International Economics 155 (2018) 92–108

Contents lists available at ScienceDirect

International Economics

journal homepage: www.elsevier.com/locate/inteco

Debt and damages: What are the chances of staying under the 2°C warming threshold?

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ARTICLE INFO

JEL classification numbers:
C51
D72
E12
O13
Q51
Q54

Keywords:
Ecological macroeconomics
Stock-flow consistency
Climate change
Integrated assessment
Debt

ABSTRACT

In a stock-flow consistent macrodynamic model featuring two crucial endogenous destabilizing channels, debt accumulation and climate change, we perform a sensitivity analysis on four fundamental parameters of the climate and economic systems: (i) the climate sensitivity, (ii) the inertia of the carbon cycle, (iii) the labor productivity growth, and (iv) the share of damages sustained by the capital stock. Our main findings are that there is a mere 0.5% chance of achieving the 2 °C global warming target of the Paris Agreement in a no policy scenario, while a carbon tax, and a carbon tax *plus* a subsidy to mitigation efforts, increase that probability to approximately 6.5% and 25.6% respectively. We also investigate the trade-off between mitigating climate change damages and staying in a sustainable debt trajectory. While implementing effective climate policies comes at the cost of increasing the debt burden, shifting some of the debt burden to the public sector significantly reduces the chance of overstepping a threshold of unsustainable debt.

1. Introduction

Since the recognition at the global level that the "burden-sharing" approach is an ethical and political dead-end for financing the transition to a sustainable development, the attention has shifted to non-binding solutions that also embark the private sector. According to the New Climate Economy Report (New Climate Economy, 2014), US$ 90 trillion are needed at the world level over the next 15 years to fund clean infrastructures that would make it possible both to reach zero net emissions and to meet the ambitious targets of the Paris Agreement of December 2015. Even if not entirely additional —many infrastructures will have to be maintained and replaced in any case— such a level of commitment can only be met by joining public and private efforts, and is likely to generate massive amounts of debt, especiallyif the energy shift is to be performed soon. Fighting climate change is a race against time: there is consequently a trade-off to consider between financial and climatic stability. As aptly put by Bank of England Governor Mark Carney:

> A wholesale re-assessment of prospects, as climate-related risks are reevaluated, could destabilize markets, spark a pro-cyclical crystallization of losses and lead to a persistent tightening of financial conditions: a climate Minsky moment (Carney, 2016).

The economic literature is curiously scarce when it comes to modeling the interplay between the financial sphere, the real

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https://doi.org/10.1016/j.inteco.2018.02.002
Received 19 October 2017; Received in revised form 14 February 2018; Accepted 15 February 2018

economy and the physical environment, which accounts for a strong perceived need for informative prospective studies.

The economic literature addresses this challenge in several complementary strands. The problem of the interacting climate and economy has long been covered by the integrated assessment modeling (IAM) literature, prominently featured in the successive IPCC reports (Stern, 2006; Stocker et al., 2013). In light of the struggles to turn the insights of these models into actions, recent contributions by top climate economists call for letting current models evolve (Revesz et al., 2014; Stern, 2016), and promising new avenues are being pursued with dynamic stochastic general equilibrium models and agent based models (Farmer et al., 2015). Another strand of the literature, ecological macroeconomics, emerges as a serious challenger to current IAM models. Rezai et al. (2013) presents how this growing body of literature may reconcile state-of-the-art macroeconomics with tenets of ecological economics on resource use and limits to growth (see also Jackson (2009) and Rezai and Stagl (2016)). Overall, these different strands of literature (also reviewed in New Climate Economy (2014)) aim at assessing the financing needs for a transition to a low-carbon economy. Besides several contributions in this special issue, however, few papers examine the financial costs of such transitions, or the systemic effects they entail (see e.g. Dafermos et al. (2017); Monasterolo and Raberto (2018) or Battiston et al. (2017)). This article, which is part of a broader research program (Bovari et al., 2018; Giraud and Grasselli, 2017), is a contribution to this general effort of properly characterizing the determinants of and the interactions between economic transitions, climate change, and finance.

Another major problem arising in the IAM literature, highlighted by Nordhaus (2017) for instance, is how to tackle the high dimensionality of the interactions between the economy and the warming environment. Large uncertainties remain on key technical, physical and economic parameters, that prove to be powerful impediments to action (Fabert et al., 2014). In this paper, we reduce as much as possible the dimensionality of the problem by combining a compact macrodynamic framework with endogenous debt (Bovari et al., 2018) to a rather small climate module extensively used in the IAM literature.

By using a model in which over-indebtedness and damages from climate change can lead to economic downturns, our contribution is to assess the extent to which simple policy levers can influence the climate and growth trajectories in a sensitivity and scenario analysis on key physical and economic parameters. We test how different climate policies advocated by the Stern-Stiglitz Commission[1] allow to avoid overshooting two thresholds that we argue to be critical for the stability of our current climate and economy, namely a temperature anomaly above +2°C (as set in the Paris Agreement) and a global debt-to-output ratio above 2.7 (at which point the total private debt would exceed the value of the current stock of assets, arguably leading to systemic defaults). Both are associated to major potential destabilizing channels: damages to the capital stock from climate change and the ability of firms to invest in repairs and adaptation.

We find that we have a mere 0.5% chance of achieving the 2°C warming target of the Paris Agreement in a no-policy (business-as-usual) scenario. Introducing climate policies as recommended by the Stern-Stiglitz Commission allows to significantly increase this probability: adding a growing carbon price trajectory increases to approximately 6.5% the chances of staying under 2°C warming, and raising the mitigation efforts with an additional 50% subsidy to investment in the backstop technology increases this probability to approximately 25.6%. We also discuss the trade-off between the two principal objectives of a sustainable debt and a sustainable climate. Effective climate policies come indeed at the cost of increasing the probability of overshooting the debt-to-output threshold from 43.2% (business-as-usual scenario) to 77.5% (with a carbon tax) approximately. Mutualizing some of the risk in the form of an additional subsidy to mitigation efforts decreases this probability to approximately 39.4%, even though it temporarily raises public net spendings.[2]

The paper is organized as follows. Section 2 briefly introduces the modeling framework that is at the basis of our analysis. Section 3 discusses more extensively the introduction of climate and economic uncertainty within this framework in order to assess the recommendations of the Stern-Stiglitz commission on carbon price. Section 4 presents our results, and our main conclusions and areas for future research are outlined in a last section.

2. Model

This paper relies on the modeling framework developed in Bovari et al. (2018), a macroeconomic model of growth that combines the economic impact of climate change with the pivotal role of private debt. The model is briefly exposed in this section. We introduce an additional public policy tool: a subsidizing mechanism on the abatement cost that is performed by the public authorities to enhance the speed of the energy shift.

2.1. *Macroeconomic model*

The macroeconomic model, sketched in this section, belongs to the literature centered around Keen (1995).[3] One appeal of this framework lies in its ability to formalize long-term economic deflation and recession as a consequence of over-indebtedness.

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[1] “The Commission’s objective is to identify indicative corridors of carbon prices which can be used to guide the design of carbon pricing instruments and other climate policies, regulations, and measures to incentivize bold climate action and stimulate learning and innovation to deliver on the ambition of the Paris Agreement and support the achievement of the Sustainable Development Goals.” — Commission website.

[2] These figures correspond to Monte Carlo simulations assuming that a third of climate damages are sustained by the capital stock. Assuming other allocations of damages does not qualitatively affect these results, as illustrated hereafter.

[3] Such as Grasselli and Lima (2012),Grasselli et al. (2014), Nguyen-Huu and Costa-Lima (2014), Grasselli and Nguyen-Huu (2015) and Giraud and Grasselli (2017) *inter alia*.

Absent climate change, real output is assumed to be produced combining the available workforce, N, and the current physical capital stock, K, with a complementary factor technology

$$Y^0 \coloneqq \min\left\{\frac{K}{\nu}, aN\right\}, \tag{1}$$

where ν and a respectively refer to the (constant) capital-to-output ratio and to the Harrod-neutral labor augmenting productivity.

