Armon Rezai

The Opportunity Cost of Climate Policy: A Question of Reference

Article (Submitted)

Original Citation:

Rezai, Armon

(2011)

The Opportunity Cost of Climate Policy: A Question of Reference.

Scandinavian Journal of Economics, 113 (4).

pp. 885-903. ISSN 0347-0520

The Opportunity Cost of Climate Policy: A Question of Reference*

Armon Rezai†

May 23, 2011

Abstract

The cost of climate policy depends on the no-policy alternative without which the *opportunity cost* of climate action cannot be determined. This reference path has to reflect the current failure in the market for carbon emissions: due to a negative externality, private investment decisions do not consider the climate damage they entail; agents overinvest in conventional capital and underinvest in climate capital. Internalization of climate damage lowers the private return to capital; agents reduce investment in favor of mitigation and consumption. Optimal climate mitigation increases welfare of the present and the future. Simulation of the inefficient no-policy scenario in DICE-07 confirms that this point numerically.

Keywords: Climate policy, intergenerational equity, sacrifice, externality, market failure, DICE-07

JEL classification numbers: C61, C70, D62, E24, H23, Q54

*Comments by G. Asheim, D. Foley, L. Karp, L. Taylor, and two anonymous referees greatly improved the paper. The usual disclaimer holds.

†Department of Socio-Economics, Vienna University of Economics and Business, email: arezai@wu.ac.at

1 Introduction

How costly is climate policy? In economic analysis, the question of "how costly" is commonly conceptualized in terms of the *opportunity cost*. In the context of climate change this cost is framed in terms of the resources present generations need to divert from consumption toward mitigation to the benefit of future generations—the sacrifice of climate policy. The discount factor looms large in this debate since it determines what weight is given to the distant benefits of mitigation relative to the sacrifice incurred today. In the (optimal) policy scenario a lower discount factor attaches greater weight to the benefits of mitigation relative to the costs and induces a shift to earlier and higher mitigation efforts.

The opportunity cost of a policy scenario, however, also crucially depends on the reference point. Virtually all researchers agree that the main economic cause of climate change is a market failure in the form of a negative externality. Stern (2007, p. 27) even regards it "[...] as market failure on the greatest scale the world has seen". Accounting for the greenhouse gas (GHG) market failure in the reference path creates the need to re-assess the conventional wisdom of a climate sacrifice. The presence of externalities renders competitive equilibrium allocations inefficient. Foley (2009) and Stern (2010) demonstrate that in the context of climate change this inefficiency induces agents to perceive the returns to productive assets larger than would be socially optimal. As private and social cost calculations diverge, agents overinvest in conventional capital and underinvest in climate capital (or mitigation). An internalization of the externality leads to a correction of price signals. The return to capital, now factoring in climate damage, falls. Agents reduce their investment in conventional capital in favor of increased mitigation and consumption. The opportunity cost might not be so large as initially thought or even be an "*opportunity benefit*".[1] More importantly, since the discount factor affects both scenarios in the same way, its level might not be so crucial after all.

This argument emphasizes the choice between conventional and mitigation investment over the one between consumption and mitigation. It is based on the assumption that investment and consumption decisions are taken endogenously and in response to price signals. Some of the most prominent integrated assessment models (IAMs), such as the PAGE model of the Stern Review (Hope, 2006) and the FUND model of Anthoff and Tol (2009), do not model investment and consumption behavior explicitly. The DICE-07 model of, most recently, Nordhaus (2008) does build on a Ramsey-Keynes framework, but still finds the presence of the sacrifice of climate policy. This is due to the usage of a theoretically inconsistent baseline case in which the externality is internalized but mitigation efforts are exogenously constrained

[1]This logic is widely understood by many economists: Nordhaus (2007) proposes a policy experiment which "... keeps consumption the same for the present but rearranges societal investments away from conventional capital (structure, equipment, education and the like) to investments in abatement of greenhouse gas emissions (in 'climate capital', so to speak)." He and many others, however, fail to acknowledge that this analysis springs from a path on which over-accumulation occurs due to the GHG externality.

to zero. Such an intertemporal allocation is efficient, since agents factor in the climate damage caused by their capital stock when making the investment choice. Each agent's awareness of her capital stock's contribution to the deleterious effects of the unmitigated emissions in combination with the absence of any mitigation instrument leads to lower returns to capital. Investment shares decrease, thereby eroding the base for a rearrangement of societal investment plans toward higher mitigation and consumption levels under optimal policy. The absence of the externality aspect in the no-policy scenarios of these models might also explain the emphasis on issues of intergenerational equity over those of market failure and imperfection in the discussion of the economics of climate change.[2]

The fact that there exists a market failure for GHG emissions has long been understood (for early acknowledgments see Nordhaus, 1977, 1994; Schelling, 1992; for more recent statements see Arrow, 2007; Dasgupta, 2008; Stern, 2007; Weitzman, 2007). Chichilnisky (1994) and Chichilnisky and Heal (1994) were among the first to correctly account for the public good nature of the atmosphere in their economic analysis. For some reason, however, these theoretical considerations have not influenced applied work. Shiell and Lyssenko (2008) recognize this shortcoming and outline a straightforward method of computing an approximate externality path in IAMs using the standard optimization software GAMS. Since their focus is on the asymp-

[2]Given that this paper deals with the importance of incorporating the externality aspect into the modeling of the no-policy reference path, I will focus on models which allow for endogenous investment decisions when referring to IAMs.

totic behavior of the reference path in previous versions of DICE, they fail to acknowledge the importance of the correctly specified reference path for the question of the opportunity cost of climate policy. Rezai et al. (2011) use a simple, small-scale IAM to demonstrate that the possibility of investment portfolio reallocation is plausible and of practical importance. The contribution of this paper is to demonstrate the absence of the sacrifice of climate policy in DICE-07, a popular IAM normally used to find the opposite.

