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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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A. DICE model full description

This part is written based on the GAMS code and [20,58]. Below, we list all equations of the DICE model used for generating the OM scenario[1]. Note that the conversion between parameter t in the DICE model and the corresponding year can be done via the following formula: year $= 2010 + 5(t-1)$.

Maximize$_{s(\cdot),\mu(\cdot)}$ $W = \sum_{t=1}^{T} R(t)U\big(c(t), L(t)\big)$
subject to
$K(t+1) = 5I(t) + (1-\delta)^5 K(t),$

[1] Note that no-mitigation scenario can be obtained if one puts $\mu(t) \equiv 0,\ 1 \le t \le T$.

$$\begin{bmatrix} M_{\mathrm{AT}}(t+1) \\ M_{\mathrm{UP}}(t+1) \\ M_{\mathrm{LO}}(t+1) \end{bmatrix} = 5 \begin{bmatrix} \xi_1 \\ 0 \\ 0 \end{bmatrix} E(t) + \begin{bmatrix} 1-\phi_{12} & \phi_{21} & 0 \\ \phi_{12} & 1-\phi_{21}-\phi_{23} & \phi_{32} \\ 0 & \phi_{23} & 1-\phi_{32} \end{bmatrix} \begin{bmatrix} M_{\mathrm{AT}}(t) \\ M_{\mathrm{UP}}(t) \\ M_{\mathrm{LO}}(t) \end{bmatrix}, \qquad \text{(A1)}$$

$$T_{\mathrm{AT}}(t+1) = T_{\mathrm{AT}}(t) + \zeta_1 \left\{ F(t+1) - \frac{\eta}{\zeta_2} T_{\mathrm{AT}}(t) - \zeta_3 [T_{\mathrm{AT}}(t) - T_{\mathrm{LO}}(t)] \right\}, \qquad \text{(A2)}$$

$$T_{\mathrm{LO}}(t+1) = T_{\mathrm{LO}}(t) + \zeta_4 [T_{\mathrm{AT}}(t) - T_{\mathrm{LO}}(t)], \qquad \text{(A3)}$$

$K(1) = K^1, M_{\mathrm{AT}}(1) = M_{\mathrm{AT}}^1, M_{\mathrm{UP}}(1) = M_{\mathrm{UP}}^1, M_{\mathrm{LO}}(1) = M_{\mathrm{LO}}^1, T_{\mathrm{AT}}(1) = T_{\mathrm{AT}}^1, T_{\mathrm{LO}}(1) = T_{\mathrm{LO}}^1,$

$0 \le \mu(t) \le 1, t = 2, \dots, t_\mu - 1,$

$0 \le \mu(t) \le 1.2, t = t_\mu, \dots,$

$\mu(1) = \mu^1.$

Here

$R(t) = (1+\rho)^{-5(t-1)},$

$U\big(c(t), L(t)\big) = L(t) \frac{c^{1-\alpha}(t)}{1-\alpha},$

$c(t) = 1000 \frac{C(t)}{L(t)},$

$Q(t) = \big(1 - \Lambda(t)\big)\Omega(t) Y(t) = C(t) + I(t),$

$$\Lambda(t) = \theta_1(t) \mu^{\theta_2}(t), \qquad \text{(A4)}$$

$\Omega(t) = \frac{1}{1+D(t)},$

$$D(t) = a T_{\mathrm{AT}}^2(t), \qquad \text{(A5)}$$

$Y(t) = A(t) K^{\gamma}(t) \left[\frac{L(t)}{1000}\right]^{1-\gamma},$

$E_{\mathrm{Ind}}(t) = \sigma(t)\big(1-\mu(t)\big) Y(t),$

$E(t) = E_{\mathrm{Ind}}(t) + E_{\mathrm{Land}}(t),$

$F(t) = \eta \log_2 \frac{M_{\mathrm{AT}}(t)}{M_{\mathrm{AT}}(1750)} + F_{\mathrm{EX}}(t),$

$\sigma(t+1) = \sigma(t) e^{-5 g_\sigma (1-d_\sigma)^{5(t-1)}}, \sigma(1) = \sigma^1,$

