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Research article

Green bonds, transition to a low-carbon economy, and intertemporal welfare allocation: Evidence from an extended DICE model

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Abstract: Short-term reductions in social welfare, expected to be caused by a currently imposed carbon tax, are among the obstacles to a rapid transition to a low-carbon economy. Using an extended DICE model, we studied the potential of green bonds to both accelerate this transition and smoothen welfare losses and gains in a socially optimal way. We showed that green bonds can indeed accelerate the transition to a low-carbon economy and that lower interest rates on bonds speed up this acceleration. Moreover, bonds can reduce short-term welfare losses; however, to eliminate welfare losses, additional compensation mechanisms are needed. For example, bonds at a 3% interest rate can decrease the peak atmospheric carbon concentrations by about 20% and shorten the initial time, during which society is worse off from 75 to 45 years. Retaining at least the same consumption level as in the no-mitigation scenario, without using bonds, is possible only through a decrease in abatement efforts. Green bonds of sufficiently low interest rates allow improving intertemporal welfare as well as achieving a more pronounced climate change mitigation with respect to both mitigation and no-mitigation scenarios without bonds.

Keywords: climate change mitigation; green bonds; intertemporal welfare allocation; welfare optimization; DICE model

1. Introduction

The Paris Climate Agreement signed in 2015 by 195 members of the United Nations Framework Convention on Climate Change (UNFCCC) highlights the importance of combining mitigation, adaptation, and finance to effectively deal with global warming and its negative impacts worldwide. However, despite a broad consensus across the scientific community that urgent actions are needed to curb greenhouse gas (GHG) emissions, finding feasible incentives and financing mechanisms for emission reduction and dealing with future damages remains a major policy challenge [1,2].

A carbon tax has been promoted to incentivize GHG emission reduction through increasing the price of fossil energy. Additionally, carbon tax revenues can be used to finance low-carbon development projects. Both should help to avoid a climate catastrophe in the long term [3,4]. However, in the short term, the introduction of a carbon tax may lead to social welfare losses due to lowered economic activity and reduced net income of households [5,6]. Thus, despite the expected benefit of avoiding a climate catastrophe in the future, politicians might be hesitant to implement a carbon tax at scale if it is likely to be unfavorable to social welfare in the near term. For instance, even the European Union (EU), which is one of the leaders in terms of climate change mitigation efforts, faces challenges regarding the introduction of a carbon tax. As of March 2023 [7], only 15 out of 27 countries of the EU have introduced the carbon tax, and the scope of each country's carbon tax differs: the tax rate varies widely from 2.18 USD per ton of CO_2 emission in Estonia up to 125.56 USD in Sweden (March 2023). The announced EU Carbon Border Adjustment Mechanism, which will put a carbon price on imports of selected products, has already experienced resistance from some states [8].

Green bonds (or climate bonds) are another approach to finance mitigation costs, which may be able to not only make climate policies more feasible and thus speed up the transition to a low-carbon economy but also avoid or at least lower short-term welfare losses [9][1]. Green bonds can be issued by companies, municipalities, states, and sovereign governments, as well as by international institutions to raise funds to finance mitigation through a variety of future-oriented long-term environmental and climate-related projects and activities [11]. These are debt instruments, by which financial investors provide funds for a defined period of time at a variable or fixed interest rate. The first green bonds (Climate Awareness Bond) were issued by the European Investment Bank in 2007 [12]. In 2021, the green bonds market reached a peak at 582 billion USD per annum with a cumulative issuance of 2.159 trillion USD from 2014 to 2022 [13]. Despite the observed exponential uptake of the green bonds market since 2012 [14], the current level is still rather low compared to what is required; for example, the OECD estimates that 6.9 trillion USD per year would be needed until 2030 to meet the climate and development objectives [15]. Some experts argue that under favorable institutional and policy

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[1] Historically, bonds have been used to fund large-scale projects ranging from infrastructure to wars [10].

arrangements (e.g., global green bonds standardization, adopting high standards of disclosure and reporting, and facilitating investment in emerging economies), the green bonds market can significantly expand [9,16].

Leaving aside political, institutional, and technical aspects of green bond issuing, in this paper, we would like to examine the potential of green bonds (i) to scale up mitigation and (ii) to reduce or even eliminate the short-term welfare losses from the transition to a low-carbon economy in a socially optimal way; we refer to the latter research question as an "intertemporal welfare allocation problem". A modeling framework that is well-suited to examine these questions is the Dynamic Integrated Climate-Economy (DICE) model family [17–20]. DICE is a stylized integrated assessment model (existing in several versions) linking a Ramsey-type global economy with climate change. Despite their simplicity, the dynamic DICE equations capture, in a tractable way, the entire causal loop between economic growth, industrial emissions, mitigation policies, global temperature, and related climate change losses. The DICE model has been calibrated to be quantitatively realistic, which enables policy makers to make informed decisions on GHG emission reduction strategies [21,22] and obtain assessments of the social cost of carbon at the global [23,24] or regional scale [25]. The latter can be done using DICE's regional extensions.

The DICE model relies on an infinitely-lived agent (ILA) framework[2], where a representative household lives through an infinitely long time period and a social planner makes decisions that define the household's consumption path, including the decisions on the allocation of funds for abatement, so as to maximize the sum of her discounted utilities over this time horizon. Thus, in this paper, we concentrate on the flow of the representative household's welfare at different moments of time and analyze welfare losses and gains over time in four alternative mitigation scenarios, in comparison to a no-mitigation scenario. Two of four mitigation scenarios are based on the DICE optimal scenario (see [20]); they include a carbon tax but no green bonds. To construct the other two scenarios, we extend the DICE model by adding green bonds, which are used strictly to finance climate change abatement costs. We come up with plausible quantitative estimates of the key policy effects of these mitigation scenarios to demonstrate the effectiveness of green bonds in terms of emission abatement and welfare change.