To do so, I examine multiple candidate solutions for the no-policy path and conclude that given current modeling standards of rational expectations only the one in which agents misleadingly perceive a zero price of emissions is plausible. In section 3, I present the DICE-07 model and how to include such a form of market failure in it. Section 4 discusses the details of the computational implementation. In section 5, I use the externality baseline to show that the alleged sacrifice of climate policy is absent in DICE. Optimal climate policy increases the welfare of the present and the future.

It is important to emphasize that the finding that there is no intergenerational trade-off at the heart of the social choice problem of global warming mitigation does not render the debate on intergenerational equity redundant. Such considerations are crucial in identifying the optimal policy response to climate change. As illustrated in figure 1 below, the preferences for discounting and consumption-smoothing are the main determinants in selecting the welfare-maximizing OPT allocation. They pin down the exact levels of mitigation efforts, world temperature, and environmental damage along the optimal plan.[3]

A qualified caveat is in order: Since DICE-07 utilizes a deterministic, infinitely-lived agent framework, it cannot discuss the important issues of true generational conflict and of risk, uncertainty, and catastrophic climate change adequately.[4]

2 How to conceptualize the no-policy baseline?

The question of how to calculate the no-policy alternative is not trivial. In the following I discuss three candidate scenarios proposed by various authors and the subtle differences between them. A permissible baseline solution needs to feature two important aspects of the current real world: (i) agents are aware of climate change and adjust their decisions to it and (ii) agents have the mitigation instrument available but effectively choose not to use it.

2.1 Business-as-usual (BAU) baseline

Consider first an economy in which the emission of GHG poses a negative externality. The externality leads the representative agent to assume that her contribution to global warming is negligible and, as a consequence, that

[3] See Asheim (2010) for a review of the literature on axiomatic analyses of intergenerational equity.

[4] The interested reader is referred to Karp and Rezai (2011) and Weitzman (2007) and the references therein.

her investments do not contribute to the problem. In calculating the returns to those investments, she ignores the climate damage caused by them. She, therefore, values the returns to her conventional investments higher than they would be under an efficient allocation of resources and overinvests in conventional capital and underinvests in mitigation efforts. If the externality is large enough, she will in fact divert no resources to mitigation. The agent, however, correctly foresees the emissions time profile and the climate damage they entail and alters her decisions accordingly.

This scenario captures both aspects of the current state of affairs: Investors have the choice between conventional and climate-friendly investments, but they mostly opt for the former so that abatement is effectively zero. Yet, they are far-sighted enough to account for climate change in their decisions and would, for example, not happily build long-lived infrastructure like a coal-fired power plant on low-lying, undefended coastal land.

Climate policy corrects the price for emissions such that the agent realizes the effect of her investment decisions on the climate. This lowers the return to conventional capital and increases the return to mitigation. The agent rearranges investments toward climate capital as envisioned by Nordhaus in his policy experiment. Rezai et al. (2011) refer to the externality baseline as *business-as-usual* or BAU. Conceptually, it is a rational-expectations competitive equilibrium, but an inefficient one due to the market imperfection.

2.2 Constrained-optimal (COPT) baseline

In the second candidate solution the externality is internalized; the agent understands her contribution to the problem and would choose positive abatement levels, but she cannot due to the exogenous, binding zero-mitigation constraint. In the absence of mitigation, the agent recognizes that the only way to avoid the deleterious effects of climate change is to avoid carbon-emitting capital stock. This insight lowers the return to conventional capital and, in turn, investment.

The effect of climate policy in this scenario is to make available the mitigation instrument. Positive investment in mitigation averts the most severe aspects of climate change and increases the return to conventional capital. This induces the agent to also increase conventional investment. Consumption and welfare levels suffer under climate policy. The climate sacrifice emerges.

Investors in this scenario are not only far-sighted enough to account for climate change in their decisions, but they also understand that it is their investments that are causing the problem. They would choose climate-friendly investments over conventional ones, but they are not allowed to do so. Instead they abandon the most harmful investments. In the example given above, the investor not only correctly refrains from low-lying, undefended coastal land, but stops building coal-fired power plants altogether. This is baseline path of Nordhaus (2008).[5] It is not a permissible baseline solution

[5] Nordhaus (2008, p.65) defines his baseline as "[...] a world in which there are no

as defined above, because agents would choose positive mitigation levels if they were allowed to. Since this allocation is optimal due to the internalization of the externality but exogenously constrained, I will refer to it as the *constrained-optimal* (COPT) baseline.

Conceptionally, it is not obvious how the zero-mitigation constraint can be justified within the representative-agent rational-expectations methodology. Perfect price signals induce rational agents with perfect foresight to adopt an optimal allocation which includes positive mitigation efforts. The COPT scenario can only be maintained if one assumes an inconsistent combination of the information available to the representative agent: on the one hand, she correctly estimates the marginal social cost of emissions in making her consumption, investment, and production decisions. On the other hand, she seems to ignore the availability of mitigation technologies, despite this understanding of the marginal social cost of emissions. To arrive at a COPT scenario, the agent has to perceive the marginal social cost of emitting as zero (the only price that justifies no mitigation), while at the same time perceiving the true carbon price in her decision on how much output to consume and how much to re-invest. These two assumptions are clearly inconsistent with

controls for two and a half centuries. In this scenario, emissions are uncontrolled until 2250, after which a full set of controls is imposed."

each other.[6]

2.3 Difference between BAU and COPT

Figure 1 illustrates the difference between COPT and BAU in relation to the optimal policy scenario (OPT) in terms of the intertemporal production possibility frontier (PPF). In the optimal policy scenario agents have available both instruments, investment and abatement. In equilibrium they choose the welfare-maximizing bequest of conventional and climate capital.