$E_{\mathrm{Land}}(t) = E_{\mathrm{Land}}^1 (1-d_E)^{t-1},$

$$F_{\mathrm{EX}}(t) = \begin{cases} F_{\mathrm{EX}}^1 + \frac{(F_{\mathrm{EX}}^2 - F_{\mathrm{EX}}^1)(t-1)}{t_F - 1}, & t = 1, \dots, t_F - 1, \\ F_{\mathrm{EX}}^2, & t = t_F, \dots; \end{cases}$$

$\theta_1(t) = \frac{\theta_1^1}{1000\, \theta_2} (1-d_\theta)^{t-1} \sigma(t),$

$L(t+1) = L(t) \left[\frac{L_{\max}}{L(t)}\right]^{g_L}, L(1) = L^1,$

$A(t+1) = \frac{A(t)}{1 - g_A \mathrm{e}^{-d_A \cdot 5(t-1)}}, A(1) = A^1.$

All parameters are listed in Table A1.

Table A1. Parameters of the DICE model.

Parameter	Value	Description (unit)
Initial values (2010)		
K^1	135	Initial capital value (trillions 2005 USD)
M_{AT}^1	830.4	Initial concentration in atmosphere (GtC)
M_{UP}^1	1527	Initial concentration in upper strata (GtC)
M_{LO}^1	10,010	Initial concentration in lower strata (GtC)
T_{AT}^1	0.8	Initial atmospheric temperature change from 1900 (^{o}C)
T_{LO}^1	0.0068	Initial lower stratum temperature change from 1900 (^{o}C)
A^1	3.8	Initial level of total factor productivity [(thousands 2005 USD/ millions of people)$^{1-\gamma}$]
L^1	6838	Initial world population (millions of people)
σ^1	0.5491	Initial carbon intensity (tons CO_2 per year/thousands 2005 USD)
μ^1	0.035	Initial emissions control rate
E_{Land}^1	3.3	Initial carbon emissions from land ($GtCO_2$ per year)
F_{EX}^1	0.25	Initial forcings of non-CO_2 GHG (W/m^2)
θ_1^1	344	Initial cost of backstop technology at 100% removal (2005 USD per ton of CO_2)
Preferences		
ρ	0.015	Rate of social time preference (1/year)
α	1.45	Elasticity of the marginal utility with regard to consumption
Population and technology		
δ	0.1	Depreciation rate on capital (1/year)
γ	0.3	Capital elasticity in production function
g_L	0.134	Exponent defining the population growth
$L_{\max}$	10500	Asymptotic population (millions of people)
g_A	0.079	Proportionality coefficient defining the total factor productivity (TFP) growth
d_A	0.006	Exponent defining the TFP growth deceleration (1/year)
Carbon cycle		
ξ_1	1/3.666	Conversion factor of emissions into concentrations ($GtC/GtCO_2$)
ϕ_{21}	0.03833	Rate of exchange of CO_2 from upper ocean to atmosphere per five years [fraction of $M_{\mathrm{UP}}(t)$]
ϕ_{12}	0.088	Rate of exchange of CO_2 from atmosphere to upper ocean per five years [fraction of $M_{\mathrm{AT}}(t)$]
ϕ_{32}	0.0003375	Rate of exchange of CO_2 from lower ocean to upper ocean per five years [fraction of $M_{\mathrm{LO}}(t)$]
ϕ_{23}	0.0025	Rate of exchange of CO_2 from upper ocean to lower ocean per five years (fraction of $M_{\mathrm{UP}}(t)$]
$M_{\mathrm{AT}}(1750)$	588	Pre-industrial level of carbon in the atmosphere (GtC)
Temperature and radiative forcings		
η	3.8	Forcings of equilibrium CO_2 doubling (W/m^2)
ζ_1	0.098	Diffusion parameter for atmospheric layer (m^2/W)
ζ_2	2.9	Equilibrium climate sensitivity (^{o}C of equilibrium CO_2 doubling)
ζ_3	0.088	Transfer coefficient from lower ocean to atmospheric layer (W/m^2/^{o}C)

ζ_4	0.025	Diffusion parameter for lower ocean layer
F_{EX}^2	0.7	2100 forcings of non-CO_2 GHG (W/m^2)
t_F	19	The time (year 2100) for which the estimation of forcings of non-CO_2 GHG is used
Emissions		
d_σ	0.001	Decline rate of decarbonization per year
g_σ	0.01	Initial decline of carbon intensity level per year
d_E	0.2	Decline rate of land emissions per five years
Other parameters		
a	0.00267	Fraction of damaged GDP with regard to 1 ^{o}C atmospheric temperature change from 1900 [1/(^{o}C)^2]
θ_2	2.8	Exponent of the control cost function
T	100	Time horizon[2] (periods)
d_θ	0.025	Initial decline of backstop cost per five years
t_μ	30	The time (year 2155) from which negative emissions are possible

