.54	219.51	213.67	200.98	57.40
Portugal	104.74	94.15	89.29	97.31	87.85	85.16	120.33	108.47	102.87	111.80	101.22	98.12	135.20
Slovak Republic	15.77	12.56	9.85	13.00	10.52	9.14	18.37	14.66	11.50	15.15	12.28	10.67	59.70
Slovenia	78.94	67.95	62.39	68.32	59.52	56.72	91.80	79.36	72.87	79.45	69.52	66.25	79.80
Spain	132.82	126.41	116.79	120.23	114.73	109.51	152.77	145.75	134.66	138.30	132.28	126.26	120.00
Sweden	226.70	200.15	186.13	207.06	183.92	176.29	262.10	231.60	215.38	239.39	212.83	204.00	39.60
Switzerland	127.76	116.64	109.36	116.41	106.91	102.88	146.22	133.48	125.14	133.24	122.35	117.73	42.40
Turkey	184.91	215.05	185.59	159.01	182.66	168.09	217.35	255.52	220.51	186.90	217.03	199.72	39.50
United Kingdom	301.47	246.01	224.31	271.39	223.85	211.87	345.71	282.47	257.56	311.22	257.03	243.27	102.60
United States	212.25	191.23	166.66	178.57	161.54	149.12	242.97	219.13	190.97	204.42	185.10	170.88	134.20

Table A2: Debt sustainability in advanced countries in the transition. $r = 2.44\%$. b_M and d_M: respectively, the maximum sustainable borrowing and the debt limit in the green economy. Max b_0^M st cb and d_0^{M*} st cb: respectively, the maximum current "maximum sustainable borrowing" consistent with the carbon budget and the corresponding debt limit. In red, countries that have general debt sustainability problems (D/Y$>$ d_M); in brown, countries for which this issue appears only in the context of performing the transition (D/Y$>$ d_0^{M*} st cb).

As shown in Table A3, with an higher interest rate of 3%, additional countries' debt levels, in particular of France, Latvia, Lithuania and Spain, become unsustainable when taking into account transition costs.

Country	Green b_M			Max b_0^M st cb			Green d_M			d_0^{M*} st cb			D/Y
	(1)	(2)-*chr*	(3)	(1)	(2)	(3)	(1)	(2)-*chr*	(3)	(1)	(2)	(3)	
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

Table A3: Debt sustainability in advanced countries: in the green economy, and under the carbon budget at the beginning of the transition. $r = 3\%$. b_M and d_M: respectively, the maximum sustainable borrowing and the debt limit in the green economy. Max b_0^M st cb and d_0^{M*} st cb: respectively, the maximum current "maximum sustainable borrowing" consistent with the carbon budget and the corresponding debt limit. In red, countries that have general debt sustainability problems (D/Y$>d_M$); in brown, countries for which this issue appears only in the context of performing the transition (D/Y$>d_0^{M*}$ st cb).

Country	Green b_M			Max b_0^M st cb			Green d_M			d_0^{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

Table A4: Debt sustainability in advanced countries: in the green economy, and under the carbon budget at the beginning of the transition. $r = 1.88\%$. b_M and d_M: respectively, the maximum sustainable borrowing and the debt limit in the green economy. Max b_0^M st cb and d_0^{M*} st cb: respectively, the maximum current "maximum sustainable borrowing" consistent with the carbon budget and the corresponding debt limit. In red, countries that have general debt sustainability problems (D/Y$>d_M$); in brown, countries for which this issue appears only in the context of performing the transition (D/Y$>d_0^{M*}$ st cb).

D.1 Sensitivity analysis for the CCS parameter c

Figure A1 shows some sensitivity analysis for the parameter c in the growth rate function, which represents the percentage of emissions that could be recapture in each 5-year period in the green economy, after the end of the transition. The higher value $c = 0.01$ is the one adopted in the rest of the paper. Lower values of c imply: an almost identical but slightly slower transition path, lower detrended GDP levels, a slower convergence to the stationary MSD, and a generally unchanged probability of default.