The dynamics of the global workforce is exogenous and calibrated to the prospective scenarios of the United Nations (2015), medium fertility, so that:

$$\beta(N) \coloneqq \frac{\dot{N}}{N} = q\left(1 - \frac{N}{P^N}\right), \tag{2}$$

where q represents the speed of the demographic transition and P^N the upper bound of the global workforce. The productive sector is assumed to follow a minimal rational behavior,

$$Y^0 = \frac{K}{\nu} = aL, \tag{3}$$

where L is the total employed labor. Thus, it defines the employment rate, $\lambda \coloneqq L/N$. Labour productivity is assumed to grow exogenously at a constant rate, $\widetilde{a}/a \coloneqq \alpha$. The production of commodities releases industrial emissions, E_{ind}, according to

$$E_{ind} \coloneqq Y^0\sigma\left(1 - n\right), \tag{4}$$

where, σ, stands for the exogenous emission intensity and, n, is the endogenous emission reduction rate of the productive sector. Indeed, a carbon tax, T_C, will be set on industrial emissions by the public authorities according to $T_C \coloneqq p_C E_{ind}$, with p_C the real price of emissions.[4] To minimize the carbon burden, the productive sector might divert a fraction of its real production, A, to perform abatement activities. The public sector might partly subsidize this abatement cost at a rate s_A, such that a real transfer $S_f^c \coloneqq s_a A Y^0$ is performed to the productive sector. Moreover, due to global warming —ultimately related to the accumulation of industrial emissions— a fraction, $\mathbf{D}^Y$, of real output is lost. As a result, the production available on the commodity market will be

$$Y \coloneqq (1 - \mathbf{D}^Y)(1 - A)Y^0. \tag{5}$$

The abatement technology, A, depends on the emission reduction rate chosen by the productive sector, n, the price of a back-stop technology, p_{BS}, —exogenously decreasing at some rate, $\delta_{p_{BS}}$—, and the emission intensity of the economy, σ, according to

$$A \coloneqq \frac{\sigma p_{BS}}{\theta} n^{\theta}, \tag{6}$$

where θ is a parameter controlling the convexity of this cost.

By setting the abatement reduction rate, n, the productive sector endogenously chooses the magnitude of the latter activities. The emission reduction rate, n, appears then to be the outcome of an arbitrage between the carbon price, p_C, the backstop technology price, p_{BS}, and the subsidizing rate by the public authorities, s_a[5]

$$n = \min\left\{\left(\frac{p_c}{(1 - s_a)p_{BS}}\right)^{\frac{1}{\theta-1}}; 1\right\}. \tag{7}$$

Introducing the unit nominal wage, w, the price of commodities, p, and the depreciation rate of capital, $\delta_{\mathbf{D}}$, nominal profits of the productive sector write

$$\Pi \coloneqq pY - wL - rD + pNS_f - p\delta_{\mathbf{D}}K, \tag{8}$$

where $NS_f \coloneqq S_f^c - T_C$ is the net transfer to the private sector, and D is the nominal debt of private non financial sector. The profit, Π, is partly distributed to shareholders according to

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[4] p_C refers to the real price per ton of CO_2-e.

[5] For the sake of clarity, the emission reduction rate, n, can be seen as the solution of a cost-minimization program between the abatement cost, AY, and the carbon tax, $p_C E_{ind}$.

$$\Pi_d(\pi) := \Delta(\pi)pY, \tag{9}$$

such that, $\Pi_r := \Pi - \Pi_d$, represents retained profits of the productive sector. Nominal profits, Π, allow us to define the profit share, $\pi := \frac{\Pi}{pY}$, that captures the current profitability of the productive sector and thus drives investments according to

$$I := \kappa(\pi)Y. \tag{10}$$

Next, the stock of capital obeys the standard rule of accumulation

$$\dot{K} := I - \delta_{\mathbf{D}}K. \tag{11}$$

The nominal credit, $\dot{D}$, bridges the gap between the self-financing capabilities of the productive sector, i.e., retained profits Π_r, and the nominal level of net investment, $pI - p\delta_{\mathbf{D}}K$, according to

$$\dot{D} := pI + \Pi_d(\pi) - \Pi - p\delta_{\mathbf{D}}K. \tag{12}$$

Finally, the relationship between the real and nominal spheres is provided by a short-term Phillips curve set on nominal wages

$$\frac{\dot{w}}{w} := \phi(\lambda). \tag{13}$$

and a relation capturing the dynamics of inflation

$$i := \frac{\dot{p}}{p} := \eta_p(mc - 1), \tag{14}$$

According to Eq. (14), prices are set as a mark-up m over the labor cost of production, $c := \frac{wL}{pY}$,[6] and relax subjected to some viscosity parameter η_p.

Finally, Appendix A displays the model's accounting structure (balance sheet, transaction flows, and flow of funds), allowing to readily check its stock-flow consistency.

2.2. Climate module feedback-loop

The climate module is directly inspired by the DICE model of Nordhaus (2017), adapted here to our continuous framework. It describes the sequence of geo-physical processes linking the various sources of emissions to the mean atmospheric temperature anomaly. More precisions about these equations can be found on Bovari et al. (2018). Total emissions E are expressed in CO_2-e units and result from two sources: (i) industrial emissions E_{ind} defined in Eq. (4) and (ii) land-use emissions E_{land} —following an exogenous dynamics, $\dot{E}_{land} := \delta_{E_{land}}E_{land}$, with $\delta_{E_{land}} < 0$ a parameter—, such that $E := E_{ind} + E_{land}$. The emission intensity σ also obeys an exogenous dynamics given by $\dot{\sigma} := g_\sigma\sigma$ and $\dot{g_\sigma} := \delta_{g_\sigma}$, with $\delta_{g_\sigma}g_\sigma < 0$ a parameter.

The carbon cycle is described through a three-layer model featuring the interactions between the atmosphere layer, denoted by AT, where emissions are released, and the biosphere-upper ocean layer denoted by UP, as well as the lower ocean layer, denoted by LO, both acting as carbon sinks. Thus, the concentration in CO_2-e ${CO_2}^i, i \in \{AT, UP, LO\}$ evolves according to the system

$$\begin{pmatrix} \dot{CO_2}^{AT} \\ \dot{CO_2}^{UP} \\ \dot{CO_2}^{LO} \end{pmatrix} := \begin{pmatrix} E \\ 0 \\ 0 \end{pmatrix} + \Phi \begin{pmatrix} CO_2^{AT} \\ CO_2^{UP} \\ CO_2^{LO} \end{pmatrix} \tag{15}$$

with

$$\Phi := \begin{pmatrix} -\phi_{12} & \phi_{12}\frac{C^{AT}}{C^{UP}} & 0 \\ \phi_{12} & -\phi_{12}\frac{C^{AT}}{C^{UP}} - \phi_{23} & \phi_{23}\frac{C^{UP}}{C^{LO}} \\ 0 & \phi_{23} & -\phi_{23}\frac{C^{UP}}{C^{LO}} \end{pmatrix},$$

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[6] This price dynamics, suggested by an anonymous referee, slightly departs from Bovari et al. (2018) as the cost of capital is not included in the dynamics. This new specification of price dynamics is in line the literature centered around Keen (1995) and also prevents situations in which the gross operating surplus would increasing faster whenever debt-to-GDP ratio gets higher.

where C^i corresponds to the CO_2-e pre-industrial concentration in the corresponding layer, $i \in \{AT, UP, LO\}$, and ϕ_{ij} stands for the diffusions coefficients between layers, $i \in \{AT, UP, LO\}$ and $j \in \{AT, UP, LO\}$.

The resulting radiative forcing in the atmospheric layer is the sum of two terms: (i) the industrial forcing, $F_{ind} := \frac{F_{2\times CO_2}}{\log(2)} \log\left(\frac{CO_2^{AT}}{C^{AT}}\right)$ where $F_{2\times CO_2}$ is the radiative forcing resulting from a doubling of the pre-industrial atmospheric concentration in CO_2-e, and (ii) an exogenous radiative forcing, F_{exo}, which is linearly growing from its initial value to a plateau in 2100 as in Nordhaus (2017).

The dynamics of temperature describes the interplay between the atmosphere and upper ocean (resp. the lower ocean), with a mean temperature anomaly, T (resp. T_0), according to

$$C\dot{T} := F - \rho T - \gamma^*(T - T_0), \tag{16}$$

$$C_0\dot{T}_0 := \gamma^*(T - T_0), \tag{17}$$

where ρ is the radiative feedback parameter, and γ^* is the heat exchange coefficient between the two layers. C (resp. C_0), refers to the heat capacity of the atmosphere, land surface and upper ocean layer (resp. to the deep ocean layer). It is worth mentioning that, within this set-up, the equilibrium climate sensitivity (ECS) —that is the equilibrium temperature anomaly that would result from a doubling of the pre-industrial CO_2 concentration— is explicitly defined by $S := F_{2\times CO_2}/\rho$.