Under the COPT reference path investment in climate capital is constrained to zero. While in equilibrium, agents still choose the welfare-maximizing bequest of conventional and climate capital, the absence of mitigation limits this possibility considerably. The COPT PPF lies further inside the OPT one as the weight put on the future increases.

If the GHG externality is not internalized, zero mitigation levels are chosen just like in COPT. The BAU competitive equilibrium is inefficient, so that the BAU PPF lies consistently inside to the COPT one. This is due to the divergence between social and private cost of carbon: If present generations want to shift consumption to the future, they forgo consumption to fund higher investment levels. Future generations, however, do not ben-

[6]The Kyoto Protocol can be seen as an argument for modeling the baseline with at least partial internalization of the externality. This reasoning, however, does not resolve the inconsistency at the heart of the COPT. Once a cap-and-trade scheme or tax system creates a positive price for emissions, agents will invest resources in mitigation. A baseline reflecting such an international agreement would be a combination of the optimal and BAU, not of the optimal and COPT.

efit from the bequest due to the high environmental damage caused by the investment-related emissions.

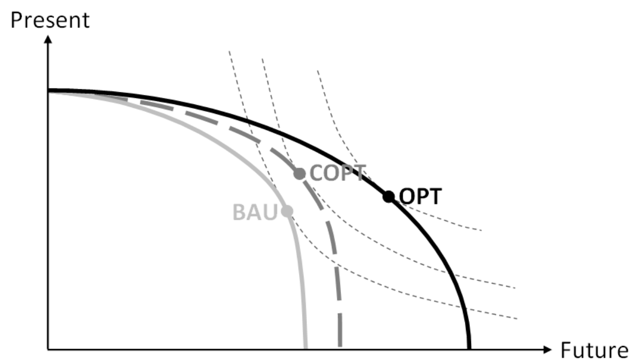

Figure 1: The production possibility frontiers in terms of present and future consumption of the optimal policy scenario (OPT) and two possible reference paths (COPT and BAU). Depending on the reference path, the adoption of optimal climate policy raises or lowers present consumption.

The debate on discounting and consumption smoothing enters figure 1 because these parameters pin down the (welfare-maximizing) competitive equilibrium allocation along the PPFs. The allocations chosen in figure 1 are representative for a wide range of parameters and reflect the numerical findings based on DICE below: the BAU allocation has the lowest consumption today and in the future due to the inefficiency. Both levels could be raised if the externality was internalized—the private cost of carbon increased to match the social cost—even in the absence of mitigation. Future generations would gain from higher levels of climate capital and lower levels of conventional capital, present generations could divert resources from investment to consumption to achieve such a portfolio reallocation. Given preferences for discounting and consumption smoothing, the COPT allocation distributes these efficiency gains by reducing investment and increasing consumption in the early decades of the program significantly.

The benefits of mitigation are large enough to induce a substitution away from consumption today toward consumption in the future. The welfare-maximizing OPT allocation yields lower consumption for the present than COPT. The alleged climate sacrifice emerges. The opportunity cost of mitigation is, however, a benefit if one chooses the BAU allocation as the reference path. The figure also illustrates that, relative to COPT, there exist allocations on the OPT schedule which do not require a sacrifice of the present while increasing future consumption. Such an allocation would, however, not be optimal, would entail higher environmental damages, and would require the issuance of government bonds along the lines of Bovenberg and Heijdra (1998) to be implementable.

2.4 Too-dumb baseline

Karp (2009) discusses a third candidate scenario. This assumes that agents ignore damages. The GAMS code accompanying DICE-07 states that Nordhaus partly uses this scenario as his baseline counter to the definition of Nordhaus (2008) cited in footnote 5.[7] While this scenario has the desirable

[7] In the 'How to Solve' sheet of the Excel version of the most recent DICE-09, Nordhaus states clearly "The "Base" sheet is the sheet with no climate policies. This is the model optimized for the savings rate. Note that the optimization is done with the damages equal to zero, and then damages are reinstated."Numerically, the scenario does not differ much from the COPT. The sacrifice argument still applies.

At close inspection of the GAMS code, this scenario becomes even more complicated. It consists of two optimization steps: first, welfare is maximized in the absence of damproperty that the representative agent treats climate change as a negative externality and is not willing to divert resources to mitigation despite its availability, it is deficient in another one: it is not a rational-expectations equilibrium, since agents systematically predict damages incorrectly and with it many relevant variables such as the return to capital.

In summary, given current modeling standards only the BAU reference path meets both conditions defined above. COPT does not fulfill condition (ii), the Too-dumb baseline fails at condition (i). Conceptionally, only BAU is consistent with the standard assumptions about expectation formation and the information set available to the agent.

3 Modeling the externality baseline in DICE-07

While Nordhaus (2008) lists the equations of DICE-07, specific assumptions about parameters and exogenous time profiles are only presented in the publicly available model's computer code. This section provides a compact guide for the GAMS-illiterate and presents the extension necessary for the intro-

age. The optimal mitigation control without damage is carried over to a second welfare maximization in which damages are present. Without further constraints, this would yield COPT since in the absence of damages the representative agent would always choose zero mitigation. There are, however, additional constraints covered in the code which yield the positive mitigation efforts reported by Nordhaus (2008): total carbon emissions have to be less than total available carbon in the form of oil (6000 Gt C), atmospheric temperature has to stay below 10°C, and the stock of carbon in the atmosphere has to stay below 4000 Gt C.

duction of the GHG externality along the lines of Shiell and Lyssenko (2008).

Conceptionally, the emissions externality is introduced to the economy by dividing it into N dynasties each endowed with $1/N$th of the aggregate capital stock and population and each with its representative agent solving the optimization problem set out below.[8] The climate dynamics are governed by the aggregate emissions of all dynasties. The externality enters through the assumption that each dynasty's representative agent takes the other dynasties' decision as exogenous but is affected by the damage inflicted by aggregate emissions. All agents play a dynamic non-cooperative game which leads to a Nash equilibrium in which each agent forecasts the path of emissions correctly and all agents take the same decisions. The difference between such an equilibrium allocation and an efficient allocation in which the externality is internalized is the fact that the agent only adjusts her controls to take account for the self-inflicted damages (i.e. $1/N$th of the GHG externality). With the exception of the climate interactions, there is no exchange between dynasties. With $N = 1$ one obtains the original DICE-07 social planner maximization problem, the solution of which is the OPT allocation.