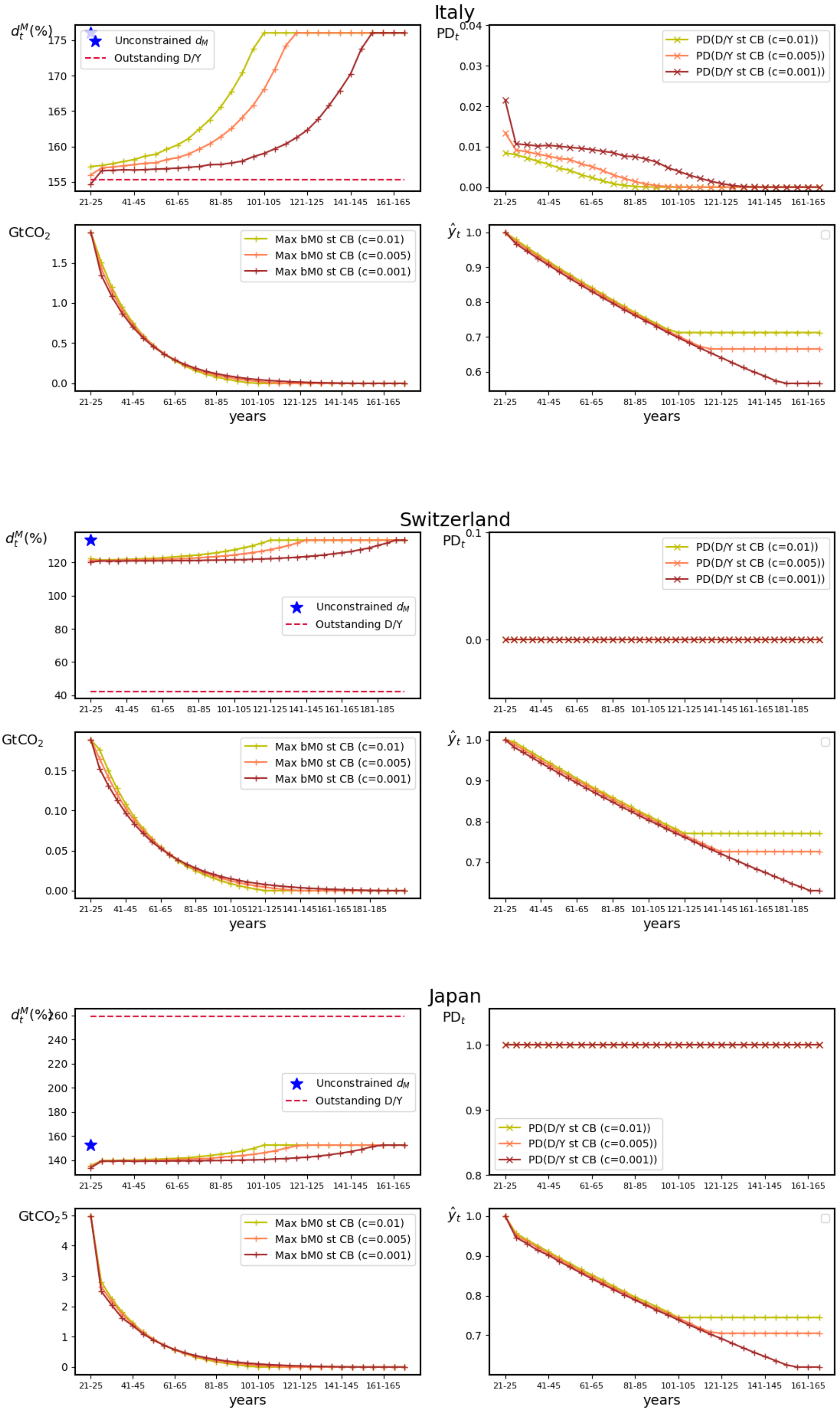

Figure A1: Sensitivity analysis for the CCS parameter c. $r = 2.44\%$. Plots for the fiscal limit d_t^M, the annual probability of default PD_t (1.0 is 100%) of 2020 debt-to-GDP ratios (outstanding D/Y, assumed to remain constant), the emissions path expressed in GtCO$_2$ maximizing the current maximum sustainable borrowing b_0^M under the carbon budget, and the normalized detrended GDP $\hat{y}_t$.

D.2 Trade-off shift in debt sustainability with climate damages

Table A5 reports, for each country, the period when the national fiscal limit under a successful global transition overcomes the national fiscal limit under a business-as-usual scenario with global emissions growing at 1.126%.

	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

Table A5: Period when the national fiscal limit under a successful global transition overcomes the national fiscal limit under a business-as-usual scenario with global emissions growing at 1.126%. $r = 2.44\%$, PL.

D.3 The case of France

Table A6 shows that France has a generally larger fiscal space than Italy (Table 7). Nonetheless the policy implication we derive is the same. The solitary and BAU scenarios, despite being still sustainable in 2101-105 (differently from Italy), show a fiscal limit very close to the reference French debt-to-GDP of 115.2%. As shown in Figure 4, the fiscal limits are projected to fall even further and below this threshold, due to climate damages. Thus, the only viable option for achieving French fiscal sustainability is an efficient and globally coordinated transition, as for Italy and all the countries analysed in this paper.

	2021-25					2101-105		
TRANSITION	COORDINATED			SOLITARY	BAU	COORDINATED	SOLITARY	BAU
green growth	optimistic	parallel	pessimistic	parallel		parallel		
$\beta = 0.064$	160.73	**137.16–137.69**	132.08	**130.63**	**142.76**	**145.51–145.88**	***116.43***	***119.97***
$\beta = 0.3$		100.28				140.47		

Table A6: The French fiscal limit amidst the transition. $r = 2.44\%$. Written in red the scenarios where debt-to-GDP is higher than the fiscal limit ($d_t = 115.2\% > d_t^M$). Colored cells highlight the benchmark scenario ($\beta = 0.064$, PL) for different degrees of political coordination in the transition (coordinated/solitary/BAU). In the green cells, the first value accounts for climate damages in the 2°C scenario, while the second ignores them. Notice that in the coordinated scenario, the stationary fiscal limit of 151.26% is achieved after 2105.