The remainder of the paper is organized as follows. Section 2 discusses relevant literature. Section 3 introduces an extended DICE model with bonds. Section 4 presents the simulation results comparing several scenarios. Section 5 provides the discussion. Section 6 presents the conclusions. Appendix A contains a complete model description. In Appendix B, we discuss two ways to introduce a damage function into the DICE model. The sensitivity of the DICE model with respect to a few alternative damage functions from the literature is investigated in Appendix C. The robustness of the outcomes of our DICE model extension with respect to the length of the time horizon (provided it is sufficiently long) is shown in Appendix D. Appendix E presents the sensitivity analysis of optimal green bond issuance amounts and optimal tax rates with respect to the bond interest rate. Appendix F contains the sensitivity analysis of the green bond interest rate necessary to completely eliminate the short-term

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[2] Technically, the dynamic optimization in DICE is done over a finite, long enough time horizon. In Appendix D, we discuss how finite-horizon solutions of DICE are related to an infinite-horizon model.

welfare losses along with the use of an additional compensation mechanism, which will be explained in detail below. Appendix G provides the results of simulations for consumption per capita in different scenarios.

2. Related literature

The issue of the intertemporal welfare allocation in the socially optimal scenario with environmental externality in an ILA framework has not received much attention in the literature yet. An exception is noted in [26], which suggested a modification of the DICE model to include an adjusted damage function and simplified climate dynamics. However, in this DICE modification, contrary to the original DICE model, the optimal mitigation policy does not lead to any short-term welfare losses with respect to the no-mitigation scenario.

A series of papers present models that deal with a related, although different, issue of intergenerational equity. This issue is typically analyzed based on an overlapping-generations (OLG) model. Before discussing the differences between the two approaches, let us briefly review relevant OLG-based papers and the major insights they present. The first attempt to investigate intergenerational equity in the DICE model was undertaken in [27,28], where the author presented an OLG model calibrated to reproduce the DICE-94 projections. In this model, appropriately chosen lump-sum intergenerational transfers smoothened the welfare distortions and ensured Pareto efficiency. The power of intergenerational transfers in the form of public debt (bonds) to eliminate inequity arising from environmental taxation was investigated for the first time in [29]. Later, using another very stylized OLG model [30], it was demonstrated that mitigation policies combined with an intergenerational fiscal policy in the form of government bonds and taxation can be Pareto improving for all generations relative to a business-as-usual (BAU) scenario of no climate change mitigation. A series of publications followed this approach and presented various OLG models that generally supported this conclusion and provided further insights more specifically in the context of climate change (see e.g., [31,32]).

The problem of intergenerational equity in an OLG framework and the problem of intertemporal welfare allocation in an ILA framework are similar in the sense that both deal with the redistribution of welfare caused by mitigation across generations or over time, respectively. Utility loss for some generations or some time moments caused by a policy can be regarded as an unwanted effect that may hinder the application of this policy in practice if the current generation is among the affected or if the utility loss occurs in the immediate future. However, generally, the two approaches are different in terms of the nature of the solution pathways that they yield. In an ILA framework, the representative agent determines their consumption path over the entire, infinitely long-time horizon by optimizing the total utility. Every time moment contributes to the total utility function with an ever-decreasing weight (social discounting). Thus, a solution in an ILA framework can be referred to as a socially optimal solution from the perspective of today. In the OLG approach, each generation makes its own decisions, which collectively define the development path. A generation's decisions are based on their own utility function. Depending on the model specification, the generation's utility may include altruistic concerns, in which case an OLG approach may yield the same optimal path as an ILA approach. For example, in [27], an OLG version of the DICE model was developed and calibrated so that both models produced similar results in the baseline scenario. Generally, ILA and OLG approaches can be considered complementary in terms of the analysis of utility distribution effects arising from policies.

3. Model

The DICE model family is based on the neoclassical economic growth theory, in which a single good is produced and constrained by the availability of production factors. Most commonly, and also in DICE, capital and labor are factors of production. The capital stock increases due to investments, and hence there is a tradeoff between greater consumption today and investment in capital, which will enable higher consumption levels in the future. In addition to the economic dynamics, the DICE model also contains a simple representation of the global carbon cycle, its impact on the global climate, as well as on the economic losses from climate change. The DICE model also illuminates a tradeoff between greater investment, more production, higher GHG emissions, more pronounced global warming, and hence greater economic losses on the one hand, and higher abatement, lower economic losses, and hence a lower consumption on the other hand. By choosing the investment/saving rate and abatement policies, a social planner maximizes the integrated discounted welfare derived from per capita household consumption and hence finds an optimal level of global warming, abatement policy, as well as the resulting paths for the economic and climate variables.

In this paper, we include green bonds and a "green" tax[3] to repay the bonds in the DICE model. This generates two more tradeoffs. The first tradeoff is associated with the total amount of bonds to be issued: a larger amount would help to ensure a higher emission reduction and hence also mitigate a larger portion of climate change losses, but on the other hand, a larger amount of bonds, possibly further increased by the interest rate, would need to be repaid later. The second tradeoff relates to the tax rate and the duration of the taxation period during which the bonds should be fully repaid including the interest rate: a lower tax rate implies a longer repayment period and hence a higher total interest payment.

Note that one of the control variables in the original DICE model is abatement cost, which can be interpreted as a proxy of a carbon tax. In our extension of the DICE model, which is described below, we use a financial instrument combining green bonds and a green tax to redistribute the burden of financing climate change mitigation between now and the future. By design, our extended DICE model allows for both bond issuance and taxation at any point in time. In the absence of green bonds, the green tax in our model would be equal to abatement cost and hence it can be treated as a carbon tax. As we will discuss below, our model results suggest that it is optimal to collect debt without taxation in the beginning and repay the debt later. In actual economies, however, a carbon tax and green bonds play rather complementary roles in financing and incentivizing climate change mitigation efforts. While the carbon tax provides a continuous financial disincentive for emitting carbon, green bonds

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[3] Note that the term *green tax* is often used to refer to the tax that is imposed on polluting industries in order to incentivize emission reduction (e.g., [33]). We use this term in the different context: this is a tax that the agents will have to pay in the future in order to pay back the debt that was used to combat emissions.

ensure that there is capital available for investment in low-carbon solutions. Combining green bonds with a carbon tax therefore ensures a balanced approach to climate policy.