Turning to DICE, it is a Ramsey-Keynes model extended to include carbon and temperature dynamics. A representative agent solves the intertem-

[8] Shiell and Lyssenko (2008) present the details of this approximate method. Since they focus on the asymptotic behavior of the policy paths, their discussion does not bring out the critical role of the externality reference path in assessing the opportunity costs of climate policy.

poral allocation problem in order to maximize the sum of total discounted utility. She has the choice of dividing output between consumption, conventional investment, and mitigation. Climate change enters the model through a damage function of temperature which decreases available output. Besides the choice variable of investment, the representative agent has the second choice of abating a certain share of current emissions, thus reducing the overall amount of GHG in the atmosphere. This second choice variable is called the control rate, $\mu(t)$, and represents the share of current emissions avoided through mitigation. GHG emissions feed into a carbon cycle which drives a temperature cycle. Higher emissions lead to a higher global temperature. The flow chart in figure 2 provides an overview of DICE. Stock variables are bold and choice variables in italics. Exogenous (shifting) factors such as population, productivity, and carbon intensity are colored gray.

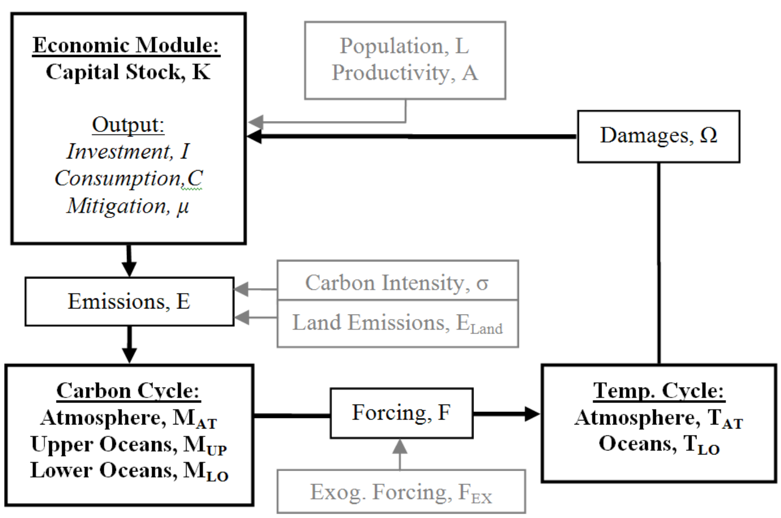

Figure 2: Flowchart of DICE, its Stock Variables (bold) and Control Variables (italics), and the exogenously shifting factors (gray)

Timing in the model is a decadal time period with most of the economic processes occurring as a yearly flow (at yearly parameter values). These flows have to be compounded to fit the overall decadal time structure. Nordhaus (2008) solves for 60 periods. Let $L(t)$ be the exogenously given world population path, ρ the yearly discounting factor, and $U[c(t)]$ per capita utility from per capita consumption, $c(t)$. Then the intertemporal decision problem is to

$$\max \sum_{t=0}^{T} \left(\frac{1}{(1+\rho)^{10t}} 10 \frac{L(t)}{N} U[c(t)] \right) \tag{1}$$

Utility is of iso-elastic form: $U[c(t)] = \frac{c(t)^{1-\eta}}{1-\eta}$. Nordhaus (2008) assumes $\eta = 2$ and $\rho = 0.015$.

Besides the climate dynamics, which are discussed below, the maximization problem is subject to the capital state equation. Let $I(t)$ be yearly investment and $\delta_K = 0.1$ yearly depreciation,

$$K(t+1) = 10I(t) + (1-\delta_K)^{10} K(t) \tag{2}$$

Potential output equals $Y(t) = A(t)K(t)^{\gamma}L(t)^{1-\gamma}$ (with $\gamma = 0.3$). Note that this is the output available to each dynasty. Given the CRS of the Cobb-Douglas technology, aggregate output $Y_{Agg}(t) = N\,Y(t)$ in equilibrium. With $\Omega\left[T_{\mathrm{AT}(t)}(t)\right]$ the concave damage function in atmospheric temperature $T_{\mathrm{AT}}(t)$ giving the share of output still usable after damages, $C(t)$ total consumption and $\Lambda[\mu(t)]$ the cost for the abatement of the control rate $\mu(t)$ (i.e. μ percent of emissions in period t) as a share of output, the output constraint for each dynasty's maximization reads

$$\Omega\left[T_{\mathrm{AT}}(t)\right]Y(t) = I(t) + C(t) + \Lambda[\mu(t)]\Omega\left[T_{\mathrm{AT}}(t)\right]Y(t). \tag{3}$$

Initial capital stock is assumed to be $K(0) = \frac{137}{N}$ trillion 2005 \$ (\$T) and initial output calibrated to $Y(0) = \frac{61.1}{N}$\$T per dynasty.