B. Two alternative ways of representing climate change damage to the GDP in the DICE model

In the GAMS code of the original DICE model, the GDP net of climate change damages and abatement is written as follows:

$$Q(t) = [1 - \Lambda(t) - D(t)]Y(t). \qquad \text{(B1)}$$

Here, $\Lambda(t)$ and $D(t)$ are defined by formulas (A4) and (A5), respectively. This formula appears also in [58], where the authors replicated the DICE model in their own code developed in MATLAB.

On the other hand, in all previous versions of the DICE model (see, e.g., [15]) as well as in most of the papers devoted to the DICE model, the following formula is used for $Q(t)$ [sometimes with different values of parameters in $\Lambda(t)$ and $D(t)$]

$$Q(t) = [1 - \Lambda(t)]\frac{1}{1+D(t)}Y(t). \qquad \text{(B2)}$$

Formulas (B1) and (B2) are equivalent within the accuracy of the first-order Taylor series approximation in the neighborhood of zero damages and zero abatement effort:

$$1 - \Lambda(t) - D(t) \approx [1 - \Lambda(t)][1 - D(t)] \approx [1 - \Lambda(t)]\frac{1}{1+D(t)}.$$

We think that formula (B2) has a slightly clearer logic because it takes advantage of the subsequent order of climate change damages and abatement costs, which can only be subtracted from the remaining GDP after the damages. Thus, in our GAMS code, we use Eq. (B2) instead of (B1), which is also consistent with the majority of literature devoted to IAMs.

C. Sensitivity analysis with regard to the damage function

[2] In the original DICE code $T = 60$.

The functional form and parameters of the damage function are some of the biggest uncertainties in the literature on IAMs. In this section, we examine how the results obtained in this paper are dependent on the choice of the damage function. To shed some light on this question, we carried out simulations with three alternative damage functions:

- Original damage function from DICE2013R: $\Omega(t) = \frac{1}{1+0.00267\, T_{AT}^2(t)}$
- Damage function from DICE-2016R [59]: $\Omega(t) = \frac{1}{1+0.00236\, T_{AT}^2(t)}$
- Weitzman damage function [60]: $\Omega(t) = \frac{1}{1+\left[\frac{T_{AT}(t)}{20.46}\right]^2+\left[\frac{T_{AT}(t)}{6.081}\right]^{6.754}}$

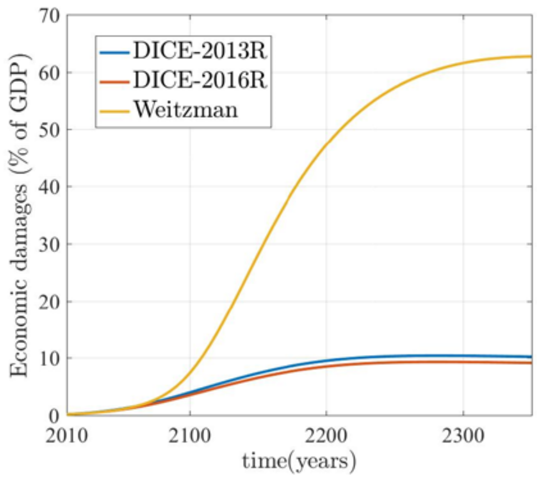

Figure C1. Climate change damages as fractions of the GDP (three alternative damage functions, the NM scenario).

Figure C1 shows climate change damages as fractions of the GDP in the NM scenario for these three damage functions. In the initial period of time (roughly before the year 2080), the differences are insignificant. Afterward, the Weitzman damage function delivers radically higher damages than the two DICE damage functions. The DICE-2016R damage function delivers values higher than the DICE-2013R by about 1%.