For a given level of temperature anomaly level, we follow Nordhaus (2017) and adopt a damage function, $\mathbf{D}(\cdot)$, summarizing the total economic impacts of global warming on the economy

$$\mathbf{D} := 1 - \frac{1}{1 + \pi_1 T + \pi_2 T^2 + \pi_3 T^{\zeta_3}}. \tag{18}$$

However, as pointed out by Dietz and Stern (2015) and Dafermos et al. (2017), global warming may have an adverse impact not only on output but also on production factors themselves, such as the capital stock. Following Dietz and Stern (2015), we consequently distribute total damages between output, $\mathbf{D}^Y$,

$$\mathbf{D}^Y := 1 - \frac{1 - \mathbf{D}}{1 - \mathbf{D}^K}, \tag{19}$$

and the stock of capital, $\mathbf{D}^K$,

$$\mathbf{D}^K := f_K \mathbf{D}, \tag{20}$$

where f_K represents the share of total damages, $\mathbf{D}$, allocated to the stock of capital.

It is worth mentioning that, throughout the simulations, we only use the damage function from Nordhaus (2014), which is illustrated in Fig. 1.

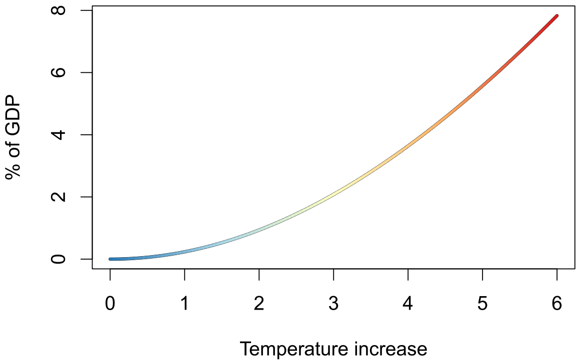

Fig. 1. Shape of the Nordhaus (2014)'s damage function.

This choice departs from Bovari et al. (2018) in testing only one damage function. The more severe specifications given by Weitzman (2011), or Dietz and Stern (2015) among others are left for further research.[7]

3. Sensitivity analysis and policy scenario setups

This section presents our simulation strategy. We first introduce how we take uncertainty into account and how we perform our sensitivity analysis, before presenting our policy scenarios.

3.1. Economic and climate uncertainties

We perform a sensitivity analysis on four uncertain parameters: (i) the labor productivity, α, (ii) the climate sensitivity, S, (iii) the size of the intermediate reservoir, i.e biosphere and upper level of the oceans, C^{UP}, and (iv) the repartition of climate change damages between capital stock and output, f_K. The latter one will be treated differently as discussed shortly.

The first three parameters have been extensively studied in the climate literature and in integrated assessment (climate-economy) models. Estimates for probability density functions (hereafter PDF) could thus be found. We approximate the PDFs from Nordhaus (2017) (see Fig. 2).[8]

It is worth mentioning that Nordhaus (2017) considers two additional parameters in his sensitivity analysis: (i) the initial value of the decarbonization rate of the economy; and (ii) the coefficient of the damage function that drives its convexity (i.e., the coefficient of order 2). The consensus on the uncertainty is weaker for the initial value of the decarbonization rate of the economy. This parameter seems, *prima facie*, to have an impact of lesser magnitude than the parameters (S, C^{UP}) on the climate module. Moreover, given our purpose in this paper —the assessment of the feasibility of the +2°C objective under specific carbon price trajectories— we focus on the certainty equivalent of Nordhaus's damage function since +2°C belongs to the range of temperature anomaly that has been empirically tested. Finally, the reduction of the dimensionality of the uncertainty allow us to perform a true Monte Carlo approach without approximations due to computational issues as chosen by Nordhaus (2017).

3.1.1. Productivity growth

As in Nordhaus (2017), over the period 2016–2100, the probability distribution adopted by the labor productivity growth is a Gaussian distribution with a mean (hereafter μ) of 2.06% and a standard deviation (hereafter σ) of 1.12%. In other words, $\alpha \sim \mathcal{N}(0.0206, 0.0112)$. Those estimates are based on a survey of experts by a team at Yale university led by Peter Christensen. This panel of experts characterized uncertainty on global output for the periods 2010–2050 and 2010–2100.

3.1.2. Equilibrium temperature sensitivity

There is an intrinsic uncertainty on the long term temperature anomaly whenever the CO_2 concentration in the atmosphere is doubled. We consider the same distribution as in Nordhaus (2017), that is a log-Gaussian distribution with $\mu = 1.107$ and $\sigma = 0.264$. In other words, $S \sim \log -\mathcal{N}(1.107, 0.264)$. Those estimates are borrowed from Gillingham et al. (2015). This distribution is result of a Bayesian procedure gathering previous studies as prior and observational data to compute the likelihood. Moreover, as validated by the climate-economy literature, this parameter captures in a synthetic way the complex interactions usually modeled in complete ocean-atmosphere models.

3.1.3. Carbon cycle

Many parameters of the carbon cycle are uncertain, although the most important one is certainly the size to the intermediate reservoir (biosphere and upper level of the oceans). Changes may have a substantial impact on the absorption property of the CO_2 into the carbon cycle. To take into account the uncertainty for this parameter, we find the parameters of a log-Gaussian distribution that are the closest to the quantile reported in Nordhaus (2017). In other words, $C^{UP} \sim \log -\mathcal{N}(5.8855763, 0.2512867)$. This uncertainty aims at mimicking the results from Friedlingstein et al. (2014) in the difference of concentration in 2100 using the RCP8.5 CO_2 emissions.

3.1.4. Allocation of damages to the capital stock

We consider the impact of a fourth parameter governing the share of damages sustained by the capital stock, f_K, as presented in Eq. (20). In our model, climate change may damage the output either directly, or indirectly by damaging the capital stock. A sensitivity analysis of this parameter is motivated by the potential contagion effect of this channel of damages into the financial environment of this paper's model. Given the radical nature of uncertainty on the specification of the damage functions in general and on damages to production factors in particular, we explore this crucial channel by testing a discrete array of values. Nordhaus and Boyer (2000) and Dietz and Stern (2015) give some point estimates of this parameter around 1/3. We consequently test three different values: $f_K = 0, 1/3, 1/2$. We take $f_K = 0$ as a reference point —e.g., no damages on capital, for compatibility with earlier work such as

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[7] However, the specification of Nordhaus (2014) is providing enough information for the purpose of the paper. Results given by other types of damage functions are very much likely to have similar consequences than the one found in Bovari et al. (2018).

[8] We assumed the distributions to be independent, as in Nordhaus's paper, since we virtually have no information on the dependence structure between the parameters.

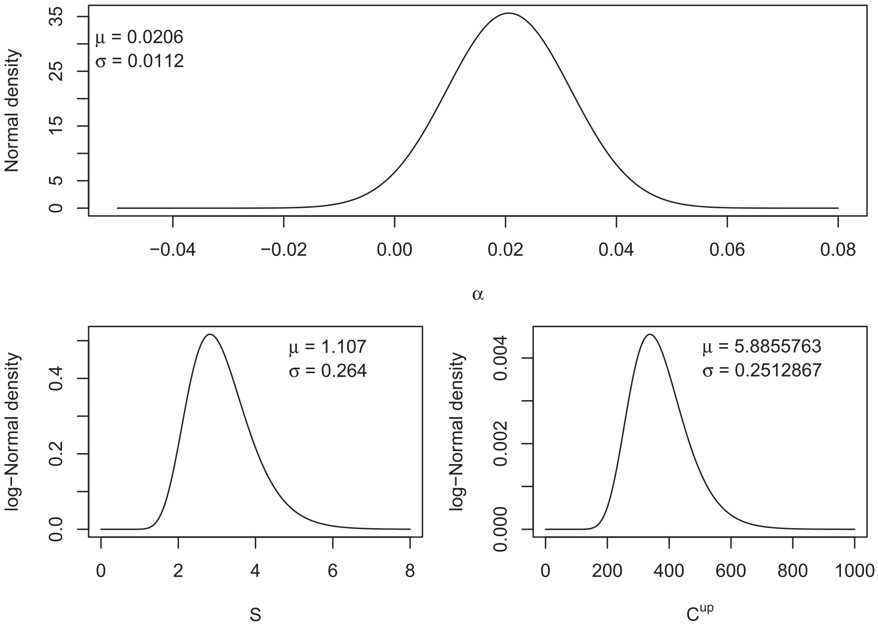

Fig. 2. Probability density functions for the vector of parameters (α, S, C^{UP}).