In what follows we present the key model equations.

3.1. Original DICE model[4]

In this section, we do not cover all equations of the DICE model, but only the ones necessary to explain the model extension we make (Section 3.2) and our simulations (Section 4). The remaining equations and all parameter values are given in Appendix A.

The main economic variables of the DICE model are the global capital stock $K(t)$ and the global gross domestic product (GDP) $Y(t)$. The GDP is produced according to the Cobb-Douglas production function $Y(t) = A(t)K^{\gamma}(t)L^{1-\gamma}(t)$. Here, $A(t)$ is the total factor productivity, $L(t)$ is population assumed to be equal to the available labor supply, and γ is the output elasticity of capital. The population dynamics and the total factor productivity are given exogenously (see Appendix A). The net output, that is, the GDP net of damages and abatement, is defined by the following formula:

$$Q(t) = [1 - \Lambda(t)]\Omega(t)Y(t) \tag{1}$$

Where

$$\Omega(t) = \frac{1}{1 + aT_{\mathrm{AT}}^{2}(t)} \tag{2}$$

is a damage multiplier reflecting the damaging effect of rising temperatures on GDP[5]; here $T_{\mathrm{AT}}(t)$ is the mean Earth surface temperature increase compared to the temperature in the year 1900 (considered as a proxy of the pre-industrial level). Abatement function $\Lambda(t)$ in (1) represents the fraction of the net output, $\Omega(t)Y(t)$, that is allocated to the mitigation of anthropogenic CO_2 emissions. It has the interpretation of the abatement cost and is defined based on the emissions reduction rate, $\mu(t) \geq 0$, as follows:

$$\Lambda(t) = \theta_1(t)\mu^{\theta_2}(t) \tag{3}$$

with $\theta_1(t)$ and θ_2 defined exogenously (see Appendix A).

The model dynamics is defined over a discrete time grid with a time step of five years. The capital stock accumulates due to investment $I(t)$:

$$K(t+1) = 5I(t) + (1-\delta)^5 K(t) \tag{4}$$

where $\delta > 0$ is the annual depreciation rate of capital.

Annual industrial CO_2 emissions are derived from the produced output and the emissions reduction rate as follows

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[4] For our analysis, we use the DICE-2013R model (henceforth, DICE model).

[5] In Appendix B, we discuss the role of the choice of a particular functional form to describe the climate change–related damages.

$$E_{\mathrm{Ind}}(t) = \sigma(t)[1 - \mu(t)]Y(t) \tag{5}$$

depending on the exogenously given carbon intensity $\sigma(t)$. Together with the projected annual land-use emissions $E_{\mathrm{Land}}(t)$ (see Appendix A), they result in the total annual CO_2 emissions, $E(t) = E_{\mathrm{Ind}}(t) + E_{\mathrm{Land}}(t)$, which are responsible for an increase in the mean Earth's surface temperature. This effect is modeled in DICE via the carbon cycle and temperature equations [see Eqs. (A1–A3) in Appendix A for details].

In the original DICE model, consumption $C(t) = Q(t) - I(t) \geq 0$ and the emissions reduction rate $\mu(t) \geq 0$ are policy variables. A social planner chooses $C(t)$ and $\mu(t)$ to maximize the social welfare function

$$W = \sum_{t=1}^{T} (1 + \rho)^{-5(t-1)} L(t)U(t) \tag{6}$$

where $U(t) = \frac{\left(C(t)/L(t)\right)^{1-\alpha}}{1-\alpha}$ is an instantaneous utility of per capita consumption $C(t)/L(t)$, α is the elasticity of consumption, and ρ is the annual social time preference, which is also referred to as the social discount rate[6]. In (9), the time horizon T is fixed.

3.2. Extended DICE model: Green bonds

Next, we introduce a public debt in the form of green bonds, that is, a flow of borrowed funds to be used exclusively to finance abatement costs[7]. We make three major assumptions. First, we assume that bonds should cover abatement costs fully. Partial coverage can be modeled similarly, but we prefer to avoid this technical complication in this paper. Second, we assume that funds are borrowed from external creditors—and hence they are not counted as a part of the households' wealth—but exhibit an exogenously given interest rate. We discuss how this may happen in reality in the Discussion section below. Third, we assume that green bonds are repaid via a specially introduced so-called "green" tax. In principle, the model allows for the collection of green tax at the same moment of time when the first green bonds are issued. The amount of green bonds, their issuing in excess of the tax revenue, as well as the period of their repayment are defined endogenously by the model.

Let $\tau(t) \in [0,1]$ be a time-dependent green tax "rate", that is, a share of the net GDP. The public debt dynamics become as follows

$$B(t+1) = (1 + r_{\mathrm{B}})^5 B(t) + 5\big(\Lambda(t) - \tau(t)\big)\Omega(t)Y(t) \tag{7}$$

where $B(t)$ is a stock of green bonds and r_{B} is a fixed constant green bond interest rate. Similar equations are used in [34,35]. To avoid a Ponzi scheme in the model, we require that at the end of the model's time horizon, all bonds are repaid so that the intertemporal budget constraint holds, that is,

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[6] A discussion of which values of the discount rate are appropriate to be used to generate long-term scenarios and their justification can be found in [17].

[7] Here, we rely on the definition of green bonds, given in [11].

$B(T) = 0$[8]. In addition, we assume the initial condition $B(1) = 0$, supposing that there is no debt at the beginning.

Mitigation and taxation can start already at the beginning of the simulation period. However, our simulations show that at the beginning, abatement costs are growing, and thus green bonds are accumulating; only after a while does taxation to repay the bonds actually take off. As abatement costs are paid via bonds and the green tax is levied on the net GDP, we rewrite equation (1) for the net output as follows:

$$Q(t) = [1 - \tau(t)]\Omega(t)Y(t) \tag{8}$$

This change affects the capital dynamics (4) via investment $I(t)$, which is a part of $Q(t)$, that is, $I(t) = Q(t) - C(t)$. With modifications defined by equations (7) and (8), we obtain the "extended DICE model".