$\Omega\left[T_{\mathrm{AT}}(t)\right]$ gives the share of output still usable after climate damages due to atmospheric temperature $T_{\mathrm{AT}}(t)$. Conversely, damages due to climate change are $1 - \Omega\left[T_{\mathrm{AT}}(t)\right]$. Nordhaus assumes an inverse quadratic damage function $\Omega\left[T_{\mathrm{AT}}(t)\right] = \frac{1}{1+\psi_1 T_{\mathrm{AT}}(t)+\psi_2 T_{\mathrm{AT}}(t)^{\psi_3}}$ with $\psi_1 = 0$, $\psi_2 = 0.00028388$, and $\psi_3 = 2$.[9] Note that with this functional form $\Omega\left[T_{\mathrm{AT}}\right] \to 1$ only as $T_{\mathrm{AT}} \to \infty$.[10]

Net industrial emissions, E_{Ind}, are the non-abated share of potential output multiplied by carbon intensity of production $\sigma(t)$: $E_{\mathrm{Ind}}(t) = 10(1 - \mu)\sigma(t)Y(t)$. Carbon intensity is measured as GtC per \$ trillion output and is assumed to decrease over time. It is calibrated at 0.13418 GtC/\$T to match 2005 data and falls at a decreasing rate over time, starting at -6.6% per decade today.[11] Total emissions are the sum of industrial and land deforestation emissions. Deforestation emissions start at 11 GtC today and are

[9] According to the fourth assessment report of the Intergovernmental Panel on Climate Change (IPCC, 2007), a temperature increase of 4°C would lead to world output losses of between 1% and 5%. $\Omega\left[T_{\mathrm{AT}}(t)\right]$ is calibrated to fit this finding. Temperature has increased by 0.73°C over the last century. Given $\Omega\left[T_{\mathrm{AT}}(t)\right]$, this corresponds with a current loss of 0.15% of output.

[10] Damages in DICE are 22% of output at a 10°C, 50% at a 20°C increase and 80% at a 40°C increase.

[11] It will have halved in 124 years and will be 15% of its current value in 60 decades. $\sigma(t) = 0.0137036e^{-t}(0.0708425 + e^{0.03t})^{\frac{1}{0.03}}$.

assumed to decrease by 10% each decade. The introduction of the pollution externality extends the emissions equation by the emissions regarded as exogenous by each dynasty

$$E(t) = E_{\text{Ind}}(t) + E_{\text{Land}}(t) + E_{\text{Exg}}(t). \tag{4}$$

In a Nash equilibrium all dynasties take the same action and $E_{\text{Exg}}(t) = (N-1)E_{\text{Ind}}(t)$. With $N = 1$, the externality is fully internalized.

In DICE-07 carbon dynamics are modeled via three reservoirs to which carbon emissions diffuse in a Markov process. First GHG are emitted into the lower atmosphere. From there, they transition according to equations (5). Total carbon (in GtC) in the lower atmosphere is $M_{\text{AT}}(t)$, in the upper oceans $M_{\text{UP}}(t)$, in the lower oceans $M_{\text{LO}}(t)$. With the specific 3×3 transition matrix, the transition equations are

$$\begin{pmatrix} M_{\text{AT}}(t) \\ M_{\text{UP}}(t) \\ M_{\text{LO}}(t) \end{pmatrix} = E(t) \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix} + \begin{pmatrix} 0.81 & 0.10 & 0 \\ 0.19 & 0.85 & 0.003 \\ 0 & 0.05 & 0.997 \end{pmatrix} \begin{pmatrix} M_{\text{AT}}(t-1) \\ M_{\text{UP}}(t-1) \\ M_{\text{LO}}(t-1) \end{pmatrix}. \tag{5}$$

Initial conditions for the carbon stocks are calibrated to match 2005 data: $M_{\text{AT}}(0) = 808.9$, $M_{\text{UP}}(0) = 1255$, and $M_{\text{LO}}(0) = 18365$. There is no limit to the capacity of either reservoir and once carbon has been emitted, it stays in the cycle.[12] This implies that in the reference scenario carbon dynamics cannot converge to a stationary state unless zero output avoids emissions.[13]

Atmospheric carbon drives atmospheric temperature through radiative forcing. The IPCC (2007) predicts that a doubling of the atmospheric carbon concentration compared to pre-industrial levels ($M_{\mathrm{AT}1750} = 596.4$ Gt C) leads to an increase in temperature of 3°C. The forcing term is calibrated to reflect this finding (through the base 2 logarithm and $\eta_2 = 3$) and also includes exogenously given forcing from non-carbon greenhouse gases $F_{\mathrm{EX}}(t)$.[14]

$$F(t) = \eta_2 \mathrm{Log}_2 \left[\frac{M_{\mathrm{AT}}(t)}{M_{\mathrm{AT}1750}} \right] + F_{\mathrm{EX}}(t) \tag{6}$$

DICE-07 also includes a cycle for global atmospheric temperature, $T_{\mathrm{AT}}(t)$, and oceanic temperature, $T_{\mathrm{LO}}(t)$. Energy moves between the two media as to equilibrate the two. Radiative forcing increases atmospheric temperature linearly:

$$\begin{pmatrix} T_{\mathrm{AT}}(t) \\ T_{\mathrm{LO}}(t) \end{pmatrix} = \begin{pmatrix} .65 & .066 \\ .05 & .95 \end{pmatrix} \begin{pmatrix} T_{\mathrm{AT}}(t-1) \\ T_{\mathrm{LO}}(t-1) \end{pmatrix} + F(t) \begin{pmatrix} .22 \\ 0 \end{pmatrix} \tag{7}$$

[12] I.e. there is no decay and in equilibrium 0.03% of total emissions will remain in the atmosphere; 91.5% will sink into the lower oceans.

[13] This is the reason why Shiell and Lyssenko (2008, p.1558) find that DICE-99 which first introduced this reservoir specification does "not yield a "realistic" long-run solution under BAU" and limit their analysis of steady states to the older model version of Nordhaus (1994).

[14] $F_{\mathrm{EX}}(t) = \mathrm{Min}[0.036t - 0.06, 0.36]$.