Nordhaus (2017). The central value implies that the capital stock sustains a third of the damages (in consumption-equivalent terms). We consider an additional value of 50% damages sustained by the capital stock as an extreme case study.

3.2. Public policy scenarios

Our paper proceeds by comparing two different public policy scenarios: a scenario with a carbon tax calibrated from the High-Level Commission on Carbon Prices (2017), and a combination of the same carbon tax *plus* a subsidy for the backstop technology. The two scenarios are discussed against a no-policy baseline where, as performed in Nordhaus (2017), the public intervention is limited to a weak carbon tax growing at a constant 2% rate per year (compatible with the calibration of the model at the initial period).

The main recommendation of the High-Level Commission on Carbon Prices (2017) is a corridor of carbon price levels consistent with achieving the Paris temperature target and the Sustainable Development Goals: from at least US\$40–80/tCO_2 by 2020 to US\$50–100/tCO_2 by 2030.[9]

For our simulation purposes, we will focus on the upper bound of the price corridor (hereafter High p_C). This choice allows us to explore the maximal potential of the carbon price recommendation made by the Stern-Stiglitz commission. Note, however, that our simulations run from 2016 to 2100 while the recommendation lies in the time range 2020–30. We assume some linear interpolations of the price of carbon for the out-of-recommendation time range.

Moreover, the Commission also concluded on the necessity to adopt context-relevant policy packages to overcome the various barriers and failures associated with carbon prices. Building on that recommendation, we consider another policy instrument, namely a subsidy on mitigation technologies. As presented in Eq. (7), the endogenous setting of the mitigation rate, n, by the productive sector as a result of a cost minimization will be speed up whenever the real cost of abatement activities, AY^0, is partly subsidized. In other words, the government intervention could be summarized as a proportional diminution of the real abatement cost (from p_{BS} to $(1 - s_a)p_{BS}$).

In summary, the three scenarios investigated in this paper are the following ones.

1. The *"No policy"* scenario is based on a Monte Carlo simulation of the model assuming a weak public intervention.[10]
2. The *"Carbon tax"* scenario is based on a Monte Carlo simulation of the model without further public intervention than the carbon price trajectory at High p_C.
3. The *"Carbon tax and subsidy"* scenario extends the *"Carbon tax"* scenario with public subsidies of 50% on abatement cost.

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[9] See Footenote 1. See also High-Level Commission on Carbon Prices (2017). No indication on the measure (real versus current) of the monetary unit is explicitly given. Some of the figures report in the report are in 2005US\$. We will therefore assume that the latter is the monetary unit.

[10] Again, for the sake of precision, this scenario is inspired by the Baseline case of Nordhaus (2017) with an exponential real carbon price path at a 2% annual growth rate.

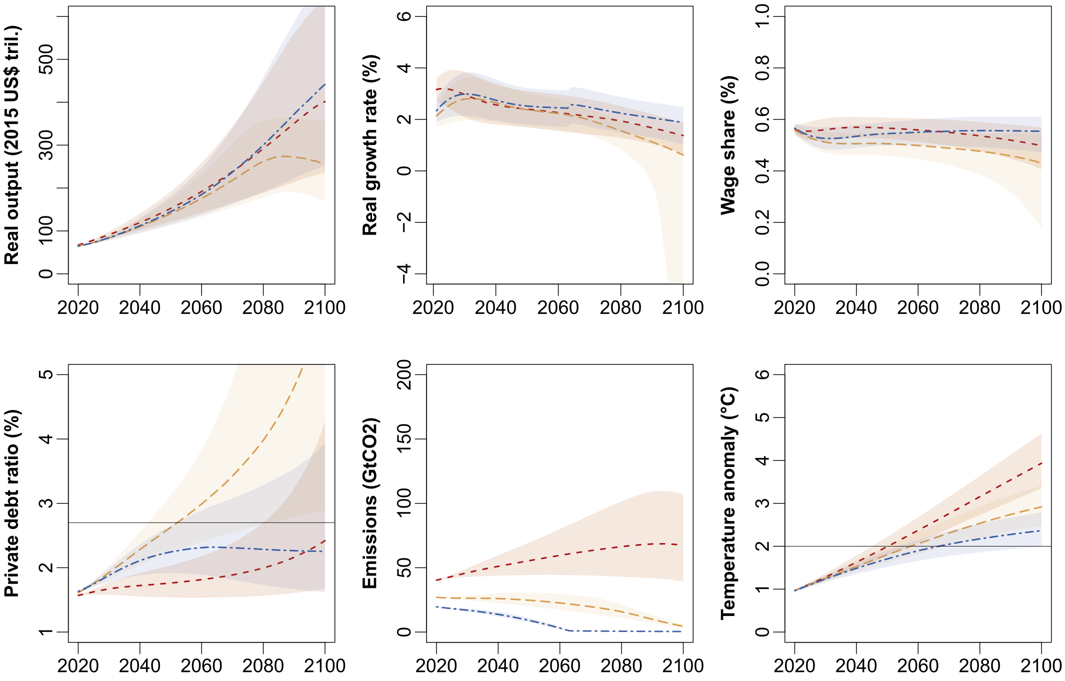

Fig. 3. [0.05; 0.95] probability interval of the *No policy*, *Carbon tax*, and *Carbon tax and subsidy* scenarios with a damage allocation to the stock of physical capital of $f_K = 33\%$ respectively in red, orange and blue shades (medians in small, long and mixed dashes). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

4. Results

In this section, we first discuss the trajectories of the main variables of the model in the various scenarios, before quantifying the probability of overshooting critical temperature and debt thresholds. A last subsection discusses the trade-off between these two thresholds.

4.1. Trajectories and narratives

Fig. 3 shows the outcome of the Monte Carlo simulations for all the scenarios with $f_K = 33\%$.[11] The red, orange, and blue shades represent the [0.25; 0.75] probability interval in the *No policy*, *Carbon tax*, and *Carbon tax and subsidy* scenarios, respectively. The median values of each Monte Carlo exercise are respectively represented by short, long and mixed dashed lines. The horizontal black lines one can see in the *debt-to-output ratio* and *temperature anomaly* quadrants represent the two thresholds discussed in the next subsection.

In the *No policy* scenario, real output grows close to the balanced growth path —the draw of α in the Monte Carlo procedure— following the exogenous labor productivity growth. The observed slowdown of real growth is mainly due to the demographic transition, growth gradually solely fueled by labor productivity. The mean yearly growth of the median GDP is 2.24% over the whole period and 2.73% for the period 2050–2100. Moreover, with a negligible carbon price the backstop technology barely takes any market share and growth is mostly fueled by fossil energy. In 2100, the median of the temperature anomaly is estimated to be 4° C, that is double the Paris Agreement's objective, and presents no sign of curbing downward. At the end of this century, a slowdown of output starts to be visible, concomitant to a rise of the private debt-to-output ratio and a fall of the wage share, and thus inflation according to Eq. (14). Even with the rather conservative damage function used here, this slowdown is bound to continue in the next century, given the cumulative nature of the climate externality.

In both the *Carbon Tax* and *Carbon tax and subsidy* scenarios, the policy instruments implemented allow to mitigate damages from climate change compared to the *no policy* scenario, by curbing emissions that even reach zero in the *subsidy* scenario. A first notable result of our simulations is that a carbon price at the upper bound of the corridor —as given by the High-Level Commission on Carbon Prices (2017)— is not enough to achieve the Paris objective in the median case. The median temperature anomaly just below 2.92°C in 2100 in the *carbon tax* scenario. We thus confirm a recommendation from the Commission's report, namely that a carbon price alone is not sufficient *per se* to reach carbon neutrality by 2100. Other policies are required. In our *subsidy* scenario, firms are also subject to a subsidy and become carbon neutral by 2064. But even then, the median temperature anomaly is 2.36°C in

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[11] The counterpart cases $f_K \in \{0\%, 50\%\}$ are discussed in the next subsection.

Table 1
Dates at which thresholds are reached.

Scenario	Variable	$\mathbf{f_{K=33\%}}$		
No policy	*Quantile*	5	50	95
	$d > 2.7$	–	–	2055
	$T > 2°C$	2072	2051	2040
Carbon tax	*Quantile*	5	50	95
	$d > 2.7$	–	2053	2037
	$T > 2°C$	–	2058	2042
Carbon tax and subsidies	*Quantile*	5	50	95
	$d > 2.7$	–	–	2039
	$T > 2°C$	–	2067	2044

2100. Table 1 brings together all the dates at which the thresholds are reached.

In the *carbon tax* scenario, the carbon tax acts as a powerful disincentive on the fossil fuel industry, whose cost of production increase dramatically. This brings the private debt-to-output to soar, reaching an unsustainable level by 2053 (in the median case). In this scenario, climate change damages are manageable, but the additional burden of the tax brings the economy to a debt-deflationary trap, and brings the real output to collapse around 2080 (while its growth rate stays 0.13 percentage points below its corresponding value in the *no policy* scenario before that).