The tax rate $\tau(t)$ is endogenous in our model and is defined through maximization of the social welfare function (9) over the entire time horizon, which leads to the emergence of bond issuing and bond repayment phases in the optimal dynamics.

3.3. The notion of Pareto improvement in the ILA framework

To define model scenarios, we involve the notion of a Pareto improvement. Recall that $U(t)$ is the instantaneous utility of households living at time t. We say that scenario i is a Pareto improvement of social welfare with respect to scenario j if $U^i(t) \geq U^j(t)$ for all $t = 1, 2, 3 \ldots$ and there exists a $t^* \geq 1$ such that $U^i(t^*) > U^j(t^*)$. Note that the similar concept of the Pareto welfare improvement in an ILA framework is used in [37].

3.4. Scenarios to be analyzed

Using our extension of the DICE model, we explore whether bonds can enhance mitigation actions, to what extent and when the GHG emissions can be abated, whether debt sustainability can be achieved, and how the introduction of bonds impacts the problem of short-term welfare losses. In order to do so, we compare optimal solutions in five scenarios.

The first two scenarios are defined using the original DICE model without any modifications; we call them "No mitigation" (NM) and "Optimal mitigation" (OM) scenarios. The NM scenario implies no mitigation effort, $\mu(t) \equiv 0$ for all time periods $t = 1, \ldots, T$; in this case, a social planner chooses a consumption path $C(t)$ to maximize the social welfare function (6). In the OM scenario (corresponding to the optimal scenario, see [20]), a social planner chooses both $C(t)$ and $\mu(t)$ to maximize the social welfare function (6).

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[8] We acknowledge that there is literature that proposes to define debt sustainability in a different way, see for example [36], where it is suggested that the debt level should converge to a certain share of the GDP. In this paper, we decided to avoid this complication.

Further, we introduce the "Optimal mitigation with bonds" (OMB) scenario, in which bonds are introduced in the DICE model and hence, in addition to $C(t)$ and $\mu(t)$, a social planner also chooses the green tax rate $\tau(t)$ to maximize the social welfare function (6).

As discussed above, the OM scenario redistributes consumption over time compared to the NM scenario: lower consumption levels (i.e., welfare losses) at present and in the near future enable financing abatement, which ensures higher consumption levels (i.e., welfare gains) in the more distant future due to avoided climate change losses. To address this intertemporal welfare allocation problem of the OM scenario, we are looking for a possibility to ensure a Pareto improvement of social welfare with respect to the NM scenario. Introducing green bonds may or may not lead to a Pareto improvement. To enable a Pareto improvement, we add an extra compensation mechanism to the model, which assures that at no time is household consumption reduced because of mitigation or because of non-optimal climate change. Namely, we denote the optimal consumption paths in the NM and OM scenarios by $C^{\mathrm{NM}}(t)$ and $C^{\mathrm{OM}}(t)$, respectively. We also introduce the "Pareto optimal mitigation" (POM) scenario, in which constraint $C(t) \geq C^{\mathrm{NM}}(t)$, $t = 1, \dots, T$ is added to the social welfare maximization problem. As stated above, the optimal path in such a model will, by definition, be a Pareto improvement of social welfare with respect to the NM scenario. Similarly, we construct the "Pareto optimal mitigation with bonds" (POMB) scenario by adding constraint $C(t) \geq \max\left(C^{\mathrm{NM}}(t), C^{\mathrm{OM}}(t)\right)$, $t = 1, \dots, T$, to provide a Pareto improvement with respect to both the NM and the OM scenarios. Note that adding such constraints in the DICE model poses the question whether such consumption, bonds, and tax paths that lead to the achievement of corresponding consumption levels exist, while bonds are fully repaid by the end of the simulation period (see Appendix F for some elaboration on this issue).

3.5. Calibration and simulations

Appendix A contains the full list of parameter values of the DICE model used in our simulations. Details on the sources for these parameter values can be found in [20]. We keep all parameter values from the original DICE model as in [20], except for the time horizon of the simulation. In this paper, we present the results for the time horizon $T = 70$ (350 years), which is 10 periods more than in the original DICE model because, in some scenarios, the atmospheric concentrations of CO_2 converge to the pre-industrial level only around this time. However, these results were computed using the extended horizon of $T = 100$ (500 years). By this, we wanted to make sure that the results are robust and not affected by the well-known effects of a finite time horizon, whereby at the end of the planning horizon it is optimal to consume the entire output (for a detailed analysis of such effects in DICE see [38] and in our model see Appendix D).

The bond equation (7) contains a new parameter, the annual bond's interest rate r_{B}, which is the only new parameter in the extended DICE model that was not defined in [20]. In the OMB scenario, we use the value $r_{\mathrm{B}} = 3\%$, which is equal to the interest rates of some long-term green bonds issued in the last decade [39,40]. It also yields an intelligible and visual distinction of phases of bond issuance and bond repayment that is convenient for the presentation of our results. Appendix E contains a sensitivity analysis of the results with respect to r_{B}, which reveals that the interest rate significantly influences the volume of issued bonds as well as the length of the repayment time.

In the POMB scenario, we use the value $r_{\mathrm{B}} = 2.2\%$, which is a numerically calculated maximum feasible interest rate for which the DICE maximization problem has an optimal solution under the additional constraint $C(t) \geq \max\left(C^{\mathrm{NM}}(t), C^{\mathrm{OM}}(t)\right), t = 1, \dots, T$ (see above). Further discussion on the calibration of bond interest rates with regard to the parameters of social welfare function (9) is relegated to Appendix F.

We run our simulations with the extended DICE model using the GAMS software. We take the original code [41] and amend it according to the introduced modifications[9] (see above). We use the CONOPT solver[10] to find an optimal solution for the model in each scenario.