Using temperature to determine environmental damage to output closes the model. The last thing to specify are the exogenous paths of population and productivity. Nordhaus (2008) follows the UN population projections which predict that world population will rise from currently 6500 to 8600 million over the next 10 to 20 decades and then stabilize at this level.[15] Total Factor Productivity is also assumed to flatten out; however, only in 600 decades at around 15500 times its current value.[16]

Under *business-as-usual*, agents adjust their controls to take into account the implications of $1/N$th of emissions and thus choose positive values of $\mu(t)$. As N increases, $\mu(t)$ tends to zero. Only as $N \to \infty$ will agents perceive the marginal social cost of emitting as zero and, therefore, choose zero mitigation efforts. This is why the method of Shiell and Lyssenko (2008) can only be considered approximate. In the numerical simulations below, N is set such that $\mu(t) < 10^{-6}$. Under COPT mitigation is exogenously constrained to zero. Abatement, however, remains important for the optimal policy scenario and for this reason the mitigation technology of DICE-07 is included in this exposition: the control variable $\mu(t)$ gives the share of emissions abated. The iso-elastic abatement cost function $\Lambda[\mu(t), t]$ maps this share into the share of output necessary to do so:

[15] Population growth starts at 10% per decade and falls below 1% per decade within 6 decades. $L(t) = 8600 - 2086e^{-0.35t}$.

[16] Productivity growth is assumed to start at 10% per decade and slowly decrease to roughly 5% in 60 decades' time. $A(t) = 422.964e^{-t}(-0.092 + e^{0.01t})^{\frac{1}{0.01}}$.

$$\Lambda[\mu(t), t] = \Psi\theta_1(t)\mu(t)^{\theta_2} \tag{8}$$

where Ψ is a participation cost markup with $\Psi = 1$ under complete participation. Abatement cost is assumed to increase as participation of countries around the world decreases. The elasticity $\theta_2 = 2.8$. $\theta_1(t)$ is a scaling factor derived from assumptions about a back-stop technology which is supposed to decrease in cost over time.[17] The assumption of decreases in mitigation costs in addition to the falling trend of carbon intensity introduces a tendency toward delaying mitigating efforts (Rezai, 2010).

As outlined above, I solve this model for three scenarios:

- OPT: The efficient allocation in which the externality is internalized ($N = 1$). Agents perceive perfect price signals and mitigation efforts are chosen optimally.

- COPT: The inconsistent, efficient reference path on which the externality is internalized ($N = 1$). Agents perceive perfect price signals and would choose optimal, positive mitigation efforts, but these are exogenously constrained to zero.

- BAU: The consistent, inefficient reference path on which the externality is not internalized. Agents perceive their emissions as negligible to the climate problem. Mitigation efforts are chosen optimally by the

[17]This time profile of $\theta_1(t)$ is such that abatement of all emissions ($\mu = 1$) costs 5.6% of GDP today, 0.9% in 30 decades, and 0.4% in 60 decades. $\theta_1(t)= 0.209(1 + e^{-0.05t})\sigma(t)$.

dynasties' representative agent given this imperfect information set. N is chosen large such that $\mu(t) = 0$.

4 Computational Implementation

All three scenarios are solved on a personal computer using the program GAMS in combination with the optimization solver CONOPT3. The OPT and COPT specification fit the program structure of GAMS readily. To implement the BAU in the nonlinear-programming framework, I follow Nordhaus and Yang (1996) and Shiell and Lyssenko (2008) in adopting an iterative approach. This starts by setting the time path of emissions exogenous to the dynasty's optimization, $E_{\text{Exg}}(t)$, at an arbitrary (but informed) level. GAMS solves for the representative dynasty's welfare-maximizing investment and mitigation choices conditional on this level of exogenous emissions. $(N-1)$ times the dynasty's emission trajectory implied by these choices defines the time profile of exogenous emissions in the next iteration step. The routine is carried out and $E_{\text{Exg}}(t)$ updated until the difference in the time profiles between iterations meets a certain criterion. In the solution reported below, the iteration stops if the sum of absolute percentage differences is less than 10^{-10}. After some tinkering with initial search parameters, the solution converged to the Nash equilibrium within a few seconds and 10 iterations.

In the BAU scenario, $N = 10^6$ to ensure that $\mu(t) < 10^{-6}$ in each time period. This implies that 99.9999% of aggregate emissions are external to the dynasties' decisions. The cost of carbon is so high that having only 99.99% of aggregate emissions external (with $N = 10^4$) would lead to mitigation efforts of up to 10% of individual emissions although these only constitute 0.01% of the aggregate. Shiell and Lyssenko (2008) set $N = 300$. The high cost of carbon and their comparatively low choice of N might explain why they found little difference between the OPT and BAU steady state in DICE-94.

5 Implications for Intergenerational Equity

The implementation of the BAU reference path into DICE reveals two important aspects: first, the incorrect choice of the COPT baseline causes a misrepresentation of the social choice problem of mitigating climate change. Allowing the representative agent to take into account the impact of production and investment on emissions lowers the return to capital and induces a shift to higher consumption and lower investment in the early decades of the program in the absence of mitigation. This boost to consumption forms the basis for the climate sacrifice. Second, if one introduces the GHG externality, this shift and the sacrifice do not occur. The externality leads to imperfect price signals in the form of inflated interest rates and an inefficiency through over-investment in conventional capital and under-investment in climate capital. The adoption of optimal climate policy achieves efficiency gains through aligning the private cost of carbon with the social one and a rearrangement of societal investments without lowering consumption; all generations can be

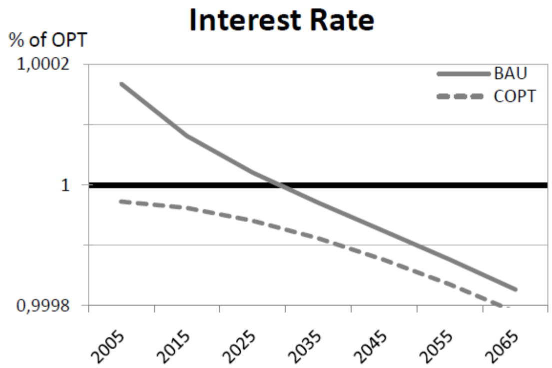

Figure 3: Interest rate relative to OPT: The absence of the mitigation instrument, lowers the return to capital stock (COPT). Under the externality climate damage is omitted in the calculation of the return to capital. The interest rate is inflated (BAU).

made better off. The theoretical considerations of Foley (2009) and Stern (2010) and the numerical results of Rezai et al. (2011) extend to DICE-07.