In the *tax and subsidy* scenario, public expenditure acts as a buffer to temper the burden of the private debt, shortly raising public net spendings above 2% of GDP between 2058 and 2073 before decreasing once the economy is decarbonized. The subsidy, combined to the carbon tax, leads the energy shift to occur earlier resulting in: (i) a fall of profits due to the carbon tax; and (ii) a rise in abatement activities, due to the subsidy that diverts output from sales. As a result, real investment in physical temporarily capacities falls, the debt burden rises and the economy slows down. However, once the energy shift is performed, the resulting temperature anomaly and damages are smaller compared to the *no policy* scenario. Consequently, while in 2040, the output is 6.27% percent below the no policy scenario, it ends 9.98% above in 2100.

The three scenarios displayed in our modeling exercise exemplify a difficult trade-off, private debt dynamics and the effects of climate change, which is faced by policy-makers regarding the energy shift. By trying to avoid harmful climate change through a restrictive carbon tax, the need for green investment places a burden on private debt that only further public intervention can mitigate. The next section explores this trade-off in more details.

4.2. *Staying under the temperature and debt thresholds*

The debt-to-output ratio and temperature anomaly flow of trajectories in Fig. 3 show that only part of the runs allow to stay safely below two specific temperature and debt thresholds. The 2°C temperature anomaly threshold and the 2.7 debt-to-output ratio threshold are informative on the dynamics of a possible global recession by shedding light on two important channels: the changes in the mean surface temperature and the total aggregate private debt. In this section, we compute the probability distribution of the temperature anomaly and private debt-to-output ratio in order to provide insights about the probability of respecting these thresholds, ultimately informing about the sustainability of the underlying policy scenarios.

Our climate change module captures some of the uncertainties on the physical response of the Earth system to GHG emissions in an aggregated way (the climate temperature sensitivity and the inertia of the upper carbon reservoirs), even if we acknowledge that climate change is multi-factorial and features many other specific feedback loops. We thus follow the Paris Agreement approach, which sets a threshold at 2°C on the temperature anomaly based on the current knowledge on climate change gathered by the IPCC. The Agreement considers that above this 2°C threshold, climate change has a risk of reaching tipping points, leading to severe and possibly uncontrolled damages to our economy and environment.[12]

Our simulation framework allows to take another important threshold of the economic sphere into account, which is informative about the financial channels of possible breakdowns of the economy. When taking private debt into account, one can explore how the service of this debt can hinder the investment capacities of firms, making it more difficult to invest in adaptation and in repairs of climate change damages. Indeed, there is a threshold at the firm level when liabilities exceed the total capital stock, at which point a rational choice would be to default. At the aggregate level, one can also consider this point to be a threshold informing on the overall private debt burden. Using the Penn World Table (Feenstra et al., 2015), we can calibrate the global average capital-to-GDP ratio at 2.7. Above this threshold, it would be rational to globally default, bringing us in uncharted economic territory.

We compute the probability distribution of the debt-to-output ratio in Fig. 4 and the temperature anomaly in Fig. 5 for the simulation outcomes of all the parameters combinations in the three policy scenarios in 2050 and 2100. In the two figures, the X-axis represents respectively the debt-to-output ratio and the temperature anomaly. The three policy scenarios are vertically stacked, for each damage allocation to the stock of physical capital considered ($f_K \in \{0\%, 33\%, 50\%\}$). For each policy scenario and each f_K ratio value, two distributions are represented. The light-blue contoured distribution represents the frequency of all the outcomes in 2050, and the darker contoured one the frequency in 2100. The vertical dashed lines represent respectively the critical thresholds of 2.7

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[12] See for instance Lenton et al. (2008), Stern (2013) or Carney (2015) for a more extensive discussion about these issues.

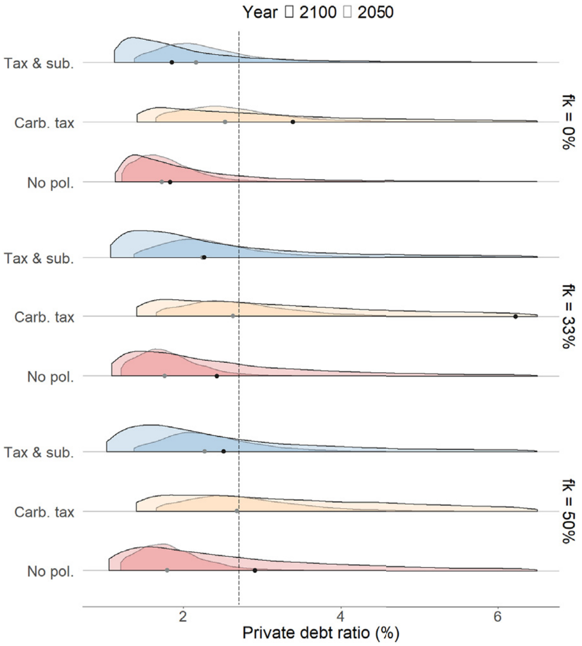

Fig. 4. Probability density function of the private debt-to-output ratio in 2050 and 2100. The median values are identified by a point, and the dashed vertical line indicates the critical debt-to-output threshold.

Table 2
Value of the survival function for the debt-to-output ratio at the point 2.7 in 2100.

$\mathbb{P}(d > 2.7)$ in %	$f_K = 0\%$	$f_K = 33\%$	$f_K = 50\%$
No policy	20.73	43.22	53.75
Carbon tax	62.38	77.53	83.14
C. tax and subsidy	23.84	39.37	46.17

debt-to-output ratio and 2°C temperature anomaly. The area under the probability density function on the right of the thresholds, or survival function values at the thresholds, can be interpreted as a probability of exceeding it, given our model structure and our knowledge of the parameter distributions.[13]

In Fig. 4 we see the effects of the increasing allocation of damages to the stock of capital on the debt-to-output ratio for each scenario, and the effects of changing the policy mix from one scenario to the other. Increasing the allocation of damage to the stock of capital has a positive effect on private debt in 2050: it shifts the whole distribution to the right, leading to a larger value of the survival function at the threshold (see also Table 2). The effect follows a clear intuition. When the capital stock bears a greater share of the damages, the necessary repairs and replacement of capital destruction increase the overall debt burden. Adding a carbon tax also shifts the distribution to the right compared to the *no policy* scenario. Indeed, the productive sector faces a higher carbon bill that reduces profits and thus increases the debt-to-GDP ratio. This highlights the trade-off faced by public authorities in balancing financial stability and climate change, as will be discussed below. This trade-off can be mitigated by using the revenues from the carbon tax to subsidize the backstop technology. As can be seen in Table 2, with a combination of tax plus subsidy, the probability of exceeding the 2.7 debt threshold is lower than in the no policy scenario (except if damages materialize entirely in output losses, that is $f_K = 0\%$).

Fig. 5 displays the probability density of the temperature anomaly in 2050 and 2100. Table 4 computes values of the survival function at the 2°C point —the probability of exceeding the temperature threshold in our setting. As can be expected, the effect appears to be much weaker than on the debt-to-output ratio. Changes in the capital stock only marginally affect emissions —through the growth engine— and thus the temperature anomaly. The impact of public policies is, however, prominent between scenarios, especially in the long run. The more stringent *subsidy* scenario has predictably a larger influence, as it triggers more abatement efforts and curbs emissions faster. Table 3 shows that from the *no policy* to the *subsidy* cases, the median decrease of temperature anomaly is close to −1.6°C.

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[13] The expression “survival function” is somewhat unfortunate in the context of the paper, as it stands for the part of the probability related to a collapse. It has to be understood as a reliability function in probability theory. That is, if $f(x)$ is the survival function of the probability variable X at the point x, then $f(x) = \mathbb{P}(X > x)$.