4. Results

4.1. Intertemporal welfare allocation problem in DICE

We first run the NM and OM scenarios of the DICE model and demonstrate the intertemporal welfare allocation problem using the blue line in Figure 1. It represents the relative difference of the instantaneous utility (IU) in the OM scenario with regard to the one in the NM scenario: $100\% \cdot [U^{\mathrm{OM}}(t) - U^{\mathrm{NM}}(t)]/U^{\mathrm{NM}}(t)$. From the beginning of the simulation period until the year 2085, the blue line lies below zero, indicating that the IU in the OM scenario is smaller than the one in the NM scenario. From the year 2085, it lies above zero, which means that the IU in the OM scenario becomes greater than the one in the NM scenario. Note that as the utility function is defined up to a linear transformation [43], the magnitudes of the utility differences cannot be meaningfully interpreted.

The blue line in Figure 1 confirms that between now and 2085, some welfare losses would need to be accepted if an optimal mitigation policy were to be implemented compared to the case of no abatement. This is because the abatement costs are to be subtracted from consumption and the avoided climate change losses are still too small to outweigh the mitigation costs. Conversely, beyond the year 2085, mitigation yields welfare gains due to avoided climate change losses.

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[9] The code for all five scenarios is publicly available here [42].

[10] Since the resultant optimization problem is not concave, one cannot guarantee that the solution found numerically is globally optimal. We carried out several experiments with different initial values for the NLP solver as well as used different NLP solvers (IPOPT, CONOPT4) and always arrived at the same solution, which suggests that it should indeed be globally optimal. Furthermore, we refer to [17,20], where it is also claimed that other solutions (other than the optimal scenario, corresponding to our OM scenario) have not been found yet.

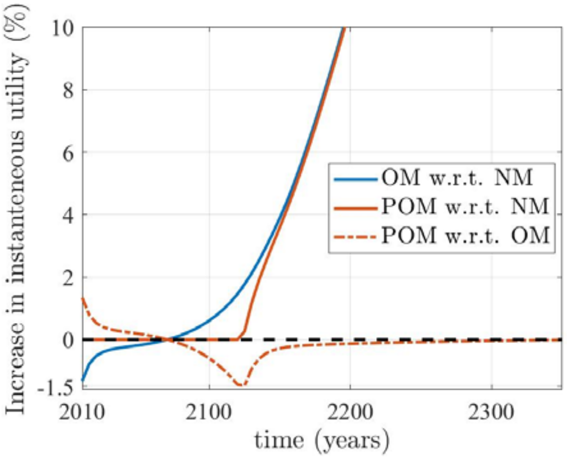

Figure 1. Percentage difference in the IUs with regard to the NM and OM scenarios.

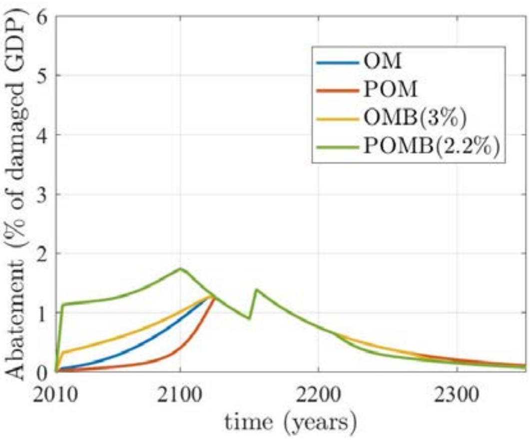

Figure 2. Abatement fraction of GDP net of damages (OM, POM, OMB, and POMB scenarios).

Next, we analyze the POM scenario that, by construction, eliminates the short-term welfare losses of the OM scenario. First, we look at the relative difference between the IU in the POM scenario with regard to the one in the NM scenario: $100\% \cdot [U^{\mathrm{POM}}(t) - U^{\mathrm{NM}}(t)]/U^{\mathrm{NM}}(t)$ (the orange solid line in Figure 1). By construction, until the year 2120, the consumption paths of the NM scenario and the POM scenario coincide; afterward, the consumption rate in the POM scenario becomes greater than the one in the NM scenario. Thus, the POM scenario indeed allows for a Pareto improvement of the NM scenario and also includes some abatement efforts. However, these abatement costs are lower than those in the OM scenario. The blue and orange lines in Figure 2 illustrate the abatement paths of the OM and POM scenarios, respectively. In order to have the NM consumption level at the beginning of the simulation period, one needs to sacrifice abatement efforts. This leads to a higher peak of the carbon stock in the atmosphere, as well as to higher damages to GDP compared to the OM scenario (see Figures 7 and 8 below for an illustration of this effect).

Now let us consider the relative difference between the IU in the POM scenario with regard to the one in the OM scenario: $100\% \cdot [U^{\mathrm{POM}}(t) - U^{\mathrm{OM}}(t)]/U^{\mathrm{OM}}(t)$ depicted by the orange dash-dot line in Figure 1. This line lies below zero from the year 2085 onward, which means that in the long term, lower welfare levels would need to be accepted if this scenario were to be implemented, compared to the case of the OM scenario. In section 4.4, we discuss a scenario with bonds that simultaneously ensures a Pareto improvement to both the NM and OM scenarios.

4.2. *Bonds to enhance mitigation efforts and to shorten the period of welfare losses*

In this section, we investigate the effects of the introduction of green bonds in the DICE model; namely, we report here the simulation results of the OMB scenario.

Despite both green bonds and green taxes being allowed throughout the entire simulation period, in the optimum, three distinct phases emerge endogenously: (I) bond issuance (2010–2115), (II) bond repayment (2120–2200), and (III) taxation for mitigation (2205 onward). Figure 3 illustrates these phases by showing the abatement and green tax rates as fractions of the net output.

In phase I, the green tax is zero and abatement is growing, reaching 1.2% of GDP by the year 2115. According to our assumptions, abatement is fully financed by bonds, and hence in phase I the public debt accumulates. Since the social planner optimizes the total welfare function over the entire simulation period, they anticipate repayment of bonds in the future and decrease consumption already in phase I compared to the one in the NM scenario. This releases additional funds for investment in capital accumulation, thanks to which the future output increases, which consequently allows for using more green bonds to finance a greater abatement effort at the beginning that can be repaid later due to higher output (see for comparison the blue and yellow lines in Figure 2). This preference to reduce consumption in phase I instead of phase II is due to a lower bond interest rate (3%) vis-à-vis a return on capital (about 5% at the beginning of the simulation period).