In general, DICE equilibrium paths follow very similar trajectories in early periods of the program. Differences in consumption levels are very small. Rezai (2010) shows that this is due to the fact that there are strong trends in parameter time profiles, multiple lags in the carbon/temperature cycles such that impacts of emissions take effect over time, and a soft damage function at moderate and high levels of atmospheric temperature. By plotting variables relative to OPT, however, one can uncover the described features of COPT and BAU in DICE-07.

Figures 3 plots the trajectories of the interest rate. The interest rate plays a central role in the allocation of resources in optimal growth frameworks. As explained in section 2, under BAU the interest rate is higher than under OPT.

The adoption of optimal climate policy lowers the private return to capital. The agent diverts resources to mitigation and consumption. In contrast, under COPT the interest rate is below its OPT level. Under optimal climate policy, consumption levels are lowered to finance mitigation and additional investment expenditure.

The effects of the interest rate on investment and consumption are shown in figure 4 and 5. Under BAU, agents choose to invest more and consume less than under OPT. However, as environmental damage increases, capital accumulation and consumption eventually fall. Welfare under BAU could be increased by tilting the investment portfolio toward less carbon-emitting and more climate capital. This is the externality-induced inefficiency of the BAU path. Under COPT, agents are aware of the deleterious effects of their investment decision and behave cooperatively. They choose to invest less and consume more than under OPT. Capital stock lies consistently below its OPT level which enables higher consumption in the early periods of the program. The adoption of an optimal mitigation response would lead to a welfare loss in the first three periods.

Due to mitigation expenditure, per capita consumption under OPT is slightly lower in two periods than under BAU. In terms of lifetime welfare, however, OPT dominates BAU. To draw welfare conclusions for distinct generations from the results of the infinitely-lived agent model, I assume that each agent lives 70 years and has optimal bequest motives. For agents alive today, i.e. the decade of 2005, figure 6 reports the remaining lifetime welfare

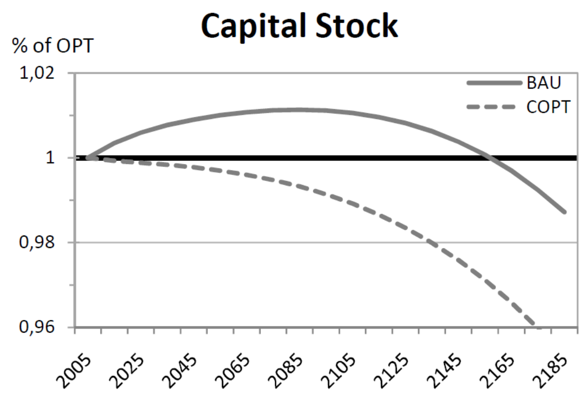

Figure 4: Capital Stock relative to OPT: In the absence of the mitigation instrument, lower levels of capital stock are efficient (COPT). The externality leads to over-accumulation (BAU).

under the different (no-)policy scenarios.

Figure 6 demonstrates once more that the adoption of an optimal policy response to climate change mitigation has very different welfare effects depending on the choice of the reference path. Under the inconsistent COPT, most cohorts alive today lose from positive mitigation efforts. Only generations born after 1985 can gain from it. Were the policy action put to a vote with a majority rule, it would be rejected. Using BAU as the reference path changes the picture of the social choice problem of mitigation completely. All generations alive today and in the future experience a welfare gain from the correction of the market failure through the implementation of institutions which enforce cost transparency. In short, using the correct reference path implies that there is no opportunity cost to mitigating climate change and that the adoption of an optimal policy response represents a Pareto improvement.

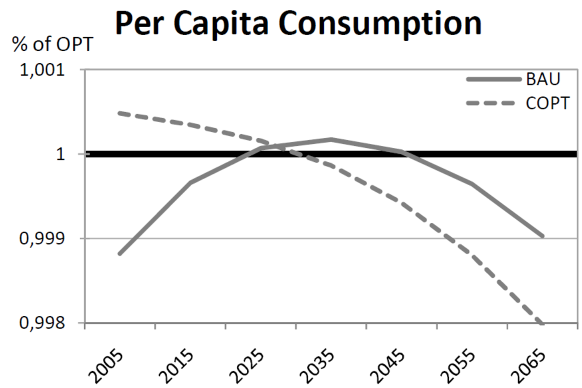

Figure 5: Per Capita Consumption relative to OPT: The COPT no-policy baseline yields higher consumption levels in the first decades. An adoption of optimal policy forces these cohorts to make a sacrifice. The externality BAU baseline does not entail a reduction in consumption.

Much of the debate on intergenerational equity centers on the choice of the discount factor since it determines what weight is given to the distant benefits of mitigation compared to the costs incurred today. These considerations are of subordinate relevance to the question of the opportunity cost of climate change mitigation, since the effects of variations in the discount factor affect the correct no-policy and the optimal policy scenario in a similar fashion. In a numerical sensitivity analysis, only a discount rate greater than $0.1/year$ would lead to a rejection by majority rule.