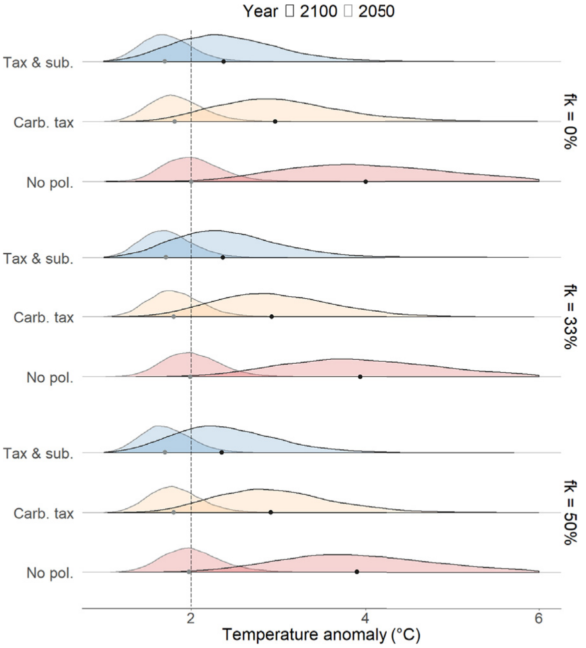

Fig. 5. Probability density function of the temperature anomaly in 2050 and 2100. The median values are identified by a point (not represented when greater than 6.5), and the dashed vertical line indicates the critical temperature anomaly threshold.

Table 3
Median value of temperature anomaly distribution in 2100 reported in Fig. 5.

°C	$f_K = 0\%$	$f_K = 33\%$	$f_K = 50\%$
No policy	4.00	3.94	3.90
Carbon tax	2.96	2.92	2.91
C. tax and subsidy	2.37	2.36	2.35

From the most pessimistic to the most optimistic scenario, we gain 25 probability points for achieving the 2°C target. In our central *No policy* scenario (with $f_K = 33\%$), there is less than 1% chance of achieving the 2°C target of the Paris Agreement, while it grows to above 6% in our *carbon tax* scenario and above 25% in our *subsidy and subsidy* scenario.

These figures are comparable to the ones recently presented in Nature Climate Change by Raftery et al. (2017) using a very different methodology. Raftery et al. (2017) make a projection based on Kaya's identity at the country level. GDP and CO_2 emissions are forecasted in a probabilistic way to compute the chances of staying below the 2°C threshold. They also find a 5% chance of meeting the Paris Agreement. Contrary to this article, however, they do not propose any theory or causal factor to disentangle the different channels at play, nor do they estimate the effect of global climate policy mixes. Their findings are consistent with our *Carbon tax* scenario, implying that a minimal public intervention in favor of abatement efforts are required to achieve this result.

As already mentioned, the comparison between scenarios in Figs. 4 and 5 shows that there is a trade-off between fighting the climate and financial instabilities. More effective climate policy mixes tend to be implemented at the cost of increasing the private debt in the long run. On one hand, the carbon tax and the subsidy from the public sector provide stronger incentives to perform the energy shift, and thus are effective in mitigating global warming and reducing its associated damages. On the other hand, a carbon tax penalizes profits and thus growth as well as the debt repayment capacities of the productive sector. Besides, the subsidy, as an additional source of funds for the productive sector, boosts profitability and thus investment and the associated nominal debt. The two opposing effects lead to different debt dynamics in the two climate policy scenarios. While in the *tax* scenario, the private debt

Table 4
Value of the survival function for the temperature anomaly at the point 2°C in 2100 for $f_K = 33\%$.

$\mathbb{P}(T > 2^\circ C)$ in %	$f_K = 33\%$
No policy	99.50
Carbon tax	93.52
C. tax and subsidy	74.38

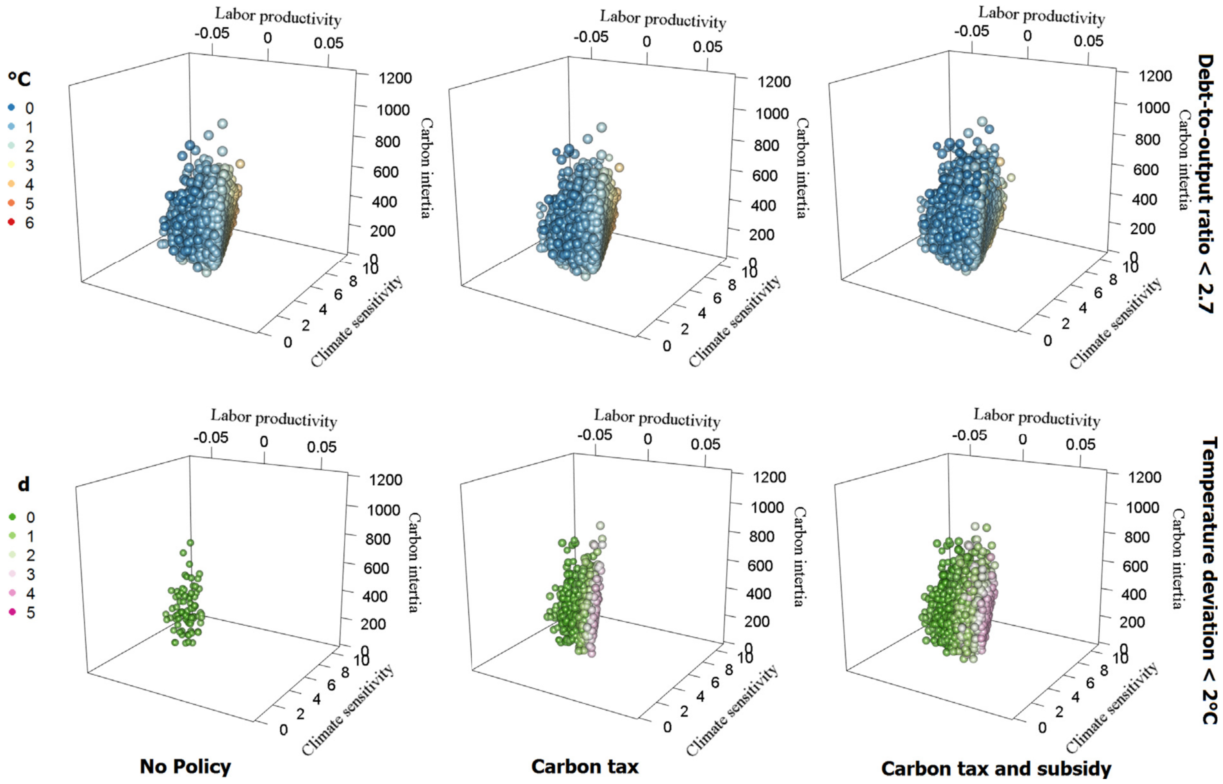

Fig. 6. Set of points (α, S, C^{up}) from the Monte Carlo simulation of all scenarios with $k = 1/3$. The upper line displays the set of initial conditions from simulations with a debt-to-output ratio below 2.7 in 2100 (the color of the points indicates the temperature anomaly of each simulation in 2100, with a colorscale on the left). The lower line displays the set of initial conditions from simulations with a temperature anomaly below 2°C in 2100 (the color of the points indicates the debt-to-output ratio level of each simulation in 2100, with a colorscale on the left). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

soars, the debt increase in the *tax and subsidy* scenario is only temporary —as it stabilizes once carbon neutrality is reached— and ensures lower temperature anomalies in 2100. These results are in line with the recommendations from the High-Level Commission on Carbon Prices (2017), calling for a wider involvement of public actors, notably in terms of co-financing.

Comparing different values for f_K in Figs. 4 and 5 and Tables 2–4 highlights the potential role of targeted adaptation efforts, or the detrimental effect of not doing so. If targeted action can reduce the share of damages sustained by the capital stock (for instance from 1/3 to 0) has little effect on the temperature anomaly, it can reduce significantly the burden of the debt and the chance of overshooting the debt-to-output threshold by more than 15 percentage points in presence of a climate policy, and up to 22 percentage points in our *no policy* scenario. On the contrary, implementing action that would increase the exposure of the stock of capital to damages from climate change (say from 1/3 to 1/2) by e.g. destroying carbon sinks or natural buffer zones, accelerating erosion, etc., would increase the chance of overshooting the debt-to-output threshold by approximately 6 percentage points in presence of a climate policy, and up to 10 percentage points in our *no policy* scenario.

4.3. Parameter spaces

The Monte Carlo analysis allows us to investigate in more details the physical and economic determinants of an overshoot. In this section, we explore the parameter values for productivity growth, climate sensitivity and inertia of the climate reservoirs that allow to stay below the thresholds.

We know from Bovari et al. (2018) that employment policy, debt relief and income distribution are effective drivers of a possible collapse. Acting on those three levers, one can move the starting point of the economy inside the so-called basin of attraction, thus ensuring the economy is in a sustainable path. The three parameters considered here—namely the climate sensitivity, the inertia of the carbon cycle, and the labor productivity growth—are not levers for public action *per se*. We can nevertheless use our results to discuss three additional types of public intervention that can influence the shape of the basin of attraction of the good equilibrium.