Phase II combines green tax, bond issuance, and bond repayment. The tax rate reaches 5% of the GDP. By the end of phase II, bonds are fully repaid. In phase III, mitigation is funded by the green tax only, and it is not optimal to use green bonds anymore. In Appendix C, we examine the robustness of this conclusion with respect to the choice of the damage function.

Now let us analyze the implications of the OMB scenario for the welfare allocation over time. The yellow solid line in Figure 4 depicts the relative difference of the IU in the OMB scenario with regard to the one in the NM scenario: $100\% \cdot [U^{\mathrm{OMB}}(t) - U^{\mathrm{NM}}(t)]/U^{\mathrm{NM}}(t)$. As in the OM scenario, in the OMB scenario, there exists an initial period of time—in this case, it is between now and the year 2055—during which a part of the household welfare would need to be sacrificed due to the redirection of a part of their consumption to investment in capital accumulation. In the subsequent period, household welfare becomes higher than in the NM scenario. Our simulations show that in the OMB scenario, green bonds shorten the period of welfare losses by 30 years compared with the OM scenario. This is achieved due to a fall in consumption between the years 2120 and 2200 in the OMB scenario in relation to the OM scenario (see also the dash-dot yellow line in Figure 4). This is the period when the bond repayment by taxation is enacted. Thus, we conclude that the OMB scenario is able to delay the welfare losses with regard to the OM scenario to a more distant future. However, bonds alone are not able to deliver a Pareto improvement of social welfare with regard to both the NM and OM scenarios[11].

Interestingly, an optimal solution in the OMB scenario exists only for low enough bond interest rates r_{B}, namely, for $r_{\mathrm{B}} \leq 5.1\%$, which is approximately the initial level of the interest rate on capital in the DICE model. Bond interest rates that are too high make green bonds too expensive to be used.

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[11] This statement holds true for any bond interest rate between 0% and 5.1% (the maximum feasible interest rate).

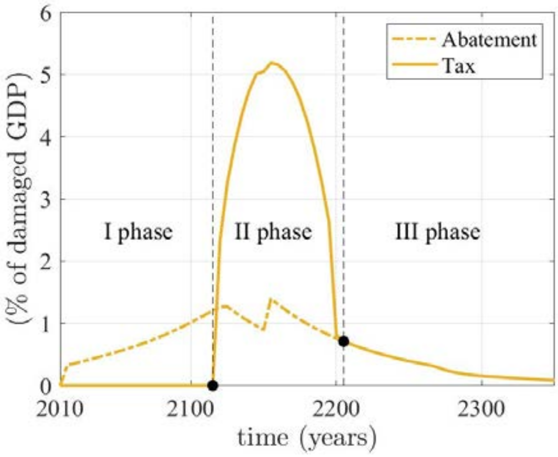

Figure 3. Abatement part and tax part of GDP net of damages (three phases, OMB scenario).

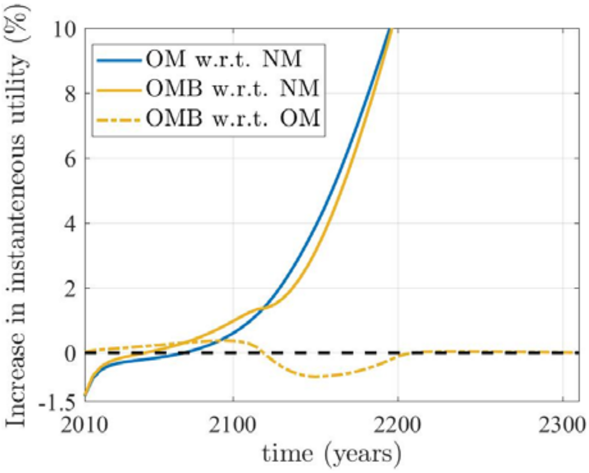

Figure 4. Percentage difference in IUs with regard to the NM and OM scenarios.

4.3. Pareto improvement to both scenarios is possible with greater mitigation efforts

Next, we address the question of whether a Pareto improvement of social welfare with regard to both the NM and OM scenarios is possible. Here again, the optimal solution in the POMB scenario exists only for low enough bond interest rates r_{B}. For the original DICE parameters, the maximum feasible interest rate is $r_{\mathrm{B}} = 2.2\%$, which is more than twice as low as in the case of the OMB scenario. It happens because of the need to support a level of consumption not lower than $\max\left(C^{\mathrm{NM}}(t), C^{\mathrm{OM}}(t)\right)$, $t = 1, \dots, T$ while repaying the bonds. Appendix F contains estimates of the maximum possible r_{B} to ensure a Pareto improvement of both the NM scenario and the OM scenario for different parameters of the social welfare function (9).

The green solid line in Figure 6 corresponds to the relative difference of the IU in the POMB scenario in relation to the one in the NM scenario: $100\% \cdot [U^{\mathrm{POMB}}(t) - U^{\mathrm{NM}}(t)]/U^{\mathrm{NM}}(t)$; the dash-dot line represents the relative difference of the IU in the POMB scenario with regard to the one in the OM scenario: $100\% \cdot [U^{\mathrm{POMB}}(t) - U^{\mathrm{OM}}(t)]/U^{\mathrm{OM}}(t)$. As we can see, the POMB scenario is indeed a Pareto improvement of social welfare to both the NM and OM scenarios. Figure 5 shows the abatement costs and the tax rate as shares of the GDP. One can again identify three phases here (as in Figure 3). This figure also illustrates that the source of the Pareto improvement of the POMB scenario with regard to both the NM and OM scenarios is the use of bonds and higher mitigation levels at the beginning of the simulation period (see also Figure 2 for comparison).