6 Conclusion

Conventional wisdom holds that present generations need to sacrifice part of their consumption to protect the world from climate change and thereby

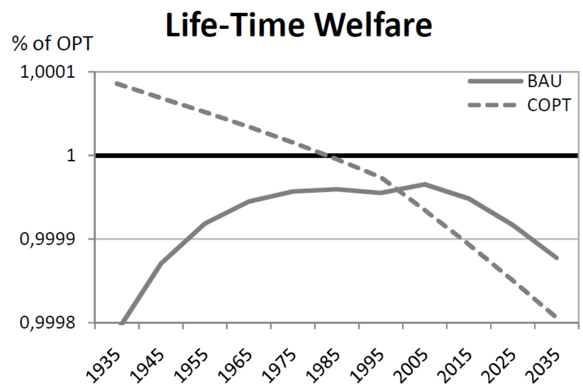

Figure 6: Lifetime Welfare of Generations born at t relative to OPT: Under COPT an optimal policy leads to a lifetime welfare loss for the majority of generations alive today. In contrast, this adoption creates a Pareto improvement for all generations under BAU. Note that for generations alive today the figure reports remaining lifetime welfare.

preserve consumption possibilities for the future. This assessment of the opportunity cost of mitigating climate change, however, rests on a theoretically inconsistent no-policy scenario (COPT). Given current methodological standards, only a reference path on which GHG emissions are a negative externality (BAU) can consistently feature zero mitigation.

Foley (2009) and Stern (2010) demonstrate that such an externality leads to a market failure and an inefficient allocation of resources. Numerical results based on DICE-07 support this point. By implementing the externality in it and solving for the equilibrium allocation, one can illustrate that under COPT consumption is inflated in early periods of the program due to low returns to capital investment. Climate policy increases the returns to capital and stimulates investment. Consumption levels fall relative to COPT in order to finance mitigation and additional investment. Present generations, therefore, have to bear a sacrifice. When using the correct reference path (BAU) this intergenerational conflict disappears. Under BAU calculations of the return to capital exclude climate damage and are above the social optimum. The internalization of the externality lowers the return to capital and discourages investment. Under climate policy, these resources are directed toward mitigation and higher consumption levels. The correction of the market failure makes all generations better off and represents a Pareto improvement. This result is even more stricking as studies based on DICE usually find the opposite.

The debate on intergenerational discounting has attracted much attention from researchers in the past. The finding that there is no intergenerational trade-off at the heart of the social choice problem of mitigation policy in standard models of climate change might help re-direct some of this attention to problems of market imperfections and remove theoretical objections to the adoption of mitigation strategies as called for in Stern (2010). It is important to note, though, that considerations of discounting and consumption smoothing remain relevant to the debate, since they identify the optimal policy response and provide answers to the questions of "how much?" and "how fast?".

References

ANTHOFF, D., AND R. S. TOL (2009): "The Impact of Climate Change on the Balanced-Growth-Equivalent: An Application of FUND," *Environmental and Resource Economics*, 43(3), 351–367.

ARROW, K. J. (2007): "Global Climate Change: A Challenge to Policy," *The Economists' Voice*, 4(3).

ASHEIM, G. B. (2010): "Intergenerational Equity," *Annual Review of Economics*, 2(1), 197–222.

BOVENBERG, A. L., AND B. J. HEIJDRA (1998): "Environmental tax policy and intergenerational distribution," *Journal of Public Economics*, 67(1), 1–24.

CHICHILNISKY, G. (1994): "North-South Trade and the Global Environment," *American Economic Review*, 84(4), 851–74.

CHICHILNISKY, G., AND G. HEAL (1994): "Who should abate carbon emissions? : An international viewpoint," *Economics Letters*, 44(4), 443–449.

DASGUPTA, P. (2008): "Discounting climate change," *Journal of Risk and Uncertainty*, 37(2), 141–169.

FOLEY, D. K. (2009): "Economic Fundamentals of Global Warming," in *Twenty-First Century Macroeconomics: Responding to the Climate Challenge*, ed. by J. M. Harris, and N. R. Goodwin, pp. 115–126. Edward Elgar.

IPCC (2007): "Summary for policymakers," in *Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, ed. by B. Metz, O. Davidson, P. Bosch, R. Dave, and L. Meyer. Cambridge University Press.

Karp, L. S. (2009): "Sacrifice, Discounting and Climate Policy: Five Questions," Discussion paper, CESifo Group Munich, CESifo Working Paper Series.

Karp, L. S., and A. Rezai (2011): "The Political Economy of Environmental Policy with Overlapping Generations," .

Nordhaus, W. D. (1977): "Economic Growth and Climate: The Carbon Dioxide Problem," *American Economic Review*, 67(1), 341–346.

——— (1994): *Managing the global commons: the economics of climate change*. MIT Press, Cambridge, Mass.

——— (2007): "A Review of the *Stern Review on the Economics of Climate Change*," *Journal of Economic Literature*, 45(3), 686–702.

——— (2008): *A Question of Balance: Economic Modeling of Global Warming*. Yale University Press, New Haven.

Nordhaus, W. D., and Z. Yang (1996): "A Regional Dynamic General-Equilibrium Model of Alternative Climate-Change Strategies," *American Economic Review*, 86(4), 741–65.

Rezai, A. (2010): "Recast the DICE and its Policy Recommendations," *Macroeconomic Dynamics*, p. forthcoming.

Rezai, A., D. K. Foley, and L. Taylor (2011): "Global Warming and Economic Externalities," *Economic Theory*, p. forthcoming.

Schelling, T. C. (1992): "Some Economics of Global Warming," *American Economic Review*, 82(1), 1–14.

Shiell, L., and N. Lyssenko (2008): "Computing business-as-usual with a representative agent and a pollution externality," *Journal of Economic Dynamics and Control*, 32(5), 1543–1568.

Stern, N. (2007): *The Economics of Climate Change: The Stern Review*. Cambridge University Press, Cambridge.

——— (2010): "Imperfections in the Economics of Public Policy, Imperfections in Markets, and Climate Change," *Journal of the European Economic Association*, 8(2-3), 253–288.

Weitzman, M. L. (2007): "A Review of the *Stern Review on the Economics of Climate Change*," *Journal of Economic Literature*, 45(3), 703–724.