The second line of Fig. 6 shows the set of initial conditions drawn from our Monte Carlo simulations that allow the economy to remain below the 2°C threshold in 2100. The range of colors from green to pink indicates the level of the debt-to-output ratio in 2100 for each simulation. It appears that the 2°C threshold is only feasible for favorable combinations of low growth and high resilience from the climate —that is a low climate sensitivity and a somewhat low inertia of the carbon cycle. For the *No policy* scenario, the corresponding set of initial conditions, which is almost negligible (≈ 0.42% of draws), is clearly restricted in a extremely favorable

Table 5
Value of the survival function for the joint temperature anomaly and debt-to-output ratio at the point (2°C,2.7).

$\mathbb{P}\left(\{T > 2^{\circ}C\} \cup \{d > 2.7\}\right)$	$f_K = 0\%$	$f_K = 33\%$	$f_K = 50\%$
No policy	99.63	99.50	99.58
Carbon tax	95.96	95.97	96.74
C. tax and subsidy	78.47	80.83	81.32

region for the climate model that exhibits negative labor productivity growth along with low climate sensitivity. This suggests that, without climate policies, only paths of low growth (even negative) might be compatible with the 2 °C objective.

More stringent climate policies significantly increase the set of favorable parameter combinations, enlarging the basin of attraction of favorable trajectories. Indeed, the scenario *Carbon tax and subsidies* allows positive labor productivity growth together with values for the climate sensitivity and the carbon inertia that are at the median value of their PDF. However, as visible in the pink shade of the dots, these additional points in the set come together with a higher debt-to-output ratio (sometimes higher than the 2.7 threshold) highlighting the trade-off faced by the public authorities discussed earlier.

The first line of Fig. 6 shows the set of initial conditions drawn from our Monte Carlo simulations that allow the economy to remain below the 2.7 debt-to-output threshold in 2100. The range of colors from blue to red indicates the level of the temperature anomaly in 2100 for the same initial values. As discussed above, climate policies have a much smaller effect on the basin of attraction of favorable debt-to-output trajectories compared to their effect on favorable temperature anomaly trajectories. While climate policies do increase the level of indebtedness, the mass of simulations going above the 2.7 debt-to-output threshold when adding a climate policy is much smaller (some percentage points, visible in Table 2). In addition, the tax and subsidy scenario has much more blue dots, indicating more favorable temperature anomaly levels. This means that a well-designed climate policy mix helps meet both thresholds: the temperature anomaly and the debt-to-output ratio. Table 5 gives the probabilities of overshooting at least one of the two thresholds. It appears that while over-indebtedness remains a large problem when adding a carbon tax, using the revenues from that tax to relieve part of the debt burden through a targeted subsidy considerably increases the probability of meeting the joint climate and debt sustainability targets (from 0.42% in the no policy scenario to approx. 3.25% with a tax only and 18.7% with an additional subsidy).

5. Conclusion

In this article, we perform a sensitivity analysis of a companion model of Bovari et al. (2018), combining two sources of instability in a rather low-dimensional, stock-flow consistent, integrated ecological macroeconomic framework: (i) global warming and (ii) private over-indebtedness. We allow three fundamental parameters of the climate and economic systems to follow a PDF taken from Nordhaus (2017): the climate sensitivity, the inertia of the carbon cycle, and the labor productivity growth. We also let another techno-climatic parameter vary in a discrete way: the share of damages sustained by the stock of capital (instead of only considering damages allocated to output). We then test how different climate policies allow avoiding the overshoot of two thresholds that we argue to be critical for the stability of our current economy and climate: (i) a temperature anomaly above the +2°C target set in the Paris Agreement, (ii) and a global debt-to-output ratio above 2.7, a value calibrated at the level of the current stock of assets. Above this 2.7 ratio, the value of the total private debt would exceed the value of the current stock of asset, arguably leading to systemic defaults. Both are associated to major potential destabilizing channels: damages to output and the capital stock from climate change, and the ability of firms to invest in repairs and adaptation.

We find that we have a mere 0.5% chance of achieving the 2°C warming target of the Paris Agreement in a no-policy scenario. Introducing climate policies, as advocated in a recent report by the High-Level Commission on Carbon Prices (2017) at the Pricing Leadership Coalition, allows to increase that probability to approximately 6.5%. We also highlight the role of additional climate policies beyond a carbon price, as well as the potential of targeted adaptation aiming at reducing the share of damages sustained by production factors (instead of considering that all damages from climate change occurs *via* changes in the output). Increasing mitigation efforts by adding a 50% subsidy to investment in the backstop technology increases the probability of meeting the 2°C target to approximately 25.6%. On the other hand, increasing adaptation efforts would have little effect on the temperature anomaly, but would reduce the burden of the debt and hence the chances of global instability. Indeed, adapting the stock of capital to climate change by reducing the share of damages it sustains from 50% to zero reduces the probability of exceeding the 2.7 debt-to-output threshold approximately from 53.75% to 20.75% (in the no-policy scenario) or from 83.5% to 62.4% (with a carbon tax).

We also shed light on the trade-off between the two principal objectives of sustainable development in our framework: a sustainable debt and a sustainable climate. By increasing the unit production cost of polluting firms, an effective carbon price comes at the cost of increasing the probability of overshooting the 2.7 debt-to-output ratio threshold from 43.2% to 77.5% approximately. Subsidizing mitigation efforts allows to alleviate a significant part of the burden of the private debt by transferring it to the public sector. This mutualization of efforts does not come at the cost of unbearable additional net public spendings.

Several important limitations should be kept in mind when interpreting our results. First, we present an aggregate model of the global economy and of the finance sector. This paper is concerned with aggregate effects, a useful first step in the analysis of a complex problem. However, geographical and sectoral disaggregations have been shown to be key, and a prerequisite for a complete understanding of the debt and damage interaction channels. The energy and finance sectors are also highly condensed in the paper. More details are desirable, especially when one seeks to understand the role of an energy vector (green electricity) that plays a role in all sectors. Second, technological aspects have also been shown to play prominent roles. R&D, knowledge effects, and the nature of the backstop technology would all deserve a closer look in a stock-flow consistent macrodynamic framework. A third interesting avenue of research is the role of different types of money, such as central money *versus* commercial money in a post-Keynesian framework (Aglietta et al., 2015).

Nevertheless, our work allows a better interpretation of the dynamics often overlooked in IAMs and policy advice such as in the High-Level Commission on Carbon Prices (2017). In particular, we highlight the role of monetary channels and debt, as well as their interactions with climate change damages, and do not presuppose a balanced growth path. This allows a finer look at possible climate policy mixes, the trade-off they imply at the global level, and the possible balance between mitigation and adaptation efforts. Further work will be required to deepen the understanding of these channels and the interactions of sectors and regions in the global energy shift.

Acknowledgments

The authors are grateful to two anonymous referees for their fruitful comments and suggestions. This work benefited from the support of the Chair Energy & Prosperity and the financial support of the Agence Nationale de la Recherche (project MeET-MaDyS, ANR-15-CE05-0028). All remaining errors are ours.

Appendices

A. Stock-flow consistency matrix

Table 6 displays balance sheets of the firms, the transactions of the economy and the flow of funds. The stock-flow consistency of the model can be readily checked. In particular, the accounting identity “investment = savings” holds by summing up the line savings in Table 6.[14]

Table 6
Balance sheet, transactions, and flow of funds in the economy.

	Households	Firms		Banks	Public Sector	Sum
Balance Sheet						
Capital stock		pK				pK
Deposits	M^h	M^c		$-M$		
Loans		$-L_c$		L_c		
Bonds	B				$-B$	
Equities	E	$-E^f$		$-E^b$		
Sum (net worth)	X^h	$X^f = 0$		$X^b = 0$	$-B$	X
Transactions		current	capital			
Consumption	$-pC$	pC				
Investment		pI	$-pI$			
Gov. Spend.		pG			$-pG$	
Acc. memo [GDP]		$[pY]$				
Wages	W	$-W$				
Capital depr.		$-(\delta + \mathbf{D}^K)pK$	$(\delta + \mathbf{D}^K)pK$			
Carbon taxes		$-pT_f$			pT_f	
Abatement subsidies		pS_f^C			$-pS_f^C$	
Int. on loans		$-r_cL_c$		r_cL_c		
Bank’s dividends	Π_b			$-\Pi_b$		
Firm’s dividends	Π_d	$-\Pi_d$				
Int. on deposits	r_MM^h	r_MM^c		$-r_MM$		
Int. on bonds	r_BB				$-r_BB$	
Column sum (balance)	S^h	$S^c = \Pi_r$	$-pI + (\delta + \mathbf{D}^K)pK$	S^b	S^g	
Flow of Funds						
Change in capital stock		$p\dot{K}$				$p\dot{K}$
Change in deposits	$\dot{M}^h$	$\dot{M}^c$		$-\dot{M}$		
Change in loans		$-\dot{L}_c$		$\dot{L}_c$		
Change in bills	$\dot{B}$				$-\dot{B}$	
Column sum (savings)	S^h	S^c		S^b	S^g	
Change in firm equity	$\dot{E}^f$	$-(S^f + \dot{p}K)$				
Change in bank equity	$\dot{E}^b$			$-S^b$		
Change in net worth	$S^h + \dot{E}$	0		0	S^g	$\dot{p}K + p\dot{K}$

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[14] See Bovari et al. (2018) for further details.

B. Calibration of the model

The calibration of the model is directly borrowed from Bovari et al. (2018). The parameters objects to the prospective analysis performed in this paper —namely: (i) the growth rate of labor productivity α; (ii) the preindustrial CO_2 capacity of the biosphere and upper ocean reservoir of the carbon cycle, $CO_{2_{UP}}$; (iii) the allocation of damages between output and capital, f_K; (iv) the equilibrium climate sensitivity, S; (v) the subsidy of the public to abatement activities, s_A; and (vi) the trajectory of the carbon price— are not displayed in this table.

Symbol	Description	Value	Remarks and sources
C	Heat capacity of the atmosphere, biosphere and upper ocean	1/.098	DICE model, Nordhaus (2017), adjusted for a continuous framework
C_0	Heat capacity of the deeper ocean	3.52	DICE model, Nordhaus (2017), adjusted for a continuous framework
$C_{AT_{pind}}$	CO_2-e preindustrial concentration in the atmosphere layer	588 Gt C	DICE model, Nordhaus (2017)
$C_{LO_{pind}}$	CO_2-e preindustrial concentration in the deeper ocean layer	1720 Gt C	DICE model, Nordhaus (2017)
div_0	Constant of the dividend function, $\Delta(\cdot)$	−0.078	Empirically calibrated, macroeconomic database, more details available upon request
div_π	Slope of the dividend function, $\Delta(\cdot)$	.553	Empirically calibrated, macroeconomic database, more details available upon request
$div_{\min}$	Minimum of the dividend function,$\Delta(\cdot)$	0	Selected among a range of reasonable values
$div_{\max}$	Maximum of the dividend function, $\Delta(\cdot)$	0.3	Selected among a range of reasonable values
$F_{2\times CO_2}$	Change in the radiative forcing resulting from a doubling of CO_2-e concentration w.r.t. to the pre-industrial period	3.681 W/m^2	DICE model, Nordhaus (2017)
F_{exo}^{start}	Initial value of the exogenous radiative forcing	0.7 W/m^2	DICE model, Nordhaus (2017)
F_{exo}^{end}	Final value of the exogenous radiative forcing	0.7 W/m^2 (after 2100)	DICE model, Nordhaus (2017)
P^N	Upper limit of the workforce dynamics in billions	7.056	Empirically calibrated, macroeconomic database, more details available upon request
P_G^N	Upper limit of the total population dynamics in billions	12	Empirically calibrated, macroeconomic database, more details available upon request
q	Speed of growth of the workforce dynamics	0.0305	Empirically calibrated, macroeconomic database, more details available upon request
q_G	Speed of growth of the total population dynamics	0.027	Empirically calibrated, macroeconomic database, more details available upon request
r	Short-term interest rate of the economy	0.02	Selected among a range of reasonable values
T_{preind}	Preindustrial temperature	13.74°C	NASA (2016)
δ	Depreciation rate of capital	0.04	Inklaar and Timmer (2013)
$\delta_{E_{Land}}$	Growth rate of land use change CO_2-e emissions	−0.022	DICE model, Nordhaus (2017), adjusted for a continuous framework
δ_{g_σ}	Variation rate of the growth of emission intensity	- 0.001	DICE model, Nordhaus (2017), adjusted for a continuous framework
$\delta_{p_{BS}}$	Exogenous growth rate of the back-stop technology price	- 0.005	DICE model, Nordhaus (2017), adjusted for a continuous framework
ζ_3	Damage function parameter	6.754	DICE model, Nordhaus (2017)
η	Relaxation parameter of the inflation	0.192	Selected among a range of reasonable values
θ	Parameter of the abatement cost function	2.6	DICE model, Nordhaus (2017)
κ_0	Constant of the investment function, $\kappa(.)$	0.0318	Empirically estimated, macroeconomic database, more details available upon request
κ_1	Slope of the investment function, $\kappa(.)$	0.575	Empirically estimated, macroeconomic database, more details available upon request
μ	Mark-up of prices over the average cost	1.875	Selected among a range of reasonable values
ν	Constant capital-to-output ratio	2.7	Inklaar and Timmer (2013)
π_1	Damage function parameter	0/°C	DICE model, Nordhaus (2017), adjusted for a continuous framework
π_2	Damage function parameter	$0.00236/°C^2$	DICE model, Nordhaus (2017)
π_3	Damage function parameter in the Weitzman case	$0.00000507/°C^{\zeta_3}$	Weitzman (2011) and Dietz and Stern (2015)
ϕ_0	Constant of short-term Phillips curve, $\phi(.)$	-.292	Empirically estimated, macroeconomic database, more details available upon request
ϕ_1	Slope of the short-term Phillips curve, $\phi(.)$	.469	Empirically estimated, macroeconomic database, more details available upon request

(*continued on next page*)

Symbol	Description	Value	Remarks and sources
Φ_{12}	Transfer coefficient for carbon from the atmosphere to the upper ocean/biosphere	0.024	DICE model, Nordhaus (2017), adjusted for a continuous framework
Φ_{23}	Transfer coefficient for carbon from the upper ocean/biosphere to the lower ocean	0.001	DICE model, Nordhaus (2017), adjusted for a continuous framework

The mentioned macroeconomic database gathers data from the World Bank, Penn University, the U.S. Bureau of Economic Analysis, and the United Nations.

C. Initial values of the model

The initial values of the model are directly borrowed from Bovari et al. (2018).

Symbol	Description	Value	Remarks/sources
CO_2^{AT}	CO_2-e concentration in the atmosphere layer	851 Gt C	DICE model, Nordhaus (2017)
CO_2^{UP}	CO_2-e concentration in the biosphere and upper ocean layer	460 Gt C	DICE model, Nordhaus (2017)
CO_2^{LO}	CO_2-e concentration in the deeper ocean layer	1740 Gt C	DICE model, Nordhaus (2017)
d	Private debt ratio of the economy	1.53	Empirically calibrated, macroeconomic database
E_{ind}	Industrial CO_2-e emissions	35.85 Gt CO_2-e	DICE model, Nordhaus (2017)
E_{land}	Exogenous land use change CO_2-e emissions	2.6 Gt CO_2-e	DICE model, Nordhaus (2017)
F_{exo}	Exogenous radiative forcing	0.5 W/m^2	DICE model, Nordhaus (2017)
g_σ	Growth rate of the emission intensity of the economy	- 0.0152	DICE model, Nordhaus (2017)
p	Composite good price level	1	Normalization constant
p_{BS}	Backstop price level	547.22	DICE model, Nordhaus (2017), compound 1-year ahead
n	Emissions reduction rate	0.03	DICE model, Nordhaus (2017)
N	Workforce of the economy in billions	4.83	Empirically calibrated, macroeconomic database
NG	Total population in billions	7.35	Empirically calibrated, macroeconomic database
T	Temperature in the atmosphere, biosphere and upper ocean layer	0.85 °C	DICE model, Nordhaus (2017)
T_0	Temperature in the deeper ocean layer	0.0068 °C	DICE model, Nordhaus (2017)
Y	Gross domestic product (at factor prices) in trillions USD	59.74	Empirically calibrated, macroeconomic database
λ	Employment rate of the economy	0.675	Empirically calibrated, macroeconomic database
ω	Wage share of the economy	0.578	Empirically calibrated, macroeconomic database

The mentioned macroeconomic database gathers data from the World Bank, Penn University, the U.S. Bureau of Economic Analysis, and the United Nations.

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