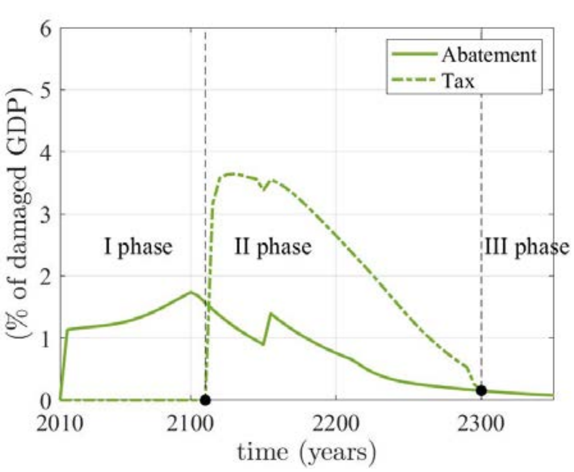

Figure 5. Abatement part and tax part of GDP net of damages (three phases, POMB scenario).

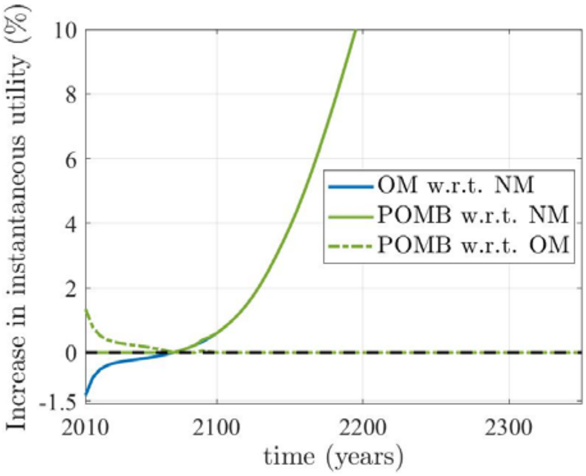

Figure 6. Percentage difference in IUs with regard to the NM and OM scenarios.

4.4. Mitigation success and climate change damages

In this section, we analyze the effects of the abatement policy in each considered scenario. We focus on two key interconnected indicators: carbon concentration in the atmosphere (Figure 7) and economic damages (Figure 8).

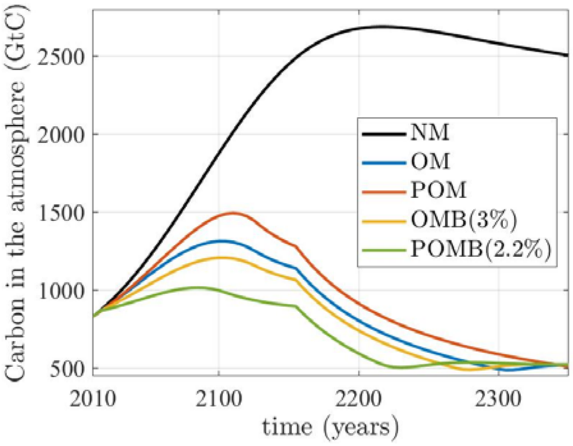

Figure 7. Atmospheric carbon concentration in GtC (all scenarios).

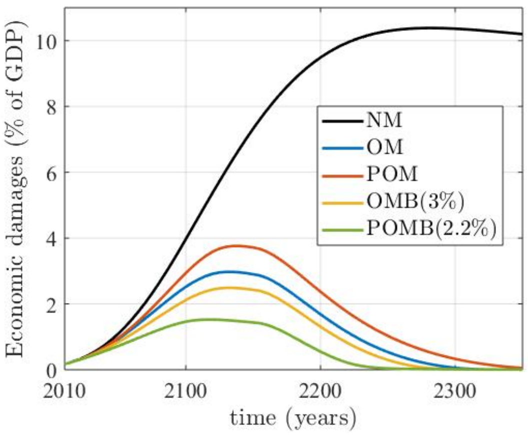

Figure 8. Percentage damages to GDP (all scenarios).

In the NM scenario, the carbon concentration in the atmosphere grows over time, from about 830 GtC in 2010 to reaching a peak of about 2700 GtC in 2215. It aggravates global warming so that economic damages from climate change reach as much as about 10% of GDP in 2280. Such significant negative economic impacts decrease industrial production, which leads to a slight decrease in GHG emissions and carbon concentration in the atmosphere from the year 2280 onward.

Clearly, this path is not sustainable. It eventually implies low social welfare levels and hence the social planner operating over a reasonably long time horizon has an incentive to mitigate GHG emissions. All mitigation scenarios analyzed in this paper, with or without bonds, converge to the equilibrium level of carbon concentration in the atmosphere (about 520 GtC) and zero climate change damages, but at different paces. Reaching the equilibrium level can take from around 200 to 350 years, depending on the scenario. Note that this transition emerges without any specially enforced terminal condition on the amount of carbon in the atmosphere; rather, it appears to be optimal in terms of social welfare to eliminate climate change and its negative effects.

The OMB and POMB scenarios (yellow and green lines in Figure 7, respectively) provide the fastest convergence, lowest peaks of carbon concentrations in the atmosphere, 20% and 33% reduction with regard to the OM scenario, respectively, and lowest maximal climate change damages relative to the GDP. Hence, bonds are an effective and efficient mechanism to finance mitigation. A lower bond interest rate in the POMB scenario ensures more extensive green bonds issued to finance abatement costs, which in turn leads to a lower peak of carbon concentrations in the atmosphere and a lower climate change damages fraction (see Figures 7 and 8, respectively). This effect is also investigated in Appendix E for the OMB scenario. The POM scenario is less effective in reducing GHG emissions than its original version, the OM scenario. This is because the increase in consumption to the levels of the NM scenario, forced at the beginning of the simulation period, leaves a smaller part of the GDP available for abatement, which leads to higher GHG emissions and a slower transition to a carbon-free economy. Nevertheless, the OMB and the POMB scenarios are superior to the OM and the POM scenarios in their effectiveness in terms of increasing climate change abatement efforts, as well as in terms of the reduction of welfare losses.