While the difference between the Weitzman damage function and the Nordhaus damage function(s) was thoroughly analyzed in [60], here we show that the results of our paper are qualitatively rather robust with respect to the choice of the damage function (between these three). Figures C2 and C3 show the abatement part of the GDP net of damages and the tax part of the GDP net of damages for the three considered damage functions. We observe that the structure of our mitigation policies does not depend on the damage function: The three phases—bonds issuance, bonds repayment, and taxation—emerge as a result of an optimal choice of the central planner, independently from the particular damage function. Expectedly, higher climate change damages lead to higher optimal abatement and taxation levels.

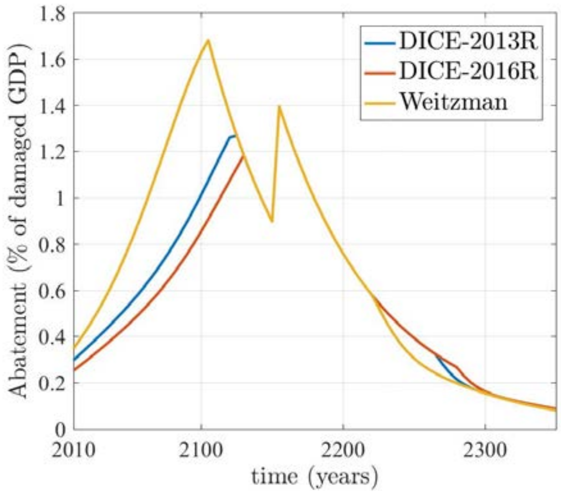

Figure C2. Abatement part of GDP net of damages (three damage functions, OMB scenario).

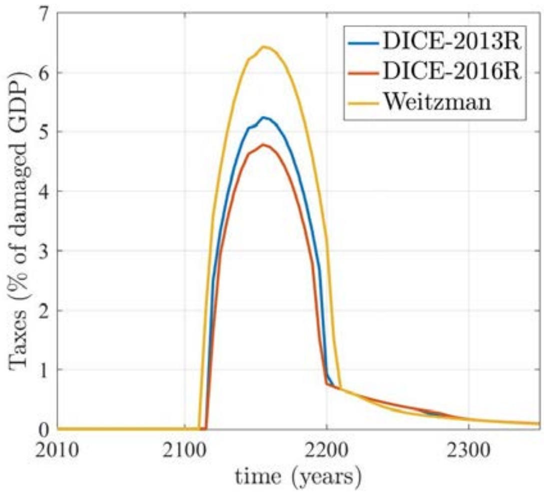

Figure C3. Tax part of GDP net of damages in per cents (three damage functions, OMB scenario).

D. Sensitivity analysis of the extended DICE model with bonds with respect to the length of the time horizon

To justify the extension of the time horizon from $T = 60$ to $T = 100$, we conduct a sensitivity analysis of optimal consumption and optimal tax rate paths with respect to the length of the time horizon T. It is well known that many macroeconomic dynamic optimization models exhibit the effect of "dying" at the end of the simulation horizon, which means that the entire output is consumed and no investments are made in the vicinity of the terminal time moment (this effect, in the DICE model, is mentioned e.g. in [38]). Importantly, it is typical in these models that over some sufficiently long time period starting from the initial time moment, the optimal solution is approximately the same for any sufficiently long time horizons. This is due to the fact that these models satisfy the optimality principle in the Bellman dynamic programming sense.

As the DICE model rests on the Ramsey-type economic growth modeling framework, we expect and indeed demonstrate these effects of a finite time horizon in this section. We use the OMB scenario for this purpose to show that even the introduction of green bonds does not change such behavior of the model. Figure D1 presents the OMB scenario–based consumption paths for time horizons from $T = 60$ (the initial value in DICE) to $T = 110$. One can see that all the paths approximately coincide (with very high accuracy for the first 50 periods—0.1% of consumption path for $T = 60$ and 0.17% of tax path for $T = 60$) over some initial and rather long time period, while moving away from the optimal "infinite-horizon path" to consume the whole output closer to the end of each simulation.

To demonstrate how different time horizons affect the newly introduced variables in our extended DICE model, we also present the paths of optimal tax rates in Figure D2. It is again clearly seen that they coincide everywhere except in short segments at the ends of each simulation period. Thus, the length of the time horizon does not affect our solutions once we cut off a segment at the end of the simulation period.

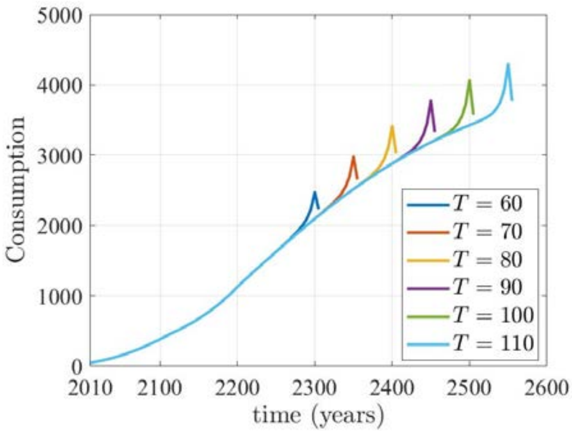

Figure D1. Consumption paths for different time horizons.

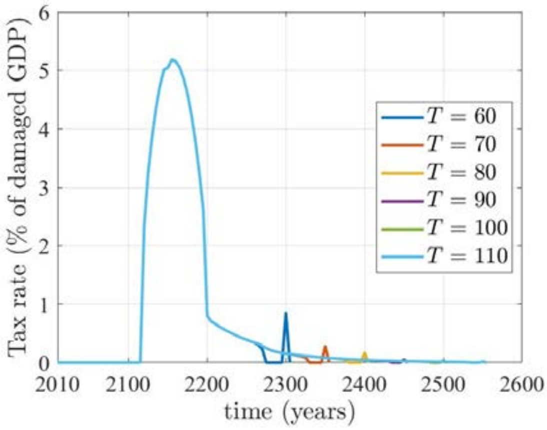

Figure D2. Tax part of GDP net of damages in percentage for different time horizons.

E. Sensitivity analysis of optimal green bonds issuance amounts and optimal tax rates with regard to the bond interest rates in the OMB scenario

In the results presented for the OMB scenario in the main text, the bond interest rate, defining the bond yields, was fixed at the constant level of 3% per annum. Here, we would like to study the effects of varying the bond interest rates, reflecting possibly different risk premia and other factors on our results.

Note that in the model in [30], the bond interest rate is equal to the return on capital, which is kept constant over time for the OLG model. In Ramsey-type models, including the DICE model, the capital return is dynamic and endogenous. Relying on the overview of interest rates and maturities of green bonds conducted by [56], we choose five alternative values of the interest rate on bonds: $r_B = 2.5\%, 3\%, 3.5\%, 4\%, 4.5\%$ and investigate the corresponding sensitivity of the OMB scenario.

Figure E1 presents the bonds-to-GDP (the GDP net of damages is used) ratio for the range of alternative interest rates. Lower interest rates on bonds naturally lead to higher maximal government debts and to longer durations of both phase I and phase II in which bonds are used to finance abatement. The interest rate of $r_{\mathrm{B}} = 4.5\%$ is indeed high: bonds are used in a very limited way, the maximal debt reaches only 3% of the net-of-damages GDP, and it takes only 35 years until they are repaid. Conversely, the interest rate of $r_{\mathrm{B}} = 2.5\%$ is rather low: bonds are used very intensely, the maximal debt goes up to as high as 400% of the net-of-damages GDP, and it takes 300 years until bonds are repaid.

Figure E2 illustrates the optimal green tax rates corresponding to the range of the considered values of the bond interest rate. The higher the interest rate is, the longer the duration of the taxation period: from 15 years in case of $r_{\mathrm{B}} = 4.5\%$ to about 150 years in case of $r_{\mathrm{B}} = 2.5\%$. Also, the lower the interest rate is, the greater the maximal level of taxation: from 1.4% of the net-of-damages GDP in case of $r_{\mathrm{B}} = 4.5\%$ to 10.6% of the net-of-damages GDP in case of $r_{\mathrm{B}} = 2.5\%$.

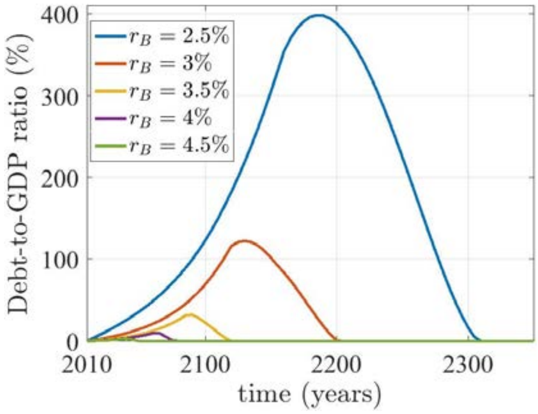

Figure E1. Bonds-to-GDP (net of damages) ratio (the OMB scenario).