5. Discussion

The critical assumption behind our modeling exercise and its conclusion is that bonds enable borrowings from “external creditors” at exogenously defined, rather low, interest rates. A detailed elaboration on external creditors in evolving real economies is beyond the aim of this paper; however, in this section, we discuss one possibility. As some economists argue, a targeted and limited injection of credit used to finance new productive economic activities can be a viable option without running into the risk of inflation [44]; in particular, these economic activities could be those aimed at achieving a low-carbon economy with less future damages from climate change [45,46] as payoffs. In special circumstances, central banks can provide liquidity and credit flow, for example, in the form of quantitative easing (QE) to buy government or commercial bonds, as was applied in the US, UK, and EU to overcome the financial crisis of 2008–2009 [47]. This type of monetary policy was used by central banks, including the European Central Bank, in the aftermath of this crisis to bail out private sector banks and governments by purchasing their bonds from the bond markets [48], which led to a de-risking of the bonds through rising bond prices and falling bond yields. The unprecedented risks that climate change poses for society should call for unprecedented measures and, hence, similar arguments and suggestions have already been made by experts in the context of green bonds [49,50]. After the financial crisis of 2008–2009, however, the greatest fraction of bonds being purchased by the Central Bank were fossil fuel–related (brown) bonds and not green bonds. Yet, in principle, governments can issue more green bonds that the Central Bank could buy, generating the above-mentioned liquidity and credit flows with the de-risking effects (see [51]).

The current US Biden Administration seems to pursue a similar strategy of climate finance in its Inflation Reduction Act [52] of 2022. Here, both are planned: temporary borrowing from the capital markets by issuing bonds, as well as future tax-supported repayments of the bonds stretched out over a longer horizon. They do not penalize carbon emissions directly in the current period but rather pursue a debt- and bond-financed mitigation and adaptation policy through active support and subsidization of the energy transition. If this above operation through green bond financing is suggested, an issue frequently raised is whether the low-income countries experiencing intensely higher frequency and severity of weather extremes should be supported by bond issuing or by grants, with some experts arguing for a mixture of both [53]. One reason concerns the differences in the economic behavior to receive loans and grants [54]. As we demonstrated, credit flowing through bond issuance is consistent with the assumption of growth models, of which DICE is one, that is likely to stipulate efficient use of resources when bond issuing and repayment through taxation are properly mixed and staggered over time.

Note that in actual economic situations, the bond interest rate is affected by a risk premium. Our model does not contain an explicit representation of bond market-determined risk premia; instead, a fixed bond interest rate is given exogenously. These exogenous interest rates could be implemented if, for example, bonds are issued and managed by a dedicated international agency, for example, a multilateral organization such as the World Bank, that will set the interest rates based on the desired and feasible mitigation ambition. The international status and importance of this agency could help to reduce the default risk of its issued green bonds, thus such an agency could de-risk green bonds [9]. Another entity to issue green bonds could be, for example, the Green Climate Fund established under the Cancún Agreements in 2010, which is an important element of the Copenhagen and Paris agreements, mandated in particular to support projects for climate change mitigation and adaptation in developing countries—and countries affected by climate change—in the form of low-cost credit and also grants. This world's largest climate fund can issue its own green bonds, which has already been considered a viable solution to attract more financing sources and expand the fund's activities [55].

In terms of benchmarking, only one other study [56] investigated a socially optimal use of green bonds in an endogenous macroeconomic growth model with climate change. In that study, however, an additional assumption was made on when bond issuance and bond repayment can occur—namely, it assumed distinct sequential stages of predetermined durations for these two processes. Our study does not make such an assumption and instead derives these stages endogenously (see Section 4.2). We chose the same bond interest rate as in [56]—3%—and found that in both models (ours and the model from [56]), the debt accumulates over time to steer the GHG levels down to the pre-industrial value. The debt is repaid through taxation: in our model, the tax rate is derived endogenously and results in approximately the same level (during the repayment phase) as the exogenously selected tax rate in [56], about 5% (see Figure 3).

6. Conclusions

Politicians in many countries point out the lack of fiscal space to support sizable investments in climate change mitigation. For an economy with long-lasting negative externalities showing up in slowly rising yet accelerating trends of average temperature and related extreme weather events, disasters, and economic damages, mitigation is a corrective measure that can be financed by a carbon tax. Yet, climate change economists doubt if generated revenues from a carbon tax can be sufficiently large and if the decarbonization processes, which the introduction of a carbon tax is supposed to trigger, can be rapid enough to combat climate change and avoid massive adverse effects. In addition, the fossil fuel price is quite volatile, and the expected linkage between the carbon tax and the de-carbonization of the economy may be too weak; thus, the renewable energy supply should be enhanced by the support of finance through the issuing of green bonds. Many economists are of the opinion that some complementary measures, such as tighter regulations, directed technical changes to new energy systems, and large-scale climate investments are also necessary [57].

Along these lines, in this paper, we have explored an option of combining green bonds and taxes to scale up finances for a transition to a low-carbon economy. By naming bonds “green”, in this paper we indicate that the borrowed funds are exclusively used for financing the transition to a low-carbon economy. Green bonds might also take the form of long-term loans from banks since both represent current borrowing with the promise to pay back in the future when some returns are generated. We have evaluated the effects of green bonds in the DICE modeling framework, which is the most widely used calibrated climate-economy model comprising the entire causal loop between economic growth, GHG emissions, temperature increase, and corresponding global warming–related economic damages. We have shown that the maximization of social welfare leads to the emergence of three temporal phases: (1) mitigation scaled up by bond financing, (2) bond repayment via a green tax, and (3) further mitigation through a green tax. Our model demonstrates that green bonds issued through external finance can indeed enhance climate change mitigation and simultaneously intertemporally smooth out the mitigation burden. The interest rate on bonds strongly influences the optimal amount of issued bonds, with a lower interest rate significantly accelerating the transition to a low-carbon economy. However, in the socially optimal scenario, green bonds alone are not able to completely eliminate welfare losses arising from climate change mitigation. An additional compensation mechanism redistributing consumption over time would be needed to ensure the removal of such losses.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

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Conflict of Interest

All authors declare no conflicts of interest in this paper.

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