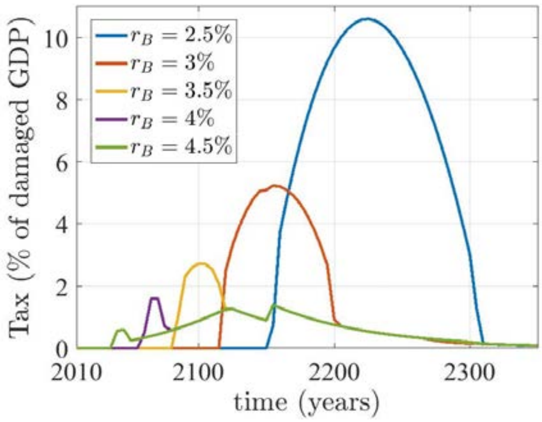

Figure E2. Green tax as a part of the GDP (net of damages) (the OMB scenario).

Also, lower interest rates on bonds lead to a more extensive use of bonds, which enables a faster convergence of carbon concentration in the atmosphere to the equilibrium level, a lower maximal amount of carbon in the atmosphere, smaller damages to the GDP, and, finally, higher overall social welfare.

F. Sensitivity analysis of maximum bond interest rate to ensure the existence of an optimal solution in the POMB scenario

Recall that the POMB scenario contains an additional mechanism of compensation for consumption losses with regard to both the NM scenario and the OM scenario:

$$C(t) \geq \max\left(C^{\mathrm{NM}}(t), C^{\mathrm{OM}}(t)\right), t = 1, \dots, T. \quad \text{(F1)}$$

Any optimal path $C(t)$ that satisfies constraint (G1) has a higher value of social welfare

$$W = \sum_{t=1}^{T} (1+\rho)^{-5(t-1)} L(t) \frac{[C(t)/L(t)]^{1-\alpha}}{1-\alpha} \quad \text{(F2)}$$

than the optimal welfare values for both the NM and OM scenarios due to the monotonicity property of W with regard to all $C(t)$, $t = 1, \dots, T$ values. Thus, such a level of consumption cannot be achieved without green bonds. The question arises as to whether it can be implemented in the scenario with green bonds.

We numerically tested different bond interest rates and found that constraints (F1) are not satisfied for some high interest rates, which means that in that case, bonds are too expensive to be repaid with given endogenous capital interest rates, and thus they are not broadly used to provide such consumption levels. Lower interest rates allow for a more extensive usage of green bonds leading to higher mitigation levels at the beginning, and thus greater output due to less damages from climate change, which may in turn allow for higher consumption levels, even with the need to repay the debt later. Hence, there exists a threshold between bond interest rates allowing for consumption levels (F1) and not allowing them. We calculated such thresholds numerically with a precision of 0.1% for different parameters of the social welfare function. Thus, these thresholds are the maximum bond interest rates allowing for consumption levels (F1) under which the Pareto improvement with regard to both NM and OM scenarios may be achieved. The results of our calculations are represented in Table F1.

Table F1. The maximum bond interest rate with regard to the rate of social time preference ρ and elasticity of the marginal utility with regard to consumption α. The values $\rho = 1.5\%$ and $\alpha = 1.45$ correspond to the original DICE calibration.

ρ \ α	1%	1.5%	2%	2.5%
0.5	NaN	1%	1.6%	2.2%
1	0.7%	1.6%	2.2%	2.9%
1.45	1.4%	2.2%	2.9%	3.6%
2	2.1%	2.9%	3.8%	4.6%
2.5	2.8%	3.8%	4.8%	5.8%

The social welfare function (F2) contains two key parameters: ρ, intertemporal social time preference, and α, the elasticity of the marginal utility with regard to consumption or the risk-aversion coefficient. The calibration of these values is an issue of extensive debate [61]. Here, we explore how the maximum bond interest rate changes depending on these parameters.

Let us first point out that both parameters affect the optimal solution in a qualitatively similar way but with a different magnitude. Namely, both higher ρ and α lead to a situation in which a social planner prefers a greater level of consumption at the beginning of the simulation period than in the middle and at the end, which then leads to lower abatement efforts. Therefore, as illustrated in Table F1, higher ρ and α lead to more freedom in the choice of bond interest rates because the mitigation is moderate. Lower ρ and α lead to a need for significantly greater abatement efforts, which need more extensive bond financing, which is then possible only with sufficiently low bond interest rates. Yet, even with very low values of ρ and α, a Pareto improvement with respect to both the NM scenario and the OM scenario cannot be achieved (corresponds to the "NaN" cell in Table F1).

G. Consumption per capita in all five scenarios

Here, we report numeric results of simulations, namely consumption per capita in thousands of USD per year for each of the five scenarios until the year 2300. Figures 1, 4, and 6 were done relying on this data.

Tabel G1. Consumption per capita in thousands of 2005 USD per year for each of the five scenarios analyzed.

Year	NM	OM	OMB (3%)	POM	POMB (2.2%)
2010	6.94	6.88	6.88	6.94	6.94
2015	7.82	7.77	7.78	7.82	7.82
2020	8.80	8.76	8.76	8.80	8.80
2025	9.88	9.83	9.84	9.88	9.88
2030	11.04	10.99	11.01	11.04	11.04
2035	12.30	12.25	12.28	12.30	12.30
2040	13.65	13.60	13.64	13.65	13.65
2045	15.10	15.04	15.09	15.10	15.10
2050	16.64	16.57	16.65	16.64	16.64
2055	18.26	18.20	18.30	18.26	18.26
2060	19.98	19.93	20.06	19.98	19.98
2065	21.78	21.75	21.91	21.78	21.78
2070	23.66	23.66	23.87	23.66	23.66
2075	25.62	25.67	25.93	25.62	25.67
2080	27.65	27.77	28.09	27.65	27.77
2085	29.73	29.97	30.34	29.73	30.14
2090	31.87	32.26	32.70	31.87	32.51
2095	34.04	34.64	35.14	34.04	34.82
2100	36.24	37.11	37.67	36.24	37.11
2105	38.44	39.68	40.26	38.44	39.68
2110	40.63	42.35	42.87	40.63	42.35
2115	42.78	45.12	45.44	42.78	45.12
2120	44.87	48.00	47.83	44.87	48.00
2125	46.88	51.00	50.31	47.46	51.00
2130	48.78	54.14	52.92	51.63	54.14
2135	50.54	57.39	55.67	55.52	57.39
2140	52.13	60.73	58.56	59.25	60.73
2145	53.54	64.17	61.60	62.91	64.17
2150	54.76	67.65	64.79	66.53	67.65
2155	55.76	71.20	68.15	70.16	71.20
2160	56.54	74.91	71.69	73.89	74.91
2165	57.12	78.75	75.41	77.74	78.75
2170	57.48	82.71	79.32	81.70	82.71
2175	57.66	86.77	83.44	85.75	86.77
2180	57.65	90.94	87.77	89.90	90.94
2185	57.49	95.19	92.32	94.13	95.19
2190	57.18	99.51	97.11	98.44	99.51
2195	56.75	103.91	102.15	102.82	103.91
2200	56.21	108.36	107.45	107.25	108.36
2205	55.58	112.86	112.51	111.74	112.86
2210	54.87	117.41	117.41	116.28	117.41
2215	54.10	121.98	122.21	120.85	121.98

2220	53.27	126.59	126.95	125.45	126.59
2225	52.40	131.22	131.66	130.07	131.22
2230	51.50	135.86	136.35	134.71	135.86
2235	50.57	140.51	141.03	139.37	140.51
2240	49.62	145.16	145.69	144.02	145.16
2245	48.65	149.80	150.34	148.68	149.80
2250	47.68	154.44	154.96	153.33	154.44
2255	46.70	159.06	159.58	157.97	159.06
2260	45.72	163.67	164.16	162.59	163.67
2265	44.74	168.25	168.73	167.20	168.25
2270	43.76	172.80	173.27	171.78	172.80
2275	42.79	177.32	177.79	176.33	177.32
2280	41.83	181.81	182.26	180.85	181.81
2285	40.87	186.26	186.68	185.34	186.26
2290	39.92	190.67	191.06	189.79	190.67
2295	38.99	195.04	195.38	194.20	195.04
2300	38.07	199.37	199.65	198.56